THE USE OF AGGREGATE FROM DEMOLITION RUBBLE IN THE MAKING OF ORDINARY AND STRUCTURAL CONCRETES

A thesis presented to the
University of Cape Town
Department of Civil Engineering

In partial fulfilment of the
requirement for the degree of
Master of Science in Engineering

by

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DECLARATION

The writer hereby declares that the work contained herein, with the exception of quoted sources, is his own work and has not been submitted to any other university.

Clayton Frick

The writer has successfully completed course work to the value of 20 credits towards the MSc degree. This thesis therefore represents half of the credit requirements for the degree.

SYNOPSIS.

The aim of this thesis is to introduce the concept of recycling demolished concrete as aggregate which is then used in fresh concrete - to be known as "recycled concrete". Various aspects of concrete technology are covered and in this way recycled concrete is compared to conventional concrete.

The work was performed in three phases, and it should serve as a guide to prospective users.

PHASE 1: Various recycled aggregates were tested according to standard specifications and were found to be satisfactory in most aspects. Recycled fine aggregate is very coarse though, and should be used with caution. The absorption and porosity of recycled aggregates should always be determined to enable their use in concrete. The specific gravity of such an aggregate should also be found to enable more accurate mix calculations. The highest compressive strengths normally possible for recycled concretes are between 56 and 71 MPa, but an average strength of 50 MPa should not be exceeded without thorough investigation, even though it is easily attainable.

PHASE 2: A wet-batching method of mix design was investigated and satisfactory recycled concretes were produced. Strength charts for such concretes are given. Methods of dry-batching are also presented, but are more complex than the wet-batch method. The water demand of recycled fine aggregates was found to be considerably higher than for natural sands, and again the use of fine recycled aggregate should be carefully considered.

PHASE 3: The mechanical properties of recycled concretes were tested and little difference found between recycled and conventional concretes. The compressive strengths were satisfactory and the elastic moduli sufficiently high, even though they were 15 to 20 percent lower than those of corresponding dense concretes. The shrinkage of recycled concrete is comparable to that of conventional concrete, and the creep potential somewhat greater, although not excessivly so.

The use of recycled coarse aggregate in both plain and structural concrete is then recommended as an alternative to the dwindling supply of natural aggregates. The use of recycled fine aggregate, however, is not recommended, although its use in low-grade or mass concrete is condoned.

DEDICATION

This work is dedicated to my parents
and to Katrina.

It is also in memory of

Richard George Nutt
Christiaan Coetzer
McKinley Morganfield.

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INTRODUCTION

1.1: The History of the Subject

The concept of recycling demolished concrete originated toward the end of World War II, when engineers were faced with the dual task of rebuilding entire cities, and clearing the vast amounts of rubble and debris that had been created.

The first known publication on the subject, written by Gluzghe (*1), a Soviet scientist, appeared in 1946. In 1947, an MSc thesis was submitted to Cornell University, United States, by Ploger (*2) who investigated the possibilities of recycling crushed concrete. In Germany during 1948, Graf (*3) also experimented in this field. Even though the subject had been researched, no records of any practical uses of recycled concrete exist.

However, the 1970s saw the advent of the energy crisis, which combined with both an increasing scarcity of dumping terrain for rubble and diminishing resources of natural aggregates, led the Europeans and North Americans to investigate the subject with revived interest.

In 1977, the USA produced about 45-million tonnes of building and highway rubble (*4). One of the world's foremost authorities on the recycling of concrete, Professor Frondistou-Yannas of the Massachusetts Institute of Technology, notes that:

> "The successful recycling of concrete from demolition wastes as a substitute aggregate for new concrete can make a contribution to solving two problems of increasing magnitude.
>
> "Firstly, an availability problem: Concrete aggregates are locally unavailable in many metropolitan areas, both because urban expansion had lead to the closing of several aggregate plants and because of enforcement of environmental laws. Consequently, it becomes neccessary to transport concrete aggregates over increasingly longer distances. This creates a serious economic problem since concrete aggregates are bulky and heavy, and the cost of their transportation is correspondingly high.
>
> "Secondly, the waste disposal problem: Recent studies indicate that the waste from demolition in the USA reaches the substantial figure of 30-million metric tonnes per annum. Since concrete accounts for about 75 percent by mass of all construction materials used, it follows that concrete will acount for three-quarters of all demolition wastes. It has become increasingly difficult and expensive to dispose of construction and demolition debris within the bounds of the increasingly critical environmental requirements. In short, contractors are running out of dumps." (*5)

For several years the Americans have been recycling concrete highways (commonly referred to as "concrete pavement" in the USA) by using portable crushing machinery to provide recycled aggregates - which are used mainly as sub-base material - and also in the fresh concrete for the new pavement (*4). This has lead to significant savings in transport costs, but recycled concrete has not really been used for any other concreting applications.

In November 1980, the North Atlantic Treaty Organization (Nato) Advanced Research Institute held an international symposium in France entitled

"Adhesion Problems in the Recycling of Concrete", co-ordinated by Pieter Kreijger of the Eindhoven University of Technology. The symposium produced publications covering demolition methods, fracture mechanics and concrete technology.(*6)

In South Africa, recycling crushed concrete is relatively uncommon: understandably so, as the population density is considerably lower than in Europe or North America, and consequently the civil engineer does not face the same problems in the manufacture of concrete and the disposal of rubble. Abundant resources of natural aggregates exist and there is sufficient space to conceal unsightly rubble dumps or landfills. Consequently, there has been no need to investigate and employ alternative concrete materials.

In certain areas of the country, local natural aggregates are not suitable - the main problems being reactive coarse aggregates and unsuitable natural Sands ~~soils~~. In these instances the appropriate aggregates have to be transported at considerable cost from another region. Additionally, in South Africa the best natural aggregates available are often used indiscriminately in all applications, even for low-key concreting jobs such as mass concrete. There is a myoptic and uneconomical use of dwindling natural re-sources, even though it may appear that these resources "will never run out".

The need for alternatives such as recycled concrete will certainly exist in the future, and the construction industry would find it advantageous to become better acquainted with the process.

1.2: The Nature of Recycled Aggregates

The aggregate, both fine and coarse, is produced by crushing demolished concrete and is generally coarse-textured and light-coloured (due to the mortar of the parent concrete). The shape of the aggregate is determined by the crushing process; for example, a more cubic shape is obtained by hand-crushing with a hammer than by using a jaw-crusher.

Phase 1 of this work will cover the testing of these recycled aggregates, with reference to relevant codes of practice.

1.3: Mix Design with Recycled Aggregates

The fact that recycled aggregates are by nature porous, and therefore will absorb water from the mix, means that the aggregate porosity should be given due attention.

South African mix design procedures are based on the Water Demand Theory, whereby the water requirement of the sand to be used is determined as a starting point of the design. Charts of concrete strengths versus cement-to-water ratios for various combinations of aggregates and cement types are available. Furthermore, there are numerous aids to the designer that suggest stone contents, sand grading, slump adjustments, etc. The constituents of a mix are usually batched in the dry condition, as the coarse natural stone is impervious and the sand is the main determinant of the water content.

Design methods for recycled aggregates in which the porosity of the aggregate is taken into account, and which follow established procedures will then be required. Phase 2 of this work will then concern itself with the development of such mix design methods.

1.4: The Mechanical Properties of Recycled Concrete

It stands to reason that the mechanical properties of the recycled concrete will depend largely on the properties of the aggregate used, as the strength of the recycled aggregate is considerably less than the strength of natural stone aggregate. Consequently, if a poor concrete is crushed for aggregate, then a superior quality of recycled concrete cannot be expected. The converse will also be true.

In Phase Three of this work, the mechanical properties of recycled concrete will be investigated and compared with the results of overseas research.

1.5: Contamination Problems in Recycled Concrete (from Young; *7)

Consideration should be given to the possible presence of contaminants in the rubble to be recycled, and thus prevent the occurrence of undesirable, harmful interactions between the contaminants present in the recycled aggregate and the fresh concrete. The sources and types of possible contaminants are shown in Table 1.1 below. Young (*7) has established two categories:

SOURCE	TYPE
1. Within the concrete	(i) Reinforcing steel (ii) Admixtures from the old concrete (iii) Chemical contaminants such as de-icing salts, oils, sea salts, etc.
2. Within the structure	(i) Metals (aluminium, zinc, copper etc) (ii) Gypsum (from plaster and dry walls) (iii) Wood (iv) Brick (v) Glass (vi) Plastics

TABLE 1.1: Sources and types of contaminants in demolished concrete

No critical contaminants are envisaged within the parent concrete. The reinforcing steel (termed "rebar" in the USA) that could damage crushers and machinery may be removed by manual and magnetic seperation. The chemical contamination and admixtures present in the crushed aggregate may affect the fresh concrete by interfering with any admixtures that might have been added to the new mix, or may alter the setting behaviour of the new concrete. Any such contamination can be determined in preliminary testing.

The de-icing salts used in North American and European paved roads and bridges contain chlorides that will attack and corrode the reinforcing steel. For plain unreinforced concretes no problems are forseen in this respect. However, an excess of chlorides causes unsightly efflorescence on the surface of the concrete.

The following deleterious substances should be avoided:

(i) Brick: Certain types of brick are highly expansive when wetted and could cause excessive cracking in the concrete. Otherwise use of brick in concrete is not a problem and has been done in practice. Brick will, however, increase the absorption of recycled aggregate, and will therefore reduce concrete workability if no allowance is made.

(ii) Wood: Wood is considered an undesirable contaminant since it is soft, swells when moistened, and is degraded by alkalis. Wood may contain natural sugars that will retard the setting of the concrete. Wood may be seperated from recycled aggregates by density seperation methods.

(iii) Gypsum: Considered to be the worst possible contaminant in demolition rubble, gypsum will occur in debris from interior drywall partitions, ceiling boards and plastered surfaces. As gypsum is soft and crumbles easily, it will occur predominantly in the fine material of recycled aggregates - this being another reason why it is advisable to avoid recycled fine aggregate.

The gypsum $CaSO_4.2H_2O$ is potentially deleterious because it reacts with the cement paste, and in so doing, sets up sulphate attack which degrades the concrete. This results in a considerable loss of strength and increased expansion properties in the concrete. In 1948, Graf (*3) set the maximum tolerance level of gypsum at 1% by weight of aggregate and this figure is still used today.

The deleterious sulphate attacks the tricalcium aluminate (C_3A) of the cement, which sets up the subsequent degradation. Researchers have stated that the resistance to sulphate attack in the case of Portland cement elements depends primarily on two factors:

(a) The cement content of the concrete, and
(b) the composition of the cement, specifically the C_3A content.

There are then factors that may be considered in the manufacture of recycled concrete if there is concern about gypsum contamination.

(iv) Glass: Waste glass can be potentially deleterious in recycled concretes as it~~s high alkali content~~ can lead to adverse ~~alkali-silica~~ reactions.

In general, wetting the aggregates will remove appreciable amounts of deleterious materials - which is another advantage in employing wet-batched methods (as discussed in Phase 2). Additionally, by avoiding the recycled fine aggregate, the presence of contaminants may be further reduced.

1.6: The Economic Feasibility of Recycling Concrete

The economic feasiblity of using recycled aggregates in fresh concrete was considered to be beyond the scope of this thesis, although some mention of the cost of materials used in local concrete will be made in Phase 2. Frondistou-Yannas conducted a study (*8) of the economic feasibility of such concretes in the USA. Her study was based on information collected from the ten recycling plants extant in 1980.

Many of the parameters involved in the Frondistou-Yannas study of American conditions apply to South African conditions. For readers with a particular interest in this aspect, reference 8 is recommended, as is another version of the study as presented to the 1980 Nato symposium - see reference 9.

2: PROCEDURE

The aim of this study is then to introduce the concept of recycling demolished concrete, and then to cover various aspects of concrete technology, so that this work may serve as as guide to prospective users. The work will be performed in three phases.

Phase 1: The Testing of Recycled Aggregates.

Various tests were performed on the range of demolished rubble aggregates and all these results are not only compared to specifications such as BS 812 and SABS 1083, but will also serve as a database for further work with recycled aggregates.

Phase 2: Mix Design with Recycled Aggregates

Using the aggregate properties generated in the first phase, different methods of mix design with their aggregates were developed. The two general categories of mix design are wet-batched and dry-batched methods.

Phase 3: The Mechanical Properties of Recycled Concrete

Concrete will be made from recycled aggregate and will be tested for mechanical properties such as compressive, flexural and tensile strengths, creep and shrinkage, and elastic modulus. A comparison will then be made with the findings of other researchers and with conventional concrete.

3.1: Introductory Theory

Making concrete from recycled aggregates would be no different from using natural aggregates if it was not for the fact that recycled aggregates are porous by nature. This porosity imparts certain special characteristics to the aggregate, causing it to behave differently in the making of concrete. A further consideration is that ~~that~~ recycled aggregates could in no way be as strong and durable as natural aggregates. Concrete producers are also concerned about the possible contamination that may exist in these aggregates made from demolished concrete rubble.

It is therefore essential that the recycled aggregates should be analyzed and tested so that a spectrum of their properties related to concreting may be available. This range of properties will serve many purposes, the two most important being:

(i) That the reputation of recycled aggregates may be enhanced by comparing them to conventional aggregates and code-of-practice requirements, and

(ii) that these properties may be used to develop more accurate and economic mix designs producing reliable concrete.

Recycled aggregates can be compared with lightweight aggregates in many ways. The fact that many lightweight aggregates are artificially produced under controlled conditions means that their qualities and strengths are of a consistent, and by now, trusted nature. Therefore, having had a humble beginning, the technology of lightweight aggregate concrete has grown to a sophisticated level, and is in frequent use worldwide. (Short and Kinniburgh, *10; Cembureau, *11; Frick, *12).

If a factual basis of aggregate properties is created, and then further data is generated for mix design using recycled aggregates as well as for the various properties of such recycled concretes, then recycled aggregate concrete could follow a path similiar to other engineering materials.

3.2: Testing Procedures

Ten different samples of concrete that were generated by the demolition of various structures such as bridges, blocks of flats and floor slabs, were used in these tests. These samples were collected as large chunks of rubble from a dumping ground on Koeberg Road, Milnerton, Cape Province. Each sample was placed inside a large, airtight plastic bucket and each bucket labelled.

Ten of these samples were only of the order of 20 kg each and were used to obtain a range of values in each of the aggregate tests that were performed. An eleventh sample was collected afterwards to serve as a stockpile of aggregate to be used in Phases 2 and 3 of this thesis - this stockpile sample had a mass of over 1000 kg.

The large chunks (50 mm to 500 mm) of rubble had to be hand-crushed by hammer down to a size suitable for a jaw-crusher. Geoplan Laboratories in Beaconvale kindly made their jaw-crusher available, and each sample was passed through this machine twice and crushed down to a maximum ~~minimum~~ size of 25 mm. Care was taken not to lose any of the sample during the crushing process.

The samples were then returned to the university laboratory where they were screened and prepared for the aggregate tests that followed.

The aggregate testing was done according to the British Standard (BS) 812:1967 - "Methods for Sampling and Testing of Mineral Aggregates, Sands and Fillers" (*13), which specifies the following procedure:

Section One: Sampling and submission of samples.

No attention to this section was necessary as the samples had been collected, crushed and returned to the laboratory with due care.

Section Two: Description and classification.

A description of each sample is required and parameters to be heeded are particle shape, surface texture, impurities, cleanliness and colour.

Section Three: Determination of particle size and shape.

The tests described here are sieve analysis, determination of the flakiness index, the elongation index, and the angularity number.

Section Four: Determination of specific gravity, water absorption, density, voids and bulking.

Methods are described for the various types and sizes of aggregates that may be tested.

Section Five: Determination of moisture content of aggregate.

Section Six: Detection of organic impurities in fine aggregate.

Section Seven: Determination of mechanical properties of aggregates.

The tests described are for:
i) aggregate impact value;
ii) aggregate crushing value;
iii) ten percent fines value;
iv) crushing strength;
v) aggregate abrasion value, and
vi) laboratory-determined polished stone value.

Since certain of the tests described by BS 812 were not relevant to the work envisaged for Phases 2 and 3, they were omitted. Limitations in the amounts of sample available also necessitated the omission of certain tests.

The following tests were performed:

1. Sieve analysis (particle size analysis).

2. Initial moisture content.

3. Particle shape indication (flakiness index, angularity number, elongation index)

4. Specific gravity, absorption, density, voids, bulking.
5. Aggregate strength indices (10% fines value and remoulded peak strength).
6. Quality indication (detection of organic impurities)

Note: (i) This is a new test developed by the writer for further indication of the strength of aggregate. It is discussed in Section 3.2.5.2.
(ii) The 10% fines value is also known as the 10% FACT value, and is the strength test for aggregates favoured by the SABS.

The descriptions of the aggregate samples are included in two of the abovementioned tests: namely the particle size analysis and the initial moisture content determination.

The tests that were omitted were therefore: the aggregate crushing strength, since core samples were required; the aggregate impact value and the aggregate abrasion value, as the latter two tests were considered to be impractical; the aggregate crushing value, because it was decided that the 10% fines crushing value would be sufficient - this was to conserve the amount of sample to be used as both the crushing value and 10% fines value test used a substantial amount of material.

3.2.1: Particle Size Analysis

Procedure:

Once the rubble had been crushed the maximum size of the particles was approximately 30mm. The aggregates were then sieved according to the specifications in SABS 1083 (*14), using the following sieve sizes for the coarse aggregates (by definition all the particles over 4,75 mm in diameter):

26,5 mm; 19,0 mm; 13,2 mm; 9,5 mm; 6,7 mm; 4.75 mm; pan.

A very small percentage of the particles was retained on the 26,5mm sieve, and the grading of the coarse aggregate was calculated only for the particles passing through the 26,5 mm sieve.

The fine aggregate which passed through the 4,75mm sieve was then further sieved using a series of sieves in a mechanical shaker for 20 minutes per load. The following SABS sieve sizes were used:

4750 µm; 2360 µm; 1180 µm; 600 µm; 300 µm; 150 µm; pan.

The grading of the fine aggregate, or "fines", was then calculated from the information gained by the sieving process.

At this stage it was found that three of the samples collected had unfortunately been spoiled - this was ascertained by comparing the total mass of the samples with their initial weights which were labelled on the buckets in which they were kept. These samples - 2, 3 and 7 - thus had to be ignored in the particle size analysis as the original and sieved masses differed substantially.

SAMPLE	1		4		5		6		8		9		10		Stockpile	
SABS sieve aperture.	% of total mass	Total % retained on sieve	%	Total % R	%	Total % R	%	Total % R	%	Total % R	%	Total % R	%	Total % R	%	Total % R
19.0 mm	13·4	13·4	21·1	21·1	8·5	8·5	17·3	17·3	16·1	16·1	4.8	4.8	13·5	13·5	25·5	25·5
13·2 mm	31·6	45·0	23·8	44·9	30·9	39·4	26·4	43·7	26·0	42·1	25·1	29·9	29·0	42·5	24·8	50·3
9·5 mm	11·3	56·3	10·9	55·8	14·8	54·2	12·2	56·0	12·3	54·4	22·8	52·7	13·0	55·5	11·6	61·9
6·70 mm	9·1	65·4	9·1	64·9	11·3	65·5	9·5	65·5	10·2	64·6	12·7	65·4	10·1	65·6	9·1	70·0
4·75 mm	6·5	71·9	6·3	71·2	7·1	72·6	6·9	72·4	7·3	71·9	8·0	73·4	7·6	73·2	5·8	76·8
2·36 mm	8·0	79·9	7·6	78·8	8·1	80·7	8·0	80·4	8·4	80·3	9·3	82·7	8·4	81·6	6·8	83·6
1·18 mm	6·0	85·9	5·1	83·9	6·7	87·4	6·6	87·0	5·6	85·9	5·6	88·3	4·9	86·5	4·3	87·9
600 μm	4·2	90·1	4·1	88·0	4·5	91·9	4·5	91·5	3·9	89·8	3·3	91·6	3·8	90·3	3·5	91·4
300 μm	4·4	94·5	4·9	92·9	3·7	95·6	4·3	95·8	4·9	94·7	4·0	95·6	4·9	95·2	5·2	96·6
150 μm	2·7	97·2	3·7	96·6	2·4	98·0	2·0	97·8	2·5	97·2	2·0	97·6	2·6	97·8	1·6	98·2
passing 150	2·8	—	3·4	—	2·0	—	2·2	—	2·8	—	2·4	—	2·2	—	1·8	—
Fineness	Moduli of the		aggregates :													
of sand	3.12		2.93		3.29		3.29		3.16		3.36		3.17		3.18	
of stone	2.52		2.58		2.40		2.55		2.49		2.27		2.50		2.86	
overall	6.99		6.99		6.93		7.07		6.98		6.83		7.00		7.44	

TABLE 3.1 : Details of the Particle Size Analysis of the Recycled Aggregate samples.

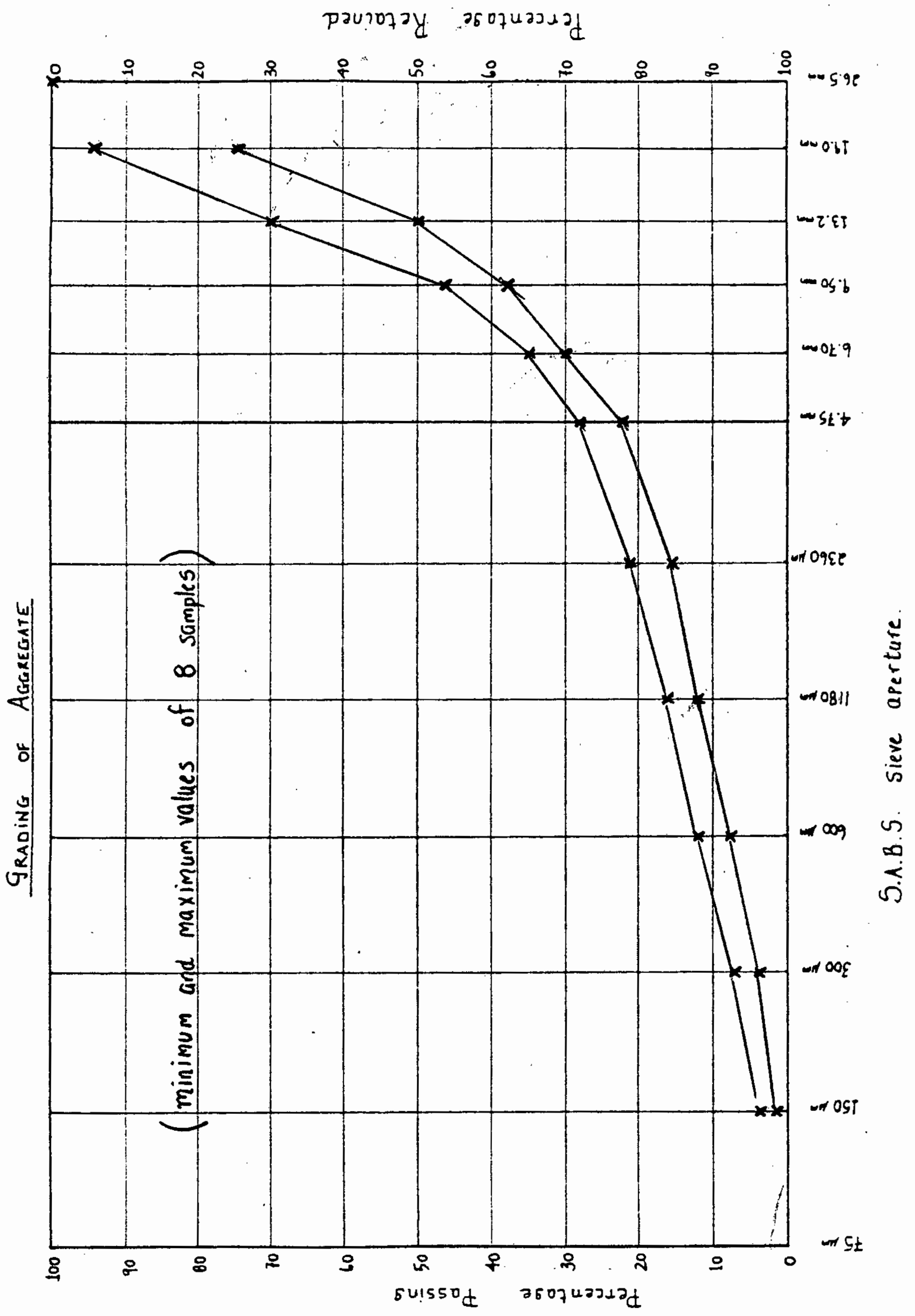


Figure 3.1 : The Grading Envelope of the Recycled Aggregates that were tested.

For each sample the fineness modulus of the "fines" was calculated by the method described in SABS 1083 (*14). A relative value is calculated for the coarse aggregates following the same reasoning as that with which the fineness modulus is determined. For the aggregate as a whole - fine and coarse fractions - an overall modulus is calculated similarly to enable comparison with one another.

All the charts showing the grading calculations of each of the samples (including the stockpile that was used in Phase 2 and 3) as well as their grading curves may be found in Appendix A1. Table 3.1 shows the summarized details of the particle size analysis, and Figure 3.1 shows the grading envelope of all the samples tested.

For the purpose of comparison, the two types of natural sand commonly available in the Cape Town area, namely the fine Cape Flats sand and the coarser Klipheuwel sand, were also analyzed and the results included.

Comments:

For eight samples in total that visibly varied from one another in colour, constituent stone and strength, the range of results are fairly narrow as can be seen from Figure 3.1. The fineness moduli of the "recycled sand" were from 2.93 to 3.36, the relative moduli of the coarse aggregates from 2.27 to 2.85 and the overall particle size moduli from 6.83 to 7.44. The recycled "fines" may thus be considered to be fairly coarse compared with the fineness modulus of 2.02 for the finer Cape Flats sand and the 2.18 of the coarser Klipheuwel sand.

3.2.2: Initial Moisture Content

Procedure:

The samples had been collected in August 1985 following a week of rain and then a week of unusually warm weather. The fines of each sample were oven-dried for at least 24 hours in pans at a temperature of 105°C.

Details of each sample are reflected in Appendix A2 and the summarized results are shown overleaf in Table 3.2. The initial moisture contents are expressed as a percentage of the oven-dried mass of the sample.

Comments:

The only value of this test is that it gives some indication of what moisture contents may be expected in rubble from samples collected from dumps and other locations. Samples 1 to 8 were collected from the Koeberg Road dumping terrain during the Cape winter - thus their moisture contents vary from approximately 5% to 8%. Sample 9 was from a demolished slab made in the UCT laboratory in 1983, and had been lying outdoors for several months before the sample was collected during the summer of 1984, hence the slightly lower initial moisture content.

The stockpile for the mix design in Phase 2 was also collected from Koeberg Road dump, but during mid-summer in 1985, hence its lower moisture content of 4.2%. Sample 10 was collected from a demolished block of flats in Sea

Point, Cape Town, during 1984 and had been air-dried on display in UCT laboratory for over a year before its moisture content was determined - hence the minimal content of 1.85%.

SAMPLE NUMBER	INITIAL MOISTURE CONTENT
1	6.98%
2	spoilt
3	spoilt
4	6.74%
5	4.96%
6	5.67%
7	spoilt
8	8.05%
9	3.94%
10	1.85%
(11) Stockpile	4.20%

Table 3.2: Initial moisture contents

Note: Spoilt samples 2, 3 and 7 were not included in Section 3.2.1.

3.2.3 Particle Shape Indication

Procedure:

Three fairly simple tests were described in BS 812 to give an indication of one aggregate's particle shape as compared to another. There are tests for:

(i) Flakiness Index;
(ii) Elongation Index, and
(iii) Angularity Number.

The procedures to be followed and apparatus used for each is included in Appendix A3.

3.2.3.1: Flakiness Index

An attempt is made to pass each of the particles individually through the gauge plate shown in the Appendix A.3 and finally the masses of each fraction are found and the flakiness index of each size fraction is then calculated. An overall flakiness index is then found. See the data in Sheets 1 to 9, also in Appendix A.3.

3.2.3.2: Elongation Index

This is a similiar test to the flakiness index test, but this time the apparatus consists of a wooden block with appropriately spaced dowels providing the gauged spacings. The particles are then fitted through the relevant slots on the apparatus.

The apparatus had to be made in the workshop, and as the spacings specified correspond to the sieve sizes indicated in BS 812, and the SABS 1083 sieve sizes differ slightly from these, the correct widths are calculated in Table 1.3 overleaf:

BS 812 SIEVE SIZES (mm)	AVERAGE SIZE (mm)	THICKNESS GAUGE (mm)	GAUGE FACTOR (mm)
25.40 - 19.05	22.225	13.34	0.600
19.05 - 12.70	15.875	9.53	0.600
12.70 - 9.52	11.110	6.68	0.601
9.52 - 6.35	7.935	4.78	0.602
SABS SIEVE SIZES (mm)	AVERAGE SIZE (mm)	CALCULATED GAUGE THICKNESS (mm)	GAUGE FACTOR (as above)
26.50 - 19.00	22.750	13.65	0.600
19.00 - 13.20	16.100	9.66	0.600
13.20 - 9.50	11.350	6.82	0.601
9.50 - 6.70	8.100	4.88	0.602

Table 3.3: Calculation of gauge widths for the elongation index

The apparatus was then made from a wooden base into which thick nails were driven to provide the gauge spacings. The gauge widths were measured afterwards and found to differ slightly from the calculated widths, and hence the correction factor reflected in the tables are shown in Sheets 1 to 9 in Appendix A3.

3.2.3.3: Angularity Number

This test requires data from the specific gravity, water absorption and voids tests discussed in Section 3.2.4 - namely, the specific gravity of the particle size fractions and the completed bulk density. The same cylinders that were specially made for Section 3.2.4 were also used.

The Angularity Number is calculated as follows:

$$A = 67 - \frac{100W}{C.G} \qquad \text{. . . equation 3.1}$$

Where W = the compacted dry ~~bulk density~~ mass of the particles;
C = the volume of the container used, and
G = the specific gravity of the particles.

The basis of reason in this calculation is that if particles are perfectly round, then 33% voids will occur in the packing matrix, hence the "67 - (*)" in the calculation. The angularity number is thus the difference between the "packing voids of particles" and "packing voids of round particles". The data for each sample are shown in Sheets 1 to 9 in Appendix A3.

SAMPLE	FLAKINESS					ELONGATION					ANGULARITY			
	I	II	III	IV	Total	I	II	III	IV	Total	I	II	III	IV
1	10	7	12	11	10	11	15	6	18	12	10.7	8.4	3.8	-
4	10	12	14	17	11	12	18	16	20	14	9.2	6.7	2.5	2.3
5	8	5	6	9	6	10	8	6	15	9	-	7.2	3.6	2.5
6	14	12	12	13	13	16	16	12	22	16	11.3	8.7	2.9	2.5
8	17	9	20	18	15	21	17	21	18	20	5.3	9.5	1.9	2.4
9	5	6	3	5	5	7	10	3	11	8	-	8.4	3.4	4.6
10	10	8	7	6	9	16	15	8	14	14	10.3	7.9	2.9	4.5
S/P*	13	10	17	18	13	17	16	19	23	17	7.5	6.3	1.2	0.3

* Stockpile

Size Fractions: I = 26.5 - 19.0 mm; II = 13.2 - 19.0 mm;
III = 9.5 - 13.2 mm; IV = 6.7 - 9.5 mm

Table 3.4: Particle shape indicators for recycled aggregates

Sample 9 had the smallest original stone size, with a maximum of 13 mm, and visibly had the roundest particles. Its flakiness index was therefore the lowest, as expected, namely a value of five. Its elongation index was also the lowest - at eight, but its angularity numbers are no different from other samples. Sample 8 had as its original stone a very angular, black hornfels of maximimum size over 52 mm (2 inches) and crushed it had the highest flakiness and elongation index, of 15 and 20 respectively. Its angularity numbers are also much the same as for the other samples.

It appears that the angularity numbers depend largely on the crushing process - that is, one crushing process will produce a certain degree of angularity and another process a different degree. The jaw-crusher used was set to produce a maximum aggregate size of 24.5 mm (one inch). Thus size fractions I and II (19.0 mm - 26.5 mm and 13.2 mm - 19.0 mm) will be most relevant to indicate an angularity degree. For size fraction II, the range of angularity is very narrow (6.3 to 9.5), and for size fraction I, the range is 5.3 to 10.7.

Another crushing process would probably produce a different degree of angularity. For example, it is known that hand crushing of aggregates produces more rounded and more cubic particles than does machine crushing. The angularity numbers in the corresponding size fractions will therefore tend to be different.

The flakiness and elongation indices seem to be more dependent on the actual aggregate properties, and hence the results were more in line with those expected from a visual examination.

The highest single value of either index was 23 (the elongation index of the mix-design stockpile for size fraction IV). This means that 23% of the aggregate particles are considered to be "elongated". The criterion for a particle being "flaky" or "elongated" is that the maximum dimension of the particles be less than a certain fraction/percentage of its maximum or average dimensions, as shown in Figure 3.2.

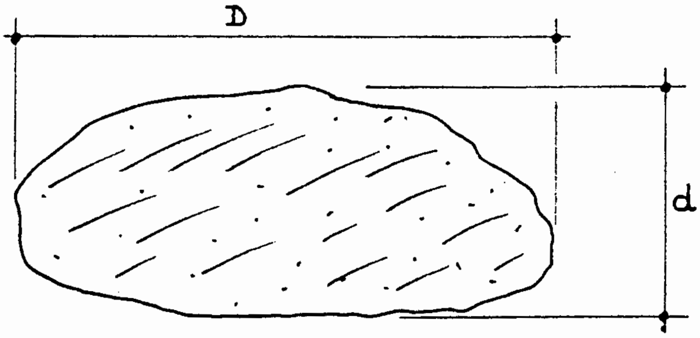


Figure 3.2: Dimensions of an aggregate particle

Two types of natural aggregates were available in the university laboratory; a 13 mm hornfels and a 19 mm granite. The hornfels is visibly quite flaky with flat and poorly-shaped particles, whilst the granite is easily seen to be more cubic in shape. The flakiness index of the hornfels was found to be 19 and its elongation index to be 20, whereas the flakiness index of the granite was four, and its elongation index to be five.

3.2.4: Specific Gravity, Absorption and Voids of Aggregates

This test is probably the most important and informative done on the rubble aggregates. The test is fairly simple, lasts 24 hours and gives some useful information concerning the rubble aggregate. The major difference between rubble aggregates and natural aggregates is the porosity of the former - and in designing concrete mixes using the recycled aggregate, this is the factor that requires attention - otherwise their mix designs would have been no different.

Just this single test on a sample produces the following information:

(i) The specific gravity and densities (dry bulk, compacted and absolute)
(ii) the porosity of the aggregate;
(iii) the absorption of the aggregate;
(iv) the voids present in the aggregate packing, and
(v) the bulking of the aggregate as it is wetted.

(Bulking occurs when an aggregate is wetted and it undergoes a volume change, usually an expansion.)

Two steel cylinders with handles and heavy bases were made in the workshop to comply with the required type of container specified in BS 812.

They were then calibrated as follows:

> The "dry mass" of the cylinder is determined, then it is filled to the brim with water and the gross mass measured. The volume of the cylinder is therefore equal to the mass of water that fills the cylinder as the density of water is 1 gram per millilitre (1 cubic centimetre equals 1 millilitre).

Cylinder 1:

TRIAL	MASS OF DRY CYLINDER	MASS OF FILLED CYLINDER	VOLUME (ml)
1	2677	4176	1499
2	2678	4174	1496
3	2677	4172	1495
		Average:	1497

Table 3.5(a): Calibration of Test Cylinder 1

Cylinder 2:

TRIAL	MASS OF DRY CYLINDER	MASS OF FILLED CYLINDER	VOLUME (ml)
1	2637	4124	1487
2	2637	4125	1488
3	2638	4125	1487
		Average:	1487

Table 3.5(b): Calibration of Test Cylinder 2

It was also found that it takes 3 to 4 ml of water to wet the walls and base of each cylinder, but this feature is ignored in the calculations as it is within the range of experimental error.

Procedure:

(i) Using oven-dried aggregate, fill the cylinder up to its brim whilst vibrating it on a vibrating table. Pieces of aggregate are then hand-fitted into any remaining gaps until the cylinder is fully packed. This level is determined to be flush with the cylinder walls by rolling the tamping rod over the cylinder walls. The rod must roll freely, indicating that the cylinder is not overfilled.

Two values are read in this step - the mass of the empty cylinder (A) and the mass of the filled cylinder (B). The mass of the dry aggregate filling the cylinder is thus found, and using the known volume of the cylinder, the compacted dry bulk density is calculable.

(ii) Fill the ~~cylinder~~ Voids with water and leave for at least 24 hours, so that the absorption is complete. The cylinder may be tapped with a tamping rod or vibrated lightly to allow trapped air bubbles to escape. Before the mass reading is taken, it should be ensured that the water level is to the brim of the cylinder.

The mass of the filled cylinder (C) is taken, and compared with the previous reading will give the total amount of water required to fill voids within the cylinder. The total volume of voids in the packing of aggregate and in the aggregate porosity is then found.

(iii) Place some mesh over the cylinder and pour the free water out of the cylinder by turning it upside down. Allow it to remain upturned for three minutes, turn upright, and reweigh the cylinder to find the mass of the cylinder and saturated aggregate (D).

Empty the saturated aggregate from the cylinder and allow it to surface dry for another three minutes, but ensure that no solid aggregate particles are lost in the process. Refill the cylinder with the surface-dried aggregate and if any bulking occurs, it should be noted and measured. The mass is again taken to give the mass of cylinder and saturated stone (E).

It is assumed that reading D still contains some free water that will add to the absorption of the aggregate, whereas reading E may reflect the loss of some water from the aggregate pieces and thereby reduce the absorption figure. The mass of the cylinder and saturated aggregate is thus taken as $\hat{D}$, which is the average of the two abovementioned readings.

Appendix A4 shows data sheets of each of the aggregate samples tested. Three size fractions of each sample - namely the 19.0 to 26.5 mm, 13.2 to 19.0 mm, and the 4.75 to 13.2 mm fractions, were tested. The calculation of each relevant parameter concerning the aggregate is shown in these sheets as well.

Results:

The calculation of the following parameters is performed in Appendix A4:

(i) compacted bulk density;
(ii) compacted saturated bulk density;
(iii) aggregate absorption coefficient;
(iv) total voids percentage;
(v) porosity percentage of aggregate by volume;
(vi) packing voids percentage;
(vii) absolute density including pores;
(viii) absolute density as solid material;
(ix) apparent specific gravity as porous material, and
(x) specific gravity as solid material.

The results are shown in Table 3.6 along with additional information from the other aggregate tests done.

The data for each size fraction may be combined to give an overall figure for that specific sample - this was done for the overall absorption percentage, overall porosity and overall absolute density as porous material.

If there are n size fractions and the masses of absorbed water are a_1; a_2 ... an (millilitres); the dry mass of samples are m_1; m_2 ... mn (millilitres), then the calculations for the the overall figures are as follows:

and av_1 ; av_2 .... av_n are the volumes of the samples

PROPERTY OF AGGREGATE	SAMPLE 1			SAMPLE 4			SAMPLE 5			SAMPLE 6			SAMPLE 8			SAMPLE 9			SAMPLE 10			MIX DESIGN STOCKPILE				
SIZE FRACTIONS (mm)	19.0 to 26.5	13.2 to 19.0	4.75 to 13.2	19.0 to 26.5	13.2 to 19.0	4.75 to 13.2	19.0 to 26.5	13.2 to 19.0	4.75 to 13.2	19.0 to 26.5	13.2 to 19.0	4.75 to 13.2	19.0 to 26.5	13.2 to 19.0	4.75 to 13.2	19.0 to 26.5	13.2 to 19.0	4.75 to 13.2	19.0 to 26.5	13.2 to 19.0	4.75 to 13.2	19.0 to 26.5	13.2 to 19.0	9.5 to 13.2	6.7 to 9.5	4.75 to 6.7
Compacted dry bulk density : kg/m^3	1299	1324	1282	1397	1356	1282	1246	1397	1360	1436	1328	1286	1436	1285	1308	N.A.	1297	1362	1365	1386	1300	1386	1342	1342	1301	1272
Compacted saturated bulk density : kg/m^3	1380	1415	1413	1446	1439	1425	1316	1468	1491	1495	1415	1428	1491	1359	1455	N.A.	1346	1468	1420	1455	1420	1459	1433	1464	1434	1470
Absolute porous density : kg/m^3	2295	2265	1984	2453	2265	1890	2269	2275	2021	2459	2289	1918	2465	2328	1960	N.A.	2163	2114	2396	2342	2006	2331	2213	2044	1955	1780
Absolute porous weight density : kN/m^3	22.51	22.22	19.47	24.06	22.22	18.54	22.26	22.50	19.83	24.12	21.96	18.81	24.19	22.83	19.23	N.A.	21.22	20.74	23.51	22.98	19.68	22.87	21.71	20.05	19.15	17.45
Absorption coefficient : %	6.21	6.71	10.27	3.44	6.15	11.12	5.58	5.79	9.59	4.14	6.39	11.04	3.84	5.76	11.24	N.A.	7.93	7.80	4.01	5.00	9.20	5.29	6.77	9.06	10.25	15.55
Porosity of aggregate : %	14.25	15.20	20.37	8.44	15.93	21.01	12.66	13.15	19.38	10.18	14.30	21.16	9.47	13.40	22.02	N.A.	17.15	16.49	9.61	11.70	18.45	12.33	14.98	18.51	11.98	27.66
Total voids : %	51.45	50.43	48.56	47.83	48.49	46.40	52.03	46.63	45.73	47.56	49.16	47.14	47.28	52.19	47.96	N.A.	52.24	46.20	48.50	47.75	47.16	47.88	48.43	46.49	46.67	48.50
Packing voids : %	43.38	41.55	35.40	43.02	40.15	32.15	45.08	38.54	32.68	41.62	40.68	32.95	41.76	44.79	33.27	N.A.	42.35	35.57	43.02	40.82	35.20	40.55	39.35	34.54	33.36	28.52
Specific Gravity : porous	2.50	2.27	1.98	2.45	2.27	1.89	2.27	2.27	2.02	2.46	2.24	1.92	2.47	2.33	1.96	N.A.	2.16	2.11	2.40	2.34	2.01	2.33	2.21	2.04	1.95	1.78
Specific Gravity : solid.	2.68	2.67	2.49	2.68	2.63	2.39	2.60	2.62	2.51	2.74	2.61	2.43	2.72	2.69	2.51	N.A.	2.61	2.53	2.65	2.65	2.46	2.66	2.60	2.51	2.44	2.46
Overall absorption : %	7.71			6.78			7.17			7.06			6.86			7.86			6.02			9.29				
Overall porosity : %	16.77			14.83			15.56			15.48			15.34			16.80			13.47			19.04				
Overall absolute density : kN/m^3	21.32			21.44			21.29			21.51			21.93			20.96			21.96			20.12				
Overall relative fineness modulus.	6.99			6.99			6.93			7.07			6.98			6.83			7.00			7.44				

TABLE 3.6. : Properties of the Recycled Aggregates found in the Section 3.2.4. tests.

overall absorption % = $\left[\frac{a_1 + a_2 + .. + an}{m_1 + m_2 + ... + mn}\right] \times 100\%$ ... equation 3.2

overall porosity % = $\left[\frac{a_1 + a_2 + ... + avn}{av_1 + av_2 + ... + avn}\right] \times 100\%$ ... equation 3.3

overall absolute density (as porous material) = $\left[\frac{m_1 + m_2 + .. + mn}{av_1 + av_2 + ... + av_n}\right]$ g/ml ... equation 3.4

These calculations are shown in Appendix A4 and included in Table 3.6 that follows.

Bulking:

The figures for bulking of aggregates are included in the test sheets of the appendix. Bulking occurs when an aggregate is wetted and it undergoes a volume change, usually an expansion. This phenomenon is only really prevalent in the fines fractions of a course aggregate (for example the fraction of 4.75 mm to 6.70 mm in diameter) and especially in sands.

To simplify the process of calculating the bulking percentage of the aggregate, the following process was used to determine this value:

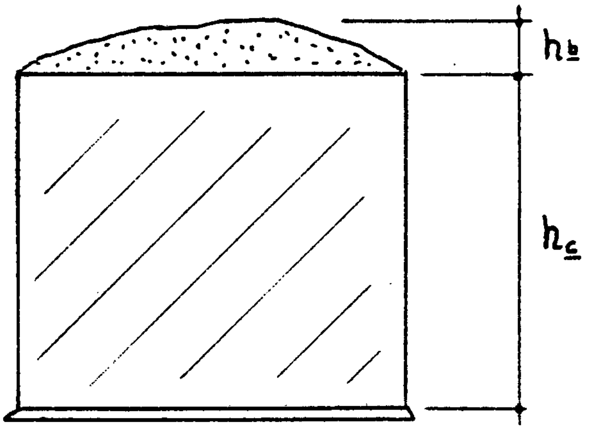


Figure 3.3: Bulking of an aggregate upon wetting.

Let the height of aggregate protruding above the the top of the cylinder be hb and the height of the cylinder be hc. The bulking percentage is therefore directly proportional to hc over hb, and using some known values, as shape coefficient can be determined so that:

bulking = $\frac{100 \times hb}{hc} \times Cb$ % .... equation 3.5

A known case comes from sample 8 in the 4.75 to 13.2 mm fraction where the hb was assumed to be 25 mm, and the bulking percentage found by weighing the material to be 7.4%. Therefore, with the cylinder height being 172.5 mm for both cylinders, the coefficient to correct for the shape of the protruding aggregate is:

$$C\underline{b} = \frac{\text{bulking} \times h\underline{c}}{100 \times h\underline{b}}$$

$$C\underline{b} = (172.5 \times 7.4)/(100 \times 25) = 0.51$$

Or, to simplify that even further;

$$\text{bulking} = \left[\frac{100.hb}{175.25}\right] \times 0{,}51\% = 0.30h\underline{b}\%$$

where h$\underline{b}$ is measured in mm.

The bulking data for all the aggregates and size fractions tested are shown in Table 3.7 overleaf.

SIZE FRACTION (mm)	SAMPLE 1	SAMPLE 4	SAMPLE 5	SAMPLE 6	SAMPLE 8	SAMPLE 9	SAMPLE 10	STOCKPILE
19.0 - 26.5	0	0	0	0	0	0	0	0
13.2 - 19.0	0	1.0	0.9	0	0	1.0	2.4	0
4.75 - 13.2	1.5	7.5	10.0	5.5	7.4	3.6	5.2	5.2

Table 3.7: Bulking percentage occurring in recycled aggregates for full saturation.

It appears that up to 10% bulking can occur in the finer fraction 4.75 mm - 13.2 mm of recycled aggregates, and the most common amount seems to be around 5%. The larger particle fractions do not appear to be affected by bulking as would be expected. Concrete producers need not concern themselves with this aspect of recycled aggregate, but for roads and pavements an engineer might take these values into account.

3.2.5 Aggregate Strength-Indicating Tests.

These tests are by nature destructive and the aggregate used is then lost to future testing. Due to a shortage of certain size fractions, only one of the two applicable tests as described in BS 812 could be performed - namely the 10 percent fines value test - and the aggregate crushing value was thus omitted. The test for 10 percent fines value is described fully in Appendix A5, although a summary thereof is presented below in Section 3.2.5.1.

The other strength-indicating test was devised by the author and will be known as the test for the "remoulded peak strength" of the aggregate. It was felt that although the 10 % fines value gave an indication of the strength of the aggregate, it was (i) too variable, and (ii) did not give an accurate account of how the aggregate would behave under compression when constricted by the mortar of the concrete. The idea of the test is thus to constrict the aggregate particles in a paste of a known high strength and thereby induce aggregate failure in a standard concrete compressive cube test. There is therefore very little matrix failure and the compressive strength attained from these cubes would reflect directly on the strength in compression of the aggregate used as it would be in a real concrete structure. The test is described in detail in Section 3.2.5.1 below.

3.2.5.1: Ten Percent Fines Value

Procedure:

Aggregate samples of the size fraction 13.2 to 9.5 mm are required for this test. They are compacted into a heavy cylinder with a tamping rod, and the final pieces are hand-packed so that the rod may roll freely over the top of the cylinder. A heavy piston is then placed over the sample and the apparatus is then positioned in a compression testing machine such as the Amsler machine available in the UCT laboratory. The piston is then forced down onto the aggregate and has to be lowered some distance to produce between 7.5 and 12.5% of "fines" (to be defined hereafter). The recommended distance for the piston to be lowered onto a honeycombed aggregate is 24 mm, but it was found during tests that 28 to 30 mm produced the best results. This distance can be gauged by using the plotter on the testing machine.

For this test the "fines" have been defined as all material passing through the 2.36 mm aperture sieve - and not the 4.75 mm sieve as would be the general boundary between coarse and fine aggregates as defined in both the British and South African codes.

When the desired displacement has been reached, the maximum load exerted to attain that distance is noted and assigned the value X. The sample is then removed from the test cylinder and sieved to find all particles passing through the 2.36 mm sieve. The percentage of fines produced is assigned the value Y and is calculated by taking the mass of fines over the total mass of the sample. The ten percent fines value is then calculated as:

$$10\% \text{ fines value} = \frac{14X}{Y + 4} \quad \text{kiloNewtons} \qquad \text{.... equation 3.6}$$

This value should only be calculated if the percentage of fines produced was within the specified limits of 7.5 and 12.5%.

The code requires that the samples tested should be of 9.5 to 13.2 mm in diameter, but it does not allow for testing of non-standard sizes following the exact same method as described. Due to limitations in the amount of samples available, and the fact that in the mix design phase it is intended to use 13.2 to 19.0 mm aggregates, the size fraction used for the 10% fines test was thus 13.2 to 19.0 mm in diameter.

Results:

The data sheets of all the various samples tested are shown in Appendix A5. The test was found to be highly variable ~~viable~~, as can be seen from the test on the 13.2 to 19.0 mm fraction of the stockpile, where the values produced were 139kN and 192 kN. Therefore, the single values attained for each of the other samples in this size fraction cannot be deemed to be sufficiently accurate. In the two tests on the 9.5 to 13.2 mm fraction of the stockpile, the values were far more consistent in that the two results were 111kN and 106 kN. So perhaps the reason why the code prefers to use this particular fraction is that is generally produces more consistent values.

Table 3.8 below shows a summary of all the 10% fines tests done:

SIZE FRACTION (mm)	SAMPLE 1	SAMPLE 4	SAMPLE 5	SAMPLE 6	SAMPLE 8	SAMPLE 9	SAMPLE 10	STOCKPILE
19.0 - 26.5	-	-	304	-	-	-	-	-
13.2 - 19.0	186	182	198	142	238	170	189	165
9.5 - 13.2	-	-	-	-	-	-	-	108

Table 3.8: Ten percent fines values in kN of recycled aggregates used.

The fact that the larger the diameters of the aggregate particles, the higher the 10% fines value, indicates that the larger size fractions contain a higher degree of the original structural stone. This fact becomes very apparent in the previous Section 3.2.4 and will be discussed in greater detail in Section 3.3.

3.2.5.2: Remoulded Peak Strength

Procedure:

As mentioned previously, this test attempts to measure the compressive strength behaviour of recycled aggregates within hardened concrete. The concept is that recycled aggregate particles are mixed with a high strength water-cement paste and cubes then cast and tested at any desired age. The fracture of the cubes will then occur in the aggregate rather than in the paste matrix. This fact was borne out by investigation of the failure surfaces of the crushed cubes.

In a competition to make the strongest concrete possible, undergraduate students in 1985 attained strengths of between 100 MPa and 110 MPa using cement-water pastes with cement/water ratios of over 4.0. The winning team produced two cubes of 111 MPa using a cement/water ratio of 4:16 (a water/cement ratio of 0.24). No sand was used in these cubes.

Some of the teams had used the same cement/water ratio but had included a 13.2 mm nominal size hornfels as stone aggregate, and only achieved up to 85 MPa. Certain aggregates are known to be the limiting factor in concrete strength, hence this test for recycled aggregates.

Initially an attempt was made to calculate the exact amount of constituents (water, cement and recycled stone) required for a mix with a cement/water ratio of 4:16. This calculation was based on the porosity voids in the compacted aggregates from Section 3.2.4. However, in attempting to apply the derived formula, there was an extreme deficiency in paste, and the values calculated for the cement powder and water had to be almost doubled to produce a satisfactory mix.

By trial and error a mix design was found that worked very well and produced workable concrete. A standard specification was then defined for this new test:

Standard specification for Remoulded Peak Strength test.

1. Use oven-dried aggregate in the 13.2 to 19.0 mm fraction;
2. Use a stone content of 1100 kg/m^3;
3. Use a cement content (preferably rapid-hardening cement) of 1000 kg/m^3;
4. Use a water/cement ratio of 0.24 - i.e. use 240 litres of water per cubic metre.
5. Prepare the mix, and if the workability is poor, then up to 6% of the stone content in additional water may be added to improve the workability. That is, up to 66 litres/m^3 may be added;
6. Prepare at least four 100 mm cubes using heavy vibro-compaction for at least one minute;
7. Crush the cubes in a compression testing machine at the desired age, that is, seven days for rapid-hardening cement or 28 days for ordinary Portland cement. The mean value in MPa is thus the remoulded peak strength of the aggregate.

Notes:

1. If aggregate from a size fraction other than the one specified is used, the test is still acceptable, although any aggregates over 19 mm in diameter would by code requirements have to be cast in 150 mm cube moulds.
2. Rapid-hardening cement is recommended as it gives the required results within seven days.
3. The selected water/cement ratio of 0.24 is arbitrary and is based on the discussion that preceded the standard specification for the test.
4. The 6% of additional water (6% of stone mass) is to allow for the absorption of the porous recycled aggregates. The value of 6% was derived from the aggregate tests in Section 3.2.4, where the overall absorption coefficients for the rubble samples tested were all at least 6%. If the actual absorption figure is known for the sample to be tested, then it may be used instead of the 6% for more accurate results.

5. The density of each cube to be crushed should preferably be determined, as the compressive strength in concrete is highly dependent on the concrete density. This merely serves as an additional parameter that the user may wish to consider in the analysis of his/her data.

6. Table 3.9 below serves as a guide to the user as to how much material needs to be batched to produce four, five and six 100 mm cubes using 13.2 to 19.0 mm aggregate for this test.

MATERIAL	AS SPECIFIED (kg/m^3)	FOUR CUBES (g)	FIVE CUBES (g)	SIX CUBES (g)
Stone	1100	5500	6000	6600
Cement	1000	5000	5455	6000
Water	240	1200	1309	1440
Additional water	66	330	360	396

Table 3.9: Recommended batch quantities in the Remoulded Peak Strength test to produce four, five or six 100 mm cubes

Results:

When the constituents were first mixed with the nett amount of water required to give the water/cement ratio of 0.24, the mixes were still very dry and would not mix properly. However, when the additional water was added, the workablility and mixability improved significantly, and although the slumps were all below 30 mm and the mixes were rather sticky, they behaved reasonably well when vibrated in the cube moulds. The cubes from each mould were all cast without much difficulty.

The cubes were cured by being left to set for 24 hours before being stripped and then submerged in water at 24^{0}C for another six days before testing.

All the cubes failed in a very brittle manner, with spalling of the surface concrete occurring at as low as 60% of the ultimate strength. The fractures of the cubes were very sudden, and this indicates that the failure had occurred in the aggregate of the concrete. Upon visual examination of the fracture surfaces, the dark, cement-rich paste matrix could easily be distinguished from the light porous mortar and dark natural stone of the original aggregate. And it was again evident that the failures had occurred mainly through the mortar (and sometimes brick) particles of the recycled aggregate, and not through the natural stone present.

The test on laboratory hornfels aggregate produced vigorous spalling of the surface concrete from around 90% of the failure strength. The fracture surfaces followed mainly through the weaker, lighter-coloured hornfels particles, which shows up the strength limitations of this particular Cape aggregate.

A summary of the data obtained is shown in Table 3.10 overleaf. All values are for aggregates in the 13.2 to 19.0 mm size fractions. For the purpose of comparison the ten percent fines values are also shown:

SAMPLE	REMOULDED PEAK STRENGTH (MPa)	CONCRETE DENSITY (kg/m^3)	10% FINES VALUE (kN)
1	64.9	2332	186
4	58.6	2277	182
5	58.0	2325	198
6	55.8	2286	142
8	62.7	2310	238
9	71.4	2333	170
10	62.0	2330	189
Stockpile	58.3	2291	165
Hornfels	78.2	2460	310

Table 3.10: The remoulded peak strengths of recycled aggregates compared to concrete density and the corresponding 10% fines value

The results of this test will be discussed fully in Section 3.3, but for now it may be noted how narrow the range of densities were in the recycled aggregate cubes, namely 2277 - 2333 kg/m^3; and also that there is not such a good correlation between the two aggregate strengths indicators, namely the remoulded fcu and the 10% fines value.

3.2.6: Quality Indication

Most researchers in the field of aggregate recycling have stressed that ~~that~~ any contaminants that may be present are usually concentrated in the fine particles of a crushed aggregate. The most common contaminants - otherwise known as deleterious materials - are gypsum, glass, wood, certain types of brick, and chemical contaminants such as salts, sugars and previously-used admixtures.

The Portland Cement Institute in Goodwood kindly tested a number of rubble fines samples for contamination, and found:

(i) No trace of chlorides was found in any of the samples;
(ii) The traces of organic material found in certain samples were extremely low and were considered negligible;
(iii) Except for samples 9 and 10, no other samples had any traces of sulphates - the exact concentration was not determined.

It is recalled that Sample 9 had been taken from a demolished slab made in the UCT laboratory in 1983 and sample 10 had been collected from a demolition site in Sea Point at the end of 1984. These two samples were then kept in the laboratory until tested at the end of 1986. The other samples were all collected from a rubble dump in Milnerton where they had been exposed to the elements for an unknown period.

It must therefore be assumed that samples 9 and 10 had either been contaminated by suphate substances whilst in the laboratory, or by the mix water in the case of sample 9, and the sulphate-bearing groundwater in the case of sample 10.

The harmful effects of the contaminants such as the sulphates and chlorides were discussed in the introduction under Section 1.5, and further mention of the matter will be made in the discussion to follow in Section 3.3.8.

3.3: DISCUSSION OF RESULTS

3.3.1: Particle Size Analysis

Table 3.11 shows the standard specifications for sand grading of SABS 1083 (*14), BS 882 (*15) and ASTM C33 (*16). It will be noticed that the grading envelope for sand with ASTM is very strict, while SABS is the most relaxed. BS actually permits four sets of envelopes which have been converted into one of the table below. In so doing, BS attempts to make the best use of the materials available. SABS has a relaxed outlook on sand grading because it considers the water demand of particular importance.

SIEVE APERTURE (mm)	SABS 1083 %	BS 882 %	ASTM C33 %
4750	90 - 100	89 - 100	95 - 100
2360	-	60 - 100	80 - 100
1180	-	30 - 100	50 - 85
600	-	15 - 100	25 - 60
300	-	5 - 70	10 - 30
150	0 - 15	0 - 15	2 - 10

Table 3.11: Standard specifications for grading of sands

The limits are placed on the sand grading because it affects the workablility, water demand, bleeding, segregation and shrinkage of the concrete. However, by proper ~~paper~~ mix-design procedures, the negative effects of a poor grading can be overcome and so the ASTM C33 standard specification may be considered by certain parties to be overly rigorous. The gradings of the recycled "sands" or fines tested are shown in Table 3.12, and it can be seen that all of them comply with SABS and BS, but often fall short of ASTM.

SIEVE (micron)	S1	S4	S5	S6	S8	S9	S10	STOCKPILE
	(Percentage passing through aperture)							
4750	100	100	100	100	100	100	100	100
2360	72	74	71	71	70	65	69	71
1180	51	56	46	47	50	44	51	52
600	36	42	30	31	36	31	37	37
300	20	24	17	15	19	16	18	14
150	10	12	8	8	10	8	9	7
Fineness modulus	3.12	2.93	3.29	3.29	3.16	3.36	3.17	3.18

TABLE 3.12: The gradings of recycled sands and their fineness moduli

ASTM requires that 80% to 100% of the sand should pass the 2360 micron sieve and it is seen that all eight recycled sands fall below this figure with a range of 65 - 75%. This implies that the recycled "sands" or fines are generally too coarse to comply with the ASTM specifications. This can further be seen from the fineness modulus.

The limits placed on the fineness modulus specified by the three codes are:

SABS 1083: $1.6 < FM < 3.5$
BS 882: no limit specified
ASTM C33: $2.3 < FM < 3.1$

Again the ASTM limit is very narrow and many natural sands commonly used by South African concrete makers would not comply with it. The fineness modulus of a sand can be adjusted by the blending of sands. The fineness moduli of the recycled "sands" were found to lie between 2.93 and 3.36 and they therefore comply with both SABS and BS - but again do not lie within the ASTM parameters.

In Section 4.2.1 the water demand of the recycled sand stockpile was found to be 258 litres per m^3 for 75 mm slump with 19 mm stone size. This figure is substantially higher than the 171 litres/m^3 found for the Klipheuwel sand that was used as a control comparison. Fulton (*17) has suggested that sands with a water demand of more than 220 litres/m^3 for 35 mm slump and 19 mm stone should not be used as it produces bad economy in the concrete. The figure of 220 litres would be equivalent to approximately 230 litres for the Portland Cement Institute's standard water demand slump of 75 mm.

The use of recycled "sand" in concrete may also lead to problems with deleterious contaminants that concentrate themselves in these fines fractions of a crushed rubble. The problems with such contaminants were discussed in Section 1.5. However, in Section 3.2.6 it was found that only two recycled fines samples contained such contamination.

For the reasons of coarse grading, high water demand and possible contamination, the use of recycled "sands" in demanding concrete operations should be avoided. However, for lower grades of mass concrete the use of these sands would certainly be acceptable, though caution should be exercised.

The grading of the coarse recycled aggregate is of no consequence as the concrete producer may specify a required grading and the modern trend is toward a "single-size" or "gap-graded" stone. Parameters such as porosity, shape and surface texture are far more important with coarse aggregates and these are discussed in the following sections.

3.3.2: Initial Moisture Content

The initial moisture contents of recycled aggregate cannot give any information about the nature of these materials and so no elaborate discussion would be necessary. The initial moisture contents depend on where and when the rubble concrete was collected and for how long, and under which conditions, it was stored. This moisture content is only really used in the dry batching of concrete constituents where adjustments are made to the water content of the mix to account for the absorbed water present in the moist sand or porous stone. This could be done to determine the effective cement/water ratio with greater precision.

3.3.3: Particle Shape of Recycled Aggregates

The shape of particles in a crushed aggregate would depend largely on the crushing process that was used. The recycled aggregates tested in this thesis were all crushed in a jaw-crusher and the consistency of shape can be seen from the flakiness and elongation indices shown in Table 3.4.

The flakiness and/or elongation of a recycled aggregate will, apart from the crushing process, depend on:

(i) The shape of the natural aggregate used in the parent concrete, and
(ii) the strength of the matrix or mortar of the parent concrete.

It stands to reason that if the stone in the parent concrete was badly shaped, it would impart its poor shape to the crushed concrete as well, especially of the mortar matrix is weak. If the mortar matrix is very strong, as for sample 9, then the crushed particle shape will be more cubic, as can be seen from Table 3.4.

The particle shape of recycled aggregates can therefore be said to be satisfactory compared to natural aggregates - It is certainly better than the poorly-shaped hornfels that is often used in the Cape Town area - although it has a much rougher surface texture.

3.3.4: The Absorption Potential of Recycled Aggregates

It is important that the absorption capablilty of a recycled aggregate be known and it may be determined fairly simply by following the procedures stipulated in Section 3.2.4.

The value of the absorption of an aggregate is called the "absorption coefficient" and it is expressed as a percentage by mass of the dry aggregate. It is directly related to the porosity of the aggregate, which is expressed as a percentage by volume of the aggregate. The realtionship is as follows:

$$\text{Absorption coefficient} = \frac{\text{mass of absorbed water}}{\text{mass of dry aggregate}} \quad \text{... equation 3.7}$$

$$\text{Porosity coefficient} = \frac{\text{volume of absorbed water}}{\text{absolute volume of porous stone}} \quad \text{... equation 3.8}$$

$$\text{Porous density kg/m}^3 = \frac{\text{mass of dry aggregate}}{\text{absolute volume of porous stone}} \quad \text{... equation 3.9}$$

$$\text{Porosity coefficient} = \text{absorption coefficient} \times \text{porous specific gravity}$$

The overall absorption coefficients and porosities were calculated for each sample in Appendix A.4 according to equations 3.2 and 3.3, and are shown below in Table 3.13.

The overall values are fairly constant for samples 1 to 10 - 6.0 to 7.9% for absorption and 13.5 to 16.8% for porosity. The values are slightly higher for the stockpile because the five size fractions were individually tested as opposed to only three fractions in the others. The overall values may certainly be used to compare one recycled aggregate to another in terms of porosity and therefore the absorption potential it will have in the concrete mix.

SAMPLE	OVERALL ABSORPTION (%)	OVERALL POROSITY (%)	ABSORPTION OF 19mm to 13,2mm FRACTION (%)
1	7.7	16.8	6.7
4	6.8	14.8	6.2
5	7.2	15.6	5.8
6	7.1	15.5	6.4
8	6.9	15.3	5.8
9	7.9	16.8	7.9
10	6.0	13.5	5.0
S/P	9.3	19.0	6.8

Table 3.13: The absorption and porosity of recycled aggregates

It is far more valuable to have these coefficients avaliable for the individual size fractions of these aggregates because if a recycled stone size of 13.2 - 19.0 mm is to be used, then the exact absorption coefficient may be used in the mix design. The values of absorption for the 13.2 to 19.0 mm fractions are also reflected in Table 3.13.

The results in Table 3.6 indicate that the porosity and absorption coefficient increases as the size fraction of the recycled aggregate becomes smaller. This indicates that the impervious natural stone of the parent concrete concentrates itself in the large-size fractions. Thus, 13.2 to 19.0 mm particles contain a greater percentage of stone than do 6 to 9 mm particles. The content of the old mortar therefore increases as the particle size reduces, meaning that a recycled "sand" is constituted mainly of this old mortar. This also explains the high water demand of recycled "sands".

The absorption coefficient will play a vital role in the mix design procedures with recycled aggregates that are developed in Phase 2.

3.3.5: The Specific Gravity and Density of Recycled Aggregates

The overall weight-densities of the recycled aggregates fell into a narrow range of 20.12 - 21.96 kN per m^3, as can be seen from Table 3.6. The overall porous specific gravities of those aggregates were thus 2.05 to 2.24. Again it is more important to rather concentrate on the densities and specific gravities of the individual size fractions.

From Table 3.6 it may also be noticed that the specific gravity of an aggregate increases (in both the solid and the porous state) with increasing particle size. This again indicates how the natural stone of the parent concrete concentrates itself in the larger particles.

PARAMETER	SAMPLE #	1	4	5	6	8	9	10	Stock Pile
Compacted dry bulk density : kg/m^3		1299	1397	1246	1436	1436	N.A.	1365	1386
Compacted saturated bulk density : kg/m^3		1380	1446	1316	1495	1491	N.A.	1420	1459
Absolute porous density : kg/m^3		2295	2453	2269	2459	2465	N.A.	2396	2331
Specific Gravity as porous material		2.30	2.45	2.27	2.46	2.47	N.A.	2.40	2.33
Specific Gravity as solid material.		2.68	2.68	2.60	2.74	2.72	N.A.	2.65	2.66
Absolute weight density : kN/m^3		22.51	24.06	22.26	24.12	24.19	N.A.	23.61	22.87

TABLE 3.14 (a) : Density-related properties of Recycled Aggregates in the 19 – 26 mm fraction.

PARAMETER	SAMPLE #	1	4	5	6	8	9	10	Stock Pile
Compacted dry bulk density : kg/m^3		1324	1356	1397	1328	1285	1247	1386	1342
Compacted saturated bulk density : kg/m^3		1413	1439	1468	1413	1359	1346	1455	1433
Absolute porous density : kg/m^3		2265	2265	2273	2239	2328	2163	2342	2213
Specific Gravity as porous material		2.27	2.27	2.27	2.24	2.33	2.16	2.34	2.21
Specific Gravity as solid material.		2.67	2.63	2.62	2.61	2.69	2.66	2.65	2.60
Absolute weight density : kN/m^3		22.22	22.22	22.30	21.96	22.83	21.22	22.98	21.72

TABLE 3.14 (b) : Density-related properties of Recycled Aggregates in the 13 – 19 mm fraction.

It may also be observed how the saturated bulk density of the compacted aggregate becomes far more constant through the size fractions as compared to the dry bulk density, which follows the trend of reducing as the particle size reduces.

The density and specific gravity values for the two most commonly used aggregate sizes, namely 13 to 19 mm and 9 to 13 mm, are tabulated in Tables 3.14 (a) and (b).

These values, especially for the porous specific gravity, will be used extensively in Phase 2 in calculating the yield of recycled mixes and thereby the mix design of a recycled concrete.

3.3.6: The Bulking of Recycled Aggregates

It was found in Section 3.2.4 that the recycled particles over 13.2 mm do not appear to bulk when wetted. In the 4.75 to 13.2 mm fraction the recycled coarse aggregates do however bulk, commonly around 6% with the highest recorded value being 10% for sample 5.

Recycled sands will certainly be prone to bulking and the engineer who wishes to work with high precision will certainly incorporate the bulking of the aggregate in his/her volume batching.

3.3.7: The Strength of Recycled Aggregates

Two destructive tests were performed on the recycled aggregates to give an indication of their strengths. They were the ~~19%~~ 10% fines crushing test according to BS 812 (*13), and the "Remoulded Peak Strength Test" devised by the author to model the compressive strength behaviour of recycled aggregates within a concrete. Details of both the tests can be found in Section 3.2.5.

The 10% fines tests was found to produce rather variable results and therefore was considered to be unsuitable to reflect on the behaviour of an aggregate when constricted by the concrete mortar. Sample 9 was visibly the strongest aggregate and yet the 10% fines test only produced a value of 170kN for it - which was the third largest out of eight samples. The range of values for this 13.2 - 19.0 mm fraction was 142 - 238 kN.

The code requirements for the 10% fines crushing values are as follows:

(i) BS 882 and 1201 (*15)

Never less than 5 tons (44 kN);
not less than 10 tons (90 kN) for concrete wearing surfaces, and
not less than 15 tons (133 kN) for "granolithic" concrete.

(ii) SABS 1083 (*14):

Not less than 70 kN for concrete not subject to abrasion, and
not less than 110 kN for concrete subject to abrasion.

These values are for the minus 13.2 mm plus 9.5 mm fraction. All the samples tested would therefore be acceptable for both grades of concrete, but again certain parties may argue that the code requirements are too rigid, and so some of the best aggregates are often used for low-grade concretes. The 10% FACT values of the recycled aggregates are shown in Table 3.8.

As expected, the Remoulded Peak Strength Test produced the highest value for Sample 9, namely 71.4 MPa, which shows up the variability of the 10% FACT test. The correlation between the two values is very bad - in Section 4.3.2.1 in Phase 2 a method of correlating a bi-variate sample is shown. The correlation coefficient r has the value here of 0.20, which shows a poor match. It was encouraging to see that Sample 6, which was visibly the poorest aggregate, was found to be the weakest in both tests. Its 10 % FACT value was only 142 kN and its remoulded peak strength 55.8 MPa.

The range of remoulded peak strengths was 55.8 - 71.4 MPa for the eight recycled aggregates. These values may be found in Table 3.10, which also shows the value of 78.2 MPa for the natural hornfels stone commonly used in concretes made at the UCT Civil Engineering laboratory. Experience in this laboratory has shown that it is extremely difficult to make concrete of above 80 MPa in compressive strength by conventional means if this 13 mm hornfels aggregate is used.

It is only when additional constituents such as water-reducing admixtures and silica fume are added that a 100 MPa concrete may be made using this particular aggregate. The remoulded peak strength thus gives a good indication of how the aggregate strength of the hornfels may be limiting.

The same concept will apply to the recycled aggregates that usually reach their peak strengths between 55 and 60 MPa. These values represent the highest possible concrete strengths that could be produced by conventional means with these recycled aggregates.

It is therefore recommended that, although remoulded strengths of up to 70 MPa may be possible with recycled aggregates, only cube strengths of up to 50 MPa should be used, particularly with these aggregates. The user should in any case check to see that the recycled stone has this capability by carrying out the simple test described fully in Section 3.2.5.2.

3.3.8: Contamination in Recycled Aggregates

The main contaminants that may be present in recycled aggregate are:

(i) soluble deleterious impurities (chemicals);
(ii) organic impurities;
(iii) sulphates (gypsum), and
(iv) chorides.

If soluble deleterious impurities or organic impurities are present in an aggregate, then the aggregate may still be used in a concrete, provided that the strength drop is not more than 15%, as recommended by SABS 1083 (*14). The ASTM standard (*16) has a similiar approach, but the permitted reduction in strength is less.

Sulphates such as gypsum interfere with the normal hydration of the cement and also reacts with the silicates and aluminates to cause expansion that could be damaging. Unfortunately no limit on sulphate content is given by SABS 1083, but Fookes (*18) has suggested the following limits:

(i) 0.4% by mass of aggregate, or
(ii) 4.0% by mass of cement.

The latter figure includes that sulphate (gypsum) included in the cement. A more relevant limitation comes from the United States Bureau of Reclamation (*19), which restricts the amount of gypsum to 0.25% by mass of the coarse aggregate.

Chlorides in concrete are considered to be undesireable because they induce corrosion of reinforcing steel and also cause unsightly efflorescence on the concrete surface. SABS 1083 requires that the chloride content by mass percentage of the Cl ion shall not exceed;

(i) 0.01% in sand for pre-stressed concrete, and
(ii) 0.03 in sand for all other concrete.

Research experience by Young (*7) and Foundistou-Yannas (*5) has shown that these contaminants usually manifest themselves in the fines of a crushed aggregate. This means that recycled sands are far more prone to contamination than the coarse aggregates. These contaminants - especially excess chloride - are often easily removed by washing the aggregate.

No contaminants, other than the sulphate in Samples 9 and 10, were found in the recycled sands that were tested by the Portland Cement Institute. However, if deleterious substances were present in a recycled aggregate, then there are methods by which they can be accounted for and their effects neutralized.

3.3.9: General

As a summary of the properties of recycled aggregates, Table 3.15 shows the various values obtained for the recycled aggregate stockpile used in Phases 2 and 3. It will be noticed that the tests were done for all five size fractions that the codes specify for coarse aggregate up to 26.5 mm.

It is noticeable how the absorption coefficient and the porosity increases as the size fraction becomes smaller. The porous specific gravity also steadily reduces as the size decreases. These indicate that the stone from the parent concrete is contained largely in the larger diameter particles. This fact is also borne out by the similiar trend followed by the compacted bulk density and the absolute mass density.

Figure 3.4 overleaf shows a plot of the different densities of the recycled aggregate versus the mean diameter of each size fraction. The trend of increasing density with increasing stone size is again borne out, but it is noticeable that, by saturating the aggregate, a degree of uniformity is reached between the different size fractions. The compacted saturated bulk densities of all five fractions are seen to lie in the narrow range of 1433 to 1470 kg/m .

A plot of the porosity and absorption figures for each size fraction of the recylced aggregate versus the mean particle diameter to a logarithmic scale produces a reasonably linear picture. These two plots are shown in Figure 3.5, which follows.

PARAMETER : SIZE FRACTION (mm)	19 - 26	13·2 - 19	9·5 - 13·2	6·7 - 9.5	4.75 - 6.7
Compacted dry bulk density : kg/m³	1386	1342	1342	1301	1272
Compacted saturated bulk density : kg/m³	1459	1433	1464	1434	1470
Absolute porous density : kg/m³	2331	2213	2044	1953	1780
Specific Gravity as porous material	2·33	2·21	2·04	1·95	1·78
Specific Gravity as solid material	2·66	2·60	2·51	2·44	2·46
Absorption Coefficient : %	5·3	6·8	9·1	10·2	15·6
Porosity of material : %	12·3	15·0	18·5	20·0	27·7

TABLE 3.15 : Summary of the properties of the Recycled Aggregate of the Mix Design Stockpile.

Figure 3.4 : Plots of the various Densities of a recycled aggregate against the mean particle diameter.

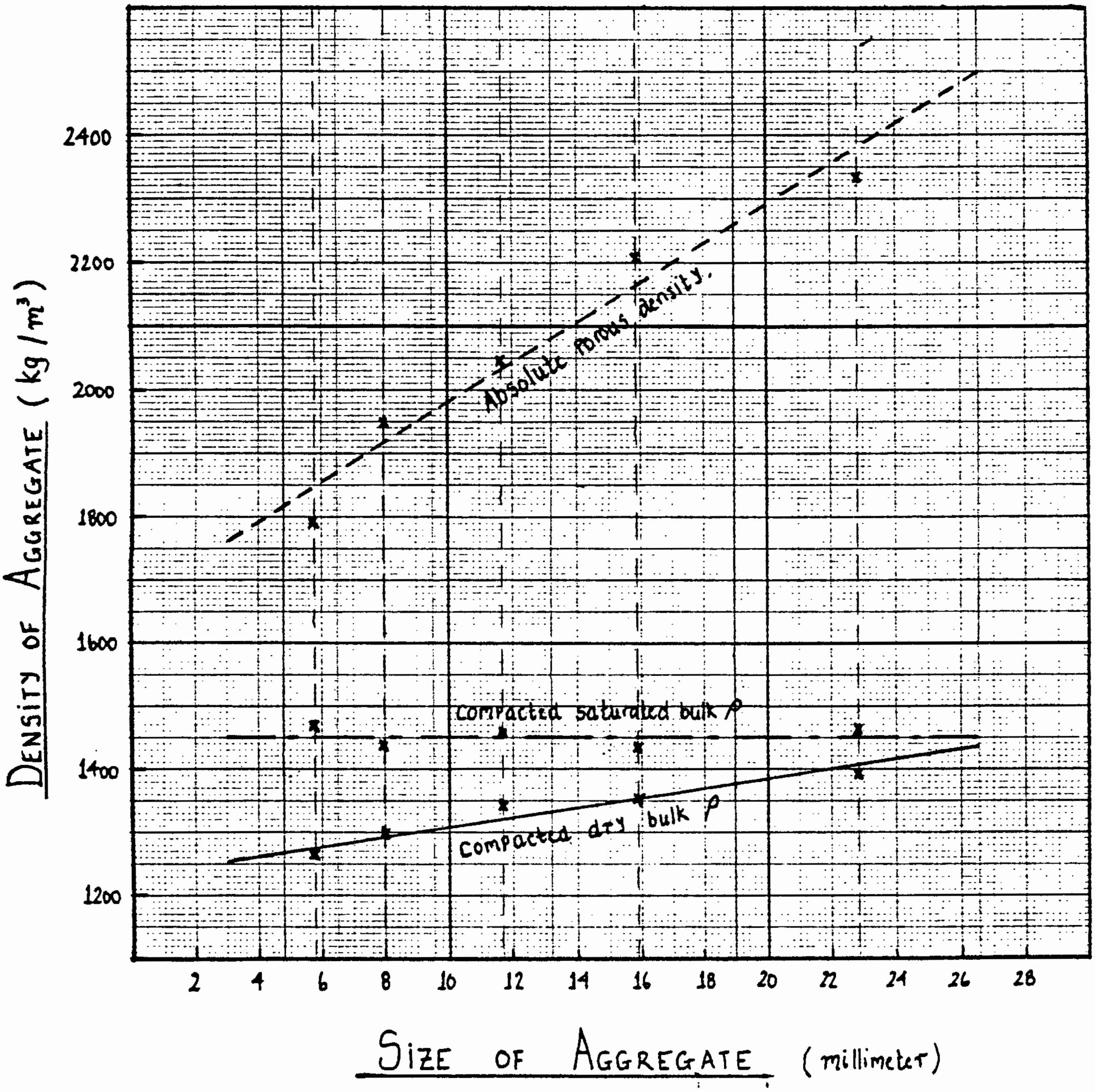
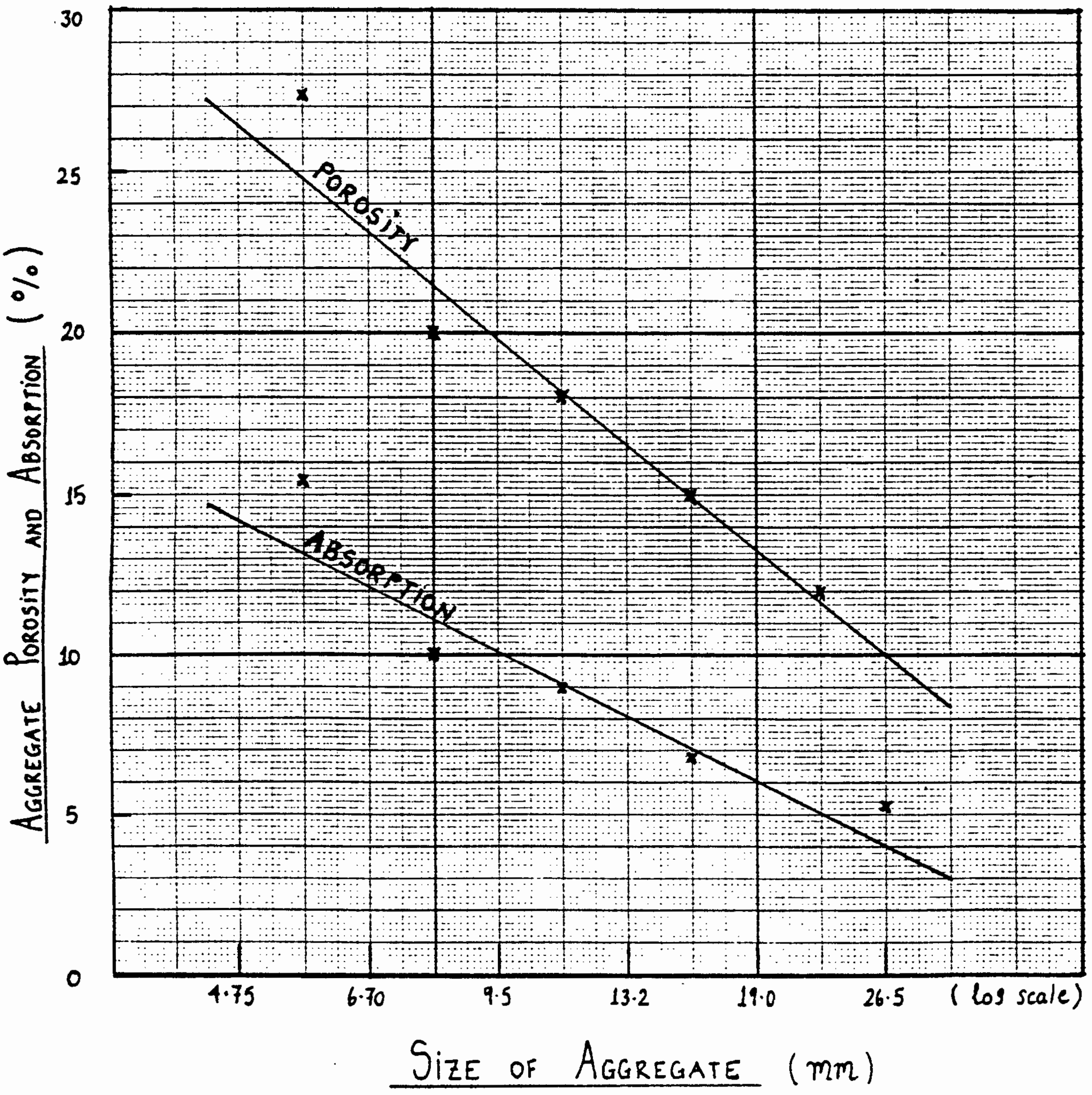


Figure 3.5 : Plots of the Porosity and Absorption of recycled aggregate against the mean particle size to a logarithmic scale.



PHASE 2: MIX DESIGN WITH RECYCLED AGGREGATE

4.1: Introductory Theory.

4.1.1: Aims of the testing to be done.

In developing a suitable mix design method for recycled aggregates, three factors were taken into account to indicate what experimental work was required. The first factor is that the overseas research stresses the fact that "lower strengths" result for recycled concrete compared to equally proportioned control using natural aggregates" - this is in contradiction to what this author has found in his BSc thesis (*20) where the recycled concretes were usually 10 - 20 % stronger than the control mixes.

The discrepancy in these findings must be due to the fact that the overseas researchers have used wet-batched methods in preparing their mixes, and therefore the absorption of mix water by the porous recycled aggregate is eliminated. In South Africa dry batching of aggregates is the preferred method, and so the dry batching of recycled porous recycled aggregate has caused a reduction in the effective water/cement ratio in the mix due to absorption of mix water. This causes the concrete to be "stronger" than the control concrete for the same apparent water/cement ratio.

The second factor considered was the recurring suggestion that recycled fine aggregate sand should be used with caution. The recycled "sand" is more prone to contamination by deleterious materials such as gypsum and glass, and should furthermore have a higher water demand than natural sands. This would be the case as recycled sands are similiar to crusher sands, which have a higher water demand than natural sands from riverbeds, pits and dunes. The merits and demerits of using fine recycled aggregates should be investigated and comparison made between its water requirements and that of natural sand.

The third factor considered is the comparison of mix designs for dry- and wet-batching to establish the most suitable and perhaps the most economical method.

The aim of this part of this work is therefore to cover a spectrum of mix design and practical concreting parameters related to recycled aggregates and to establish a method of mix design for such concretes that is easy to follow and will produce reliable concrete.

4.1.2: DRY- and WET-batching

The moisture condition of the aggregates upon batching has always been a vital factor for consideration in producing concrete. In the Introduction of Phase 1 in Section 3.1 mention was made of how lightweight aggregates have become widely accepted and used worldwide as their technology has developed. The trend in the use of lightweight aggregates is to batch them in a pre-soaked state in order to eliminate the effects of their porosity upon the effective water/cement ratio and furthermore to bring the aggregate to some degree of uniformity in terms of moisture content.

In the case of recycled aggregate, the effects of its porosity upon a concrete are even more pronounced in terms of effective water/cement ratio. This is because the pores of recycled aggregates are very small and the water is able to penetrate throughout the entire part of the aggregate particle that is made up of the mortar - so it can effectively remove a significant amount of water from the mix and retain it in its pores. On the other hand, the pores of lightweight aggregates are usually larger than those of recycled aggregates, and these pores are most often sealed because the water cannot penetrate the impervious matrix material of the aggregate. Therefore, lightweight aggregates will not remove so much water from the mix water as to significantly alter the effective water/cement ratio.

In attempting to bring an aggregate to a uniform moisture content throughout for a mixing and costing operation, the aggregate can:

(i) be stockpiled in a very sheltered area where it will remain in an air-dried condition with a uniform water content, or;
(ii) be oven-dried prior to mixing so that it is completely devoid of moisture, or
(iii) be pre-soaked and handled in a manner that keeps it fully saturated and uniform.

In a laboratory, oven-drying of aggregate is usually easily done, but on a construction site the oven drying of large volumes of aggregates will be impractical and expensive. Stockpiling of aggregates is the usual way in which aggregates are kept on site and then "dry batched" from the stockpile. In the case of coarse natural aggregate, very little attention need be paid to the moisture content of the stone upon batching as it is negligible, even after rain. With the fine aggregate a daily record of moisture content is kept and the water content of the concrete mix is adjusted accordingly.

If porous recycled aggregate is to be used on site, it would be possible to handle it in the same way as is done with sands, that is, stockpiled and daily moisture content checks performed. It could also be "dry batched" into the mix, or it may be more convenient to pre-soak the aggregate then wet-batch it into the mix. A problem likely to be encountered is to achieve a uniform water content in the aggregate upon batching. The water that a porous aggregate will take with it into the mix from being wet-batched is firstly the pore water inside the particles, and secondly some degree of surface water wetting the particle. The problem lies therefore with the surface wetness rather than the water within the pores. But all that is needed is some standard procedure to take the aggregate from the watered stockpile, shake it, screen it, or which ever, and leave a uniform surface wetness as it enters the mix.

If no attention is paid to keeping the same surface wetness, a situation may arise where a strength drop may occur because an additional amount of water entered the mix via surface water of the aggregate and therefore increased the water/cement ratio.

4.1.3: Water Demand of a Sand

The amount of water required to produce a concrete mix of desired cement/ water ratio and slump is known as the water requirement. Since the coarse aggregate for conventional concrete is usually impervious and non-porous, the water requirement is dependent on the type of sand used.

The South African method of designing a concrete mix follows this concept, known as Water Demand Theory. The sand to be used is identified, and using other parameters such as stone content and maximum stone size, desired slump (workability) and method of compaction, the water requirement of mix is estimated. Many aids in the form of listed values and adjustments are available to do this (for example, refer to the Fulton and Crawford handbook: *21). The cement/water ratio is derived from known strength charts and the cement content then calculated. In this way, all the mix quantities for stone, sand, cement and water may be calculated for 1m^3 of concrete.

However, for the sake of comparing different sands, a standard set of parameters have been defined for a concrete mix, and this particular mix's water requirement becomes know as the "water demand" of that sand. The standard definition is:

> "The water demand of a sand is that amount of water required to produce 1m^3 of concrete of slump 75mm using a maximum stone size of 19mm."

The ~~cement content or~~ desired strength does therefore not contribute to the water demand.

Fulton (*17) suggests that sands of water demand exceeding 220 litres per cubic metre should be avoided for concrete manufacture, as they cause an increase in the cement content required for the desired strength - the concrete produced is therefore more expensive.

4.1.4: Defining Workability of Concrete

Various terms describe how a concrete mix behaves whilst being mixed, transported, placed, compacted, and surface finished. Terms such as: workability, plasticity, consistency and mobility are used to describe these concrete characteristics, but in fact have been defined for different attributes of the mix.

> Granger (*22) has defined mobility as applicable to plastic concrete in the same sense that "fluidity" is applied to liquids, that is, the reciprocal of viscosity.
>
> Powers (*23) has defined plasticity as that property of concrete by virtue of which it may undergo the process of moulding without losing its continuity, without rupture.
>
> Consistency is generally considered to relate to the wetness or dryness of the mix, but it has been very closely associated with the standard slump test as the term used to describe the fresh concrete.
>
> The term most applicable to the handling, transportation, placing and compaction of concrete is workability. This has been defined, for example, by Powers (*23) as "that property of the plastic concrete mixture which determines the ease with which it can be placed, and the degree to which it resists segregation". The British Road Research Laboratory has a more technical definition (*24):

> "Workability being that property of concrete which determines the amount of useful internal work necessary to produce a full compaction."

Confusion sometimes arises when attempts are made to define "workability", and this is attributed to the fact that "workability" is not a single, but a composite, property. According to the Cement and Concrete Association of Australia (*25) the property includes:

(i) The effort required to cause the concrete to assume a required shape;
(ii) the effort required to compact the concrete;
(iii) the degree of resistance to segregation;
(iv) the degree of resistance to bleeding, and
(v) the effort required to produce a satisfactory surface finish.

There are various tests for "workability", listed below, which will not be described in detail here, as they are discussed in various concrete text-books such as Fulton (*17) and Neville (*26). The tests are:

(i) Flow test.
(ii) Ball penetration test.
(iii) Slump test.
(iv) Compacting factor test.
(v) Vebe consistometer test.

The slump test is the most commonly used. Indeed, South Africans rarely use any of the other tests.

Two more factors that may be noted relating to the slump of concrete is that:

(i) Rapid-hardening cement will reduce the slump of the concrete mix by 30 - 40 mm if it is substituted for ordinary Portland cement because of its greater fineness (*17).
(ii) The larger the stone size, the lower the water demand of the sand to be used, or conversely, the smaller the stone size, the less the slump. This is because of the increase in specific surface of the aggregate (*17).

4.1.5: Mortar Excess in Concrete

It is a known fact that increasing the stone content of mix results in a greater yield of concrete, and so too much cement and sand in a mix might be uneconomical. A well-balanced concrete may be considered to be one in which the amount of mortar exactly fills the packing voids of the coarse aggregate and also covers the surface with a thin layer.

In theory, one could calculate exactly what volume of mortar would make that ideal balance, but in practice the mortar "interferes" with the packing of the coarse aggregate and a mortar deficiency will result. This means that there wil not be enough mortar to fill the packing voids and cover the surface.

For most concreting applications, it is usually desirable that there be an "excess of mortar" such that all the packing voids are filled and the small amount of mortar still covers the top surface of the casting. In this way a smooth finish may be achieved whithout any stones protruding from the concrete.

4.1.5.1: Theoretical Mortar Excess (TME)

For a particular concrete mix of known constituent properties, the value of mortar excess may be calculated by considering the volume of mortar present against the expected volume of packing voids expected from the ~~concrete~~ stone in a compacted state. This value is known as the "theoretical mortar excess" and is expressed as a percentage of the bulk volume of the compacted stones.

In practice, however, this calculation will greatly overestimate the amount of excess mortar that would measured, because it assumes that the coarse aggregate particles remain closely packed during the compaction of the concrete. But in reality, the mortar squeezes in between the coarse particles, forcing them apart and thereby increases the volume that the mortar would have to fill in the concrete matrix, and so the TME will not result, but a lesser value instead.

4.1.5.2: Actual Mortar Excess (AME)

For the reasons stated above in Section 4.1.5.1, the "actual mortar excess" is much less than the theoretical mortar excess. The AME may be measured by poking a ruler into the fresh concrete surface and measuring the depth of mortar before reaching the coarse aggregate. The excess is again expressed as a percentage of the bulk volume of the coarse aggregate packing.

For most concreting jobs it would be desirable to have an AME of approximately ten percent, as this will allow adequate surface finishing of the concrete.

4.2: TESTING PROCEDURES.

4.2.1: Water Demand of Recycled "Sand".

Procedure:

Two identical mixes of a typical concrete will be made using the same amounts of water and cement, and the same natural impervious stone. Klipheuwel sand will be used in the first mix, and recycled "sand" in the second. When the mixes have been prepared they will be brought to the same slump value of 75 mm by standard adjustment methods, and the final water contents will be compared. Cubes will be cast from each mix to test the compressive strengths of each mix.

Rapid-hardening cement will be used and both the sand types will be oven-dried at 105°C for 24 hours before use. The cubes will be water-cured and tested after seven days.

Mix Design

The concrete should be of medium strength, so a water/cement ratio of 0.70 was used. From the Fulton and Crawford booklet (*21) a suggested stone content for the vibro-compacted concrete with maximum stone size of 13 mm is 1000kg/m³. The water demand of the Klipheuwel sand of fineness modulus 2.13 was estimated to be 200 litres/m³.

The mix quantities were calculated to be:

stone = 1000kg/m³; water = 200 litres/m³; water/cement = 0.70.
cement content = 200/0.70 = 286 kg/m³, rounded off to 280 kg/m³.

So, to find the mass of sand required to produce 1m³ of concrete, the following formula is used:

$$\frac{\text{mass of stone}}{\text{RD stone}} + \frac{\text{mass of sand}}{\text{RD sand}} + \frac{\text{mass of cement}}{\text{RD cement}} + \frac{\text{mass of water}}{\text{RD water}} \quad /1000 = 1m^3.$$

(equation 4.1)

where the relative densities (RD) or specific gravities of the materials are:

Natural stone = 2.72; cement = 3.14;
natural sand = 2.72, and water = 1.00

The mass of sand required is:

$$\text{Mass of sand} = 2.72 * 1000 - \frac{1000}{2.72} + \frac{280}{3.14} + \frac{200}{1.00}$$

$$= 930 \text{ kg/m}^3$$

The natural hornfels aggregate in the UCT laboratory was found to be very dirty and badly screened, and thus contained both large and small particles. A sufficient quantity of this coarse aggregate was then sieved to get a "single-size" stone of diameter 13.2 to 19.0 mm. The stone was then washed to remove the dirt, and oven-dried at 105°C for 24 hours.

When the constituents of the final mix were placed in the mixer, it was found that the water demand of the sand had been grossly overestimated. Two successive mix adjustments did not bring the mix slump down to 75 mm. The mix was then aborted and a second attempt made. This time the water was added in small amounts until the required 75 mm slump was reached.

The batched quantities of solid constituents for MIX 1 were:

stone = 9000 g (13.2 - 19.0 mm)
sand = 8370 g (Klipheuwel sand; FM = 2.13)
cement = 2520 g (rapid-hardening cement)

After 1000 ml of water had been added, the slump was still zero. With 1300 ml of water, the slump was only 20 mm. At 1585 ml the slump reached the desired value of 75 mm. In casting the four 100 mm cubes it was noticeable that a large mortar excess existed in this rather sloppy mix.

The second mix was made using the same proportions as for MIX 1, except that a recycled "sand" of fineness modulus 3.18 was used. The maximum particle size of this recycled sand, taken from the stockpile of crushed rubble, was 4.75 mm, whereas the maximum sized particles in the Klipheuwel sand were only 2.38 mm. The grading of these two sands is detailed in Appendix A1.

The batched amounts of solid constituents for MIX 2 were:

stone = 9500 g (13.2 -19.0 mm)
sand = 8835 g (recycled sand, FM = 3.18)
cement = 2660 g (rapid-hardening cement)

The water was added incrementally: after 2000 ml there was no ~~workability~~ slump; at 2610 ml the slump was 55 mm; at 2730 ml the slump was 65 mm, and at 2815 ml the slump had reached the desired value of 75 mm. Again, the mix was sloppy, with a large mortar excess. This procedure was carried out in a relatively short time and was done in a draft-free, cool environment, and so litte, if any, evaporation from the mix would have occurred. Four 100 mm cubes were then cast.

Results:

If the slump of Mix 2 is plotted against the amount of water added, as in Figure 4.1 overleaf, a fairly straight line is produced, as expected. The coarse "rubble sand" (or recycled sand) reduces the workability of the concrete, especially in the lower slump region, but once sufficient free water is available to lubricate the particles, the slump follows the linear path shown.

From the batched quantities, the "per cubic metre" quantities are now calculated to enable comparison of the two mixes (equation 4.1 from before is again used). The volume of a mix is calculated for the quantities batched and these are then scaled up so that one cubic metre of concrete would be produced.

For MIX 1 with the Klipheuwel sand:

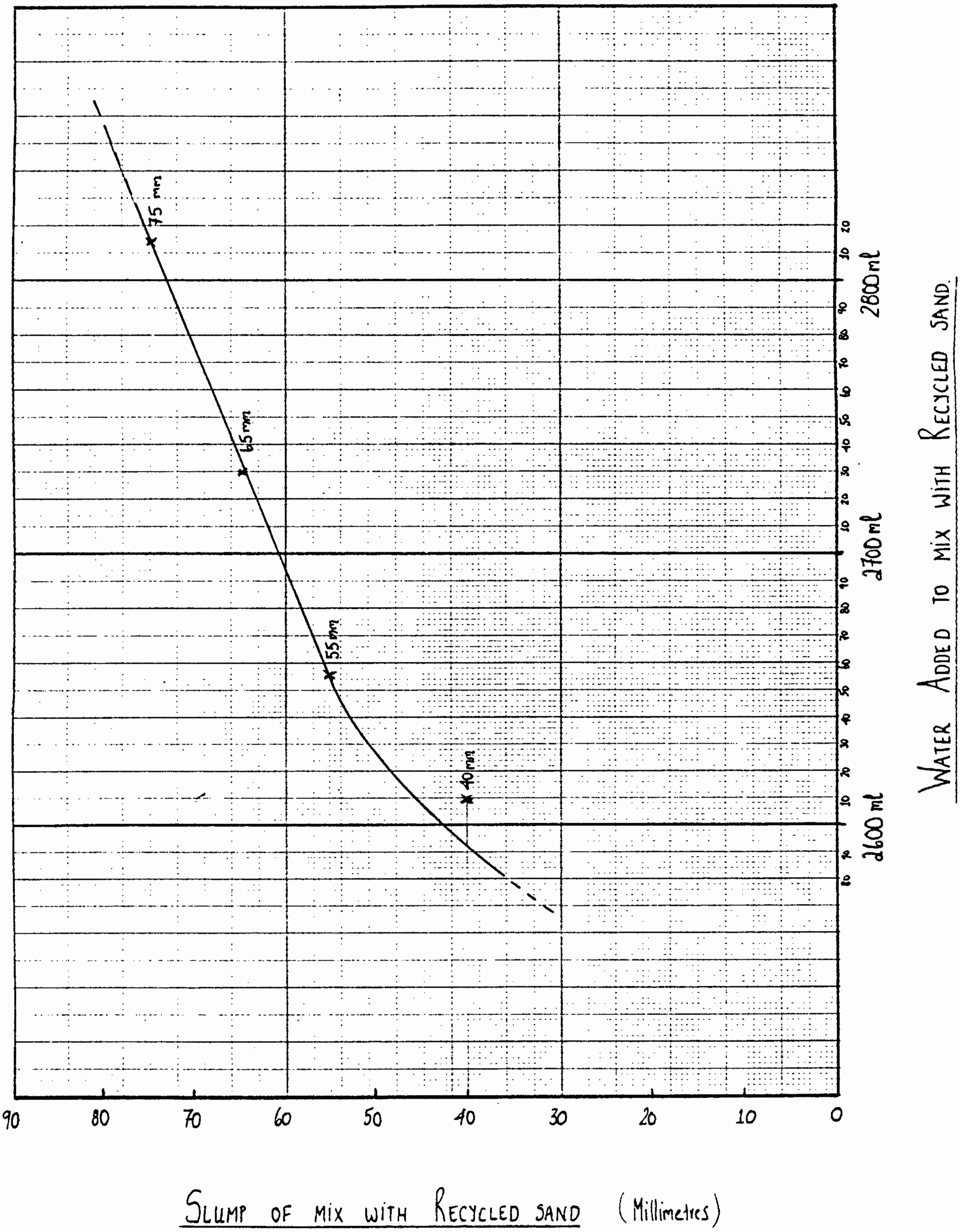
batched quantities:
stone = 9.000 kg
sand = 8.370 kg
cement = 2.520 kg
water = 1.585 kg

$$\text{batched volume} = \left[\frac{9.000}{2.72} + \frac{8.370}{2.72} + \frac{2.520}{3.14} + \frac{1.585}{1.00}\right] \div 1000 \text{ m}^3$$

$$= 0.008\ 744 \text{ m}^3$$

$$\text{scale factor} = 0.008\ 774 = 113.98$$

Figure 4.1. : Slump of MIX 2 as the water content increases.



per 1 m^3 of concrete: stone = 1026 kg
sand = 954 kg
cement = 387 kg
water = 181 kg

MIX 1
Klipheuwel sand

for a 75 mm slump with a 13 mm nominal stone.

For MIX 2 with recycled "sand" of relative density 2.65:

batched quantities: stone = 9.500 kg
sand = 8.835 kg
cement = 2.660 kg
water = 2.815 kg

$$\text{batched volume} = \left[\frac{9.500}{2.72} + \frac{8.835}{2.65} + \frac{2.660}{3.14} + \frac{2.815}{1.00} \right] \div 1000 \text{ m}^3$$

$$= 0.010\ 489 \text{ m}^3$$

scale factor = 0.010 489 = 95.340

per 1 m^3 of concrete: stone = 906 kg
sand = 842 kg
cement = 254 kg
water = 268 kg

MIX 2
Recycled "sand"

for a 75 mm slump and a 13 mm nominal stone

The water requirements of the two sands for 1 m^3 of concrete with 75 mm slump and 13 mm stone size, using rapid-hardening cement, are:

Klipheuwel sand : 181 litres
Recycled "sand" : 268 litres

The standard definition used by the Portland Cement Institute of South Africa for water demand is for 1 m^3 of concrete with 75 mm slump and a maximum stone size of 19 mm. Tables in Fulton (*17) suggest that 10 litres/m have to be subtracted from these figures to get them to correspond to the 19 mm stone size. This is because the smaller the stone size in the mix, the higher the specific surface area of the stone, and therefore the lower the slump (workability). If ordinary Portland cement had been used instead, the two figures would be slightly lower by the same amount, as the slumps of OPC concrete are generally 30 to 40 mm more than RHC concrete.

The water demands of the two sands, using rapid-hardening cement, are:

Klipheuwel sand : 171 litres
Recycled sand : 258 litres

The water demand of the recycled "sand" is therefore 51% more than that of the natural sand, and in using this sand for concrete, the cement content of the concrete mixes produced would have to be higher than those concretes using natural sands to attain simili~~a~~r strengths (cement/water ratios). Fulton suggested that sands with water demands exceeding 220 litres should be avoided for this reason.

In the post-graduate course CE 5G1 of 1985 "The Properties of Concrete" (*27) the costs of concrete materials in the Western Cape were given as:

cement : R6.00 per 50 kg pocket.
stone : R21.00 per tonne,
sand : R10.00 per tonne,
water : negligible.

A cost comparison can now be drawn between the two mixes. It is assumed that recycled "sands" will be cheaper than natural sands - at say R9.00 per tonne - otherwise concrete producers would not consider using it.

Cost of MIX 1 with Klipheuwel sand:

cost = (1.026 * 21) + (0.954 * 10) + (287 * 6/50)

= R65.53 per cubic metre

Cost of MIX 2 with recycled sand:

cost = (0.906 * 21) + (0.842 * 9) + (254 * 6/50)

= R57.08 per cubic metre

The mix with the recycled "sand" is marginally cheaper, but it should be noted that as its cement/water ratio is only 0.95 compared with the 1.59 mix of the natural sand. Experience in the laboratory indicates that recycled sand does not withhold any of its absorbed water from the hydration process and the effective cement/water ratio is then not altered.

MIX 2 will therefore be much weaker than MIX 1 and a cost comparison should only be made if they have equal strength potential, that is, equal cement/water ratios.

A calculation can be made to bring MIX 2 with the recycled sand up to the same cement/water ratio as MIX 1.

water requirement = 268 litres/m^3
desired cement/water ratio = 1.59
cement content = 425 kg/m^3

mass of stone and sand $= 2.72 * \quad 1000 - (268 + \frac{425}{3.14})$

$= 1623$ kg/m^3

Use the same stone/sand ratio as before, therefore:

sand content = 782 kg/m^3
stone content = 841 kg/m^3

The mass of sand may be reduced as it is less dense than the stone, and for the calculation a common value equal to the relative density (RD) of stone was used - the RD of the recycled "sand" was 2.65.

sand content = 782 * 2.65/2.72 = 762 kg/m^3

the volume of the quantities may be checked by:

$$\text{volume} = \left[\frac{841}{2.72} + \frac{762}{2.65} + \frac{425}{3.14} + \frac{268}{1.00} \right] \div 1000 = 1.000 \text{ m}^3$$

It is assumed that the two mixes will now produce approximately equal compressive strengths and the cost comparison is again made. The cost of MIX 1 per cubic metre of concrete with Klipheuwel sand was R65.53. The cost of MIX 2 is now:

$$\text{cost} = (0.841 * 21) + (0.762 * 9) * (425 * 6/50) = \text{R}75.52/\text{m}^3$$

There is therefore R10.00 difference between the two concretes, using a hypothetical price of R9.00 per tonne of recycled "sand". In using the recycled sand to produce this medium-strength concrete, the increase in cost is therefore 15.2%. It is therefore recommended that recycled "sand" be used with caution, or simply avoided, not only because it produces more expensive concrete, but also because it may contain contaminants that could have harmful effects on the concrete in the long term.

The hypothetical cost of the recycled aggregate given above is pessimistic, as in the United States recycled aggregate can cost as little as half the price of natural aggregates (*9).

At seven days age the cubes were weighed and tested. The results are shown in Table 4.1 below.

SAND TYPE	SPECIMEN NUMBER	WEIGHT (g)	fcu (MPa)	MEAN VALUES
Klipheuwel sand	1.1	2459	34.4	W = 2465 g
FM = 2.13	1.2	2455	32.8	fcu = 33.2 MPa
	1.3	2456	32.6	
	1.4	2490	33.0	
Recycled "sand"	2.1	2332	15.0	W = 2323 g
FM = 3.18	2.2	2310	14.4	fcu = 14.2 MPa
	2.3	2327	13.5	
	2.4	2324	14.0	

Table 4.1: Test results of cubes in the water demand tests

The density of the concrete in MIX 1 was therefore 2465 kg/m^3 with a mean cube strength of 33.2 MPa. The density of the concrete in MIX 2 was 2323 kg/m^3, which is about 6% less than MIX 1, and its mean cube strength was 14.2 MPa.

It may be worthwhile to comment on the failures of the two sets of cubes. Upon inspection of the crushed cubes, both sets seemed fairly crumbly internally, indicating that they may have been oversanded and it may be remembered that both mixes had a large mortar excess. The difference in coarseness of the mortar could also be seen, and some of the larger particles near 4.75 mm could be seen in the mortar of MIX 2. The cubes of MIX 1 failed at distinct values with no hesitation or recovery occurring as their f_{cu}s were reached. The cubes of MIX 2 with the recyled sand had distinct hesitation occurring at exactly 13.3 MPa each time (94% of f_{cu}) but then recovered to fail at a slightly higher value. This is probably due to the aggregate interlock of the coarse sand particles and the "work hardening" type of effect it has on the concrete matrix.

4.2.2.: A Method of Mix Design using Coarse Recycled Aggregates.

Procedure: (WET BATCH)

From the factors discussed in Section 4.1.1 it was decided that a wet-batching method would be investigated whereby the coarse recycled aggregate is pre-soaked in water to allow full absorption to occur, and then batched into the mixer. Recycled "sand" was not used, but rather the coarse natural pit sand available in the Western Cape, namely the Klipheuwel sand with a fineness modulus of 2.13. The aggregate size used was the most commonly used "gap-graded" or "single-sized" aggregate of diameter 13.2 to 19.0 mm. Rapid-hardening cement was used so that strength results could be obtained at the seven-day age, and for the sake of comparison, the seven-day RHC strengths may be assumed to be approximately equivalent to the 28-day strengths for OPC. The only real difference is that in using RHC the workability of the concrete is reduced somewhat, and the corresponding water requirements for OPC are slighty less than for RHC.

Concrete mixes were made in which the stone/sand ratio and the water/cement ratio were varied:

Stone/sand ratios by weight:

20
80:~~70~~
70:30
60:40
50:50
40:60

Cement/water ratios by weight:

1.00
1.25
1.50
1.75
2.00
2.25
2.50
2.75
3.00

For each mix the slump was approximately 60 mm and the mortar excess or deficiency was measured and compared to the calculated theoretical value. Cubes were cast from each mix and their compressive strengths determined at seven days, as rapid-hardening cement was used.

Mix Designs:

In the water demand test from Section 5.2.1, the water demand of the sand to be used was 171 litres per m^3 - this was for the same stone size that was used in these tests. In a trial mix where the coarse recycled aggregate was wet-batched (filled pores and surface-wet condition), the water requirement for the same sand and the desired slump of 60 mm was found to be 163 litres per cubic metre.

Cement Water Ratio	Water (kg/m³)	Cement (kg/m³)	Aggregate (kg/m³)
1.00	163	163	2057
1.25	163	204	2023
1.50	163	245	1989
1.75	163	285	1955
2.00	163	326	1921
2.25	163	367	1887
2.50	163	408	1853
2.75	163	448	1819
3.00	163	489	1785

TABLE 4.2. Calculation of mix quantities for the mixes to be tested in PHASE 2.

The cement contents of each variation in cement/water ratio was calculated by multiplying the cement/water ratio applicable by 163 kg/m^3.

The calculation of the recycled stone and natural sand contents was then done:

The specific gravities, or relative densities, of the two materials were:

Coarse recycled aggregate : 2.60 (from Phase 1 tests)
Klipheuwel sand : 2.64 (from Davis, *28)

for calculation purposes the average value of 2.62 was used.

Equation 4.1 was used again for this calculation:

let the combined mass/m^3 of stone and sand be A

$$\underline{A} = 2.62 * (1000 - \frac{\text{cement}}{3.14} - \text{water})$$

if cement is denoted by C, water by W and the cement/water ratio by f, then:

$$\underline{A} = 2.62 * (1000 - \frac{fW}{3.14} - \underline{W}) \quad \text{. . . equation 4.2}$$

The quantities of mix materials required can be seen in Table 4.2 overleaf. The variation of the stone/sand ratio was then calculated from the total fine and coarse aggregate figure A that was calculated using equation 4.2.

The final set of mixes that were to be done with their mix quantities specified were then established by splitting the aggregate into the appropriate ratio. Allowance was made for the absorption of the recycled stone, this was done by dry-batching the aggregate and then adding the appropriate quantity of water that the mass of stone would have absorbed, but wet-batching of the aggregate had been decided on previously. This meant that the figure calculated for the dry stone was adjusted by some factor so that the wet-batched stone would include the absorption figure.

In other words, the aggregate could have been oven-dried, and then the figure of 6.77% in additional water (found for this particular recycled aggregate) added to the mix to cancel out the absorption effect of the porous stone. But this is a rather laborious process, and not practical for site conditions and so it would be much easier to soak the aggregate in water overnight and then simply batch 106.77% of the dry mass of stone calculated. The adjustment factor mentioned was therefore 1.0677.

The possible absorption of water by the fine aggregate had been fully accounted for in the water requirement figure of 163 litres/m^3. It was, however, required that daily checks be made and the total water content of the mixes then adjusted accordingly. These moisture checks are reflected in Appendix A6, and the correction to each mix is shown on the respective result sheet shown in Appendix A6.

Mix Number	Mix Code.	Cement Water Ratio	WATER (ℓ/m^3)	CEMENT (kg/m^3)	SAND (kg/m^3)	DRY STONE. (kg/m^3)	WET STONE. (kg/m^3)
1	100-20	1.00	163	163	411	1646	1757
2	100-30	1.00	163	163	617	1440	1537
3	100-40	1·00	163	163	823	1234	1318
4	100-50	1·00	163	163	1028	1028	1098
5	100-60	1·00	163	163	1234	823	878
6	125-20	1·25	163	204	405	1618	1728
7	125-30	1·25	163	204	607	1416	1512
8	125-40	1·25	163	204	809	1214	1296
9	125-50	1·25	163	204	1011	1011	1080
10	125-60	1·25	163	204	1214	809	864
11	150-20	1·50	163	245	398	1591	1699
12	150-30	1·50	163	245	597	1392	1487
13	150-40	1·50	163	245	796	1193	1274
14	150-50	1·50	163	245	994	994	1062
15	150-60	1·50	163	245	1193	796	849
16	175-20	1·75	163	285	391	1564	1670
17	175-30	1·75	163	285	586	1368	1461
18	175-40	1·75	163	285	782	1173	1252
19	175-50	1·75	163	285	977	977	1044
20	175-60	1·75	163	285	1173	782	835
21	200-20	2·00	163	326	384	1537	1641
22	200-30	2·00	163	326	576	1345	1436
23	200-40	2·00	163	326	768	1153	1231
24	200-50	2·00	163	326	960	960	1025
25	200-60	2·00	163	326	1153	768	820
26	225-20	2·25	163	367	377	1510	1612
27	225-30	2·25	163	367	566	1321	1410
28	225-40	2·25	163	367	755	1132	1209
29	225-50	2·25	163	367	943	943	1007
30	225-60	2·25	163	367	1132	755	806
31	250-20	2·50	163	408	371	1482	1583
32	250-30	2·50	163	408	556	1297	1385
33	250-40	2·50	163	408	741	1112	1187
34	250-50	2·50	163	408	926	926	989
35	250-60	2·50	163	408	1112	741	791
36	275-20	2·75	163	448	364	1455	1554
37	275-30	2·75	163	448	546	1273	1359
38	275-40	2·75	163	448	728	1091	1165
39	275-50	2·75	163	448	909	909	971
40	275-60	2·75	163	448	1091	728	777
41	300-20	3·00	163	489	357	1428	1525
42	300-30	3·00	163	489	535	1249	1334
43	300-40	3·00	163	489	714	1071	1134
44	300-50	3·00	163	489	892	892	953
45	300-60	3·00	163	489	1071	714	762

TABLE 4.3. : Mix Quantities calculated for the Test Mixes.

The final test mix quantities are shown in Table 4.3 overleaf. There are nine different cement/water ratios and five different stone/sand ratios, therefore, 45 mixes in total. Each mix has a number from 1 to 45, as well as a mix code based on its cement/water ratio and sand percentage. For example:

a mix of c/w = 1.75 and stone/sand = 60:40 will have the code 175-40.

The process to be followed for each test mix is as follows:

1. Batch the quantities of materials into the mixer once the specified masses have been weighed out.

   SST = saturated natural aggregate = dry mass (DST) * 1.0677;
   S = air-dried Klipheuwel sand (moisture content to be checked);
   C = rapid-hardening cement;
   W = water;

2. Once the water has been added to the mix, the mixer must be left to run for two minutes to allow thorough mixing.

3. Perform a slump test, a Vebe test, and measure the mortar excess, in the Vebe container. The aim is to get the slump to between 50 and 70 mm. If the slump is more than 70 mm, then add more sand and stone in the correct proportions to reduce the slump. If the slump is less than 50 mm, then cement powder and water in the correct ratio should be added and the slump test redone. It is best that only one attempt be made to correct the slump, otherwise the mix will stiffen as time elapses and subsequent slump values will be inaccurate. All observations made should be recorded on the result sheet for each mix. These sheets are shown in Appendix A6.

4. At least four 100 mm cubes should be made and as much ~~stone~~ concrete as possible should be fitted into each cube whilst it is vibro-compacted for 60 seconds. The cubes should then be weighed and tested in compression at the age of seven days.

Determining the Mortar Excess

1. Actual Mortar Excess (AME)

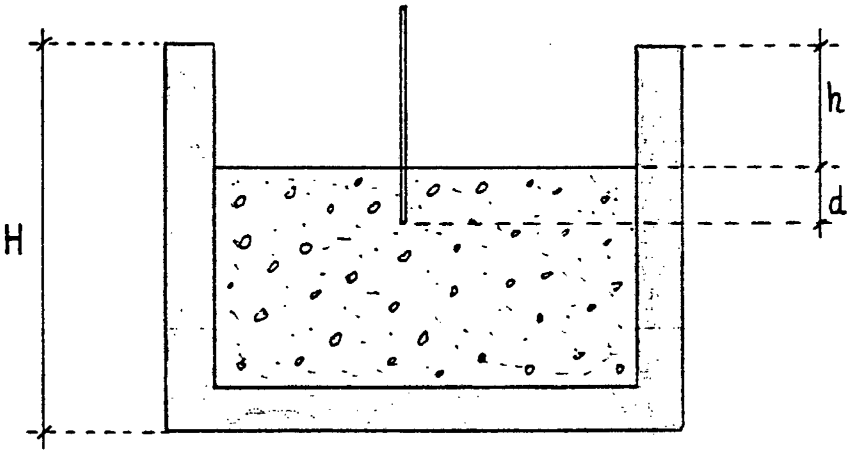


Figure 4.2: Measurement of Actual Mortar Excess

The actual mortar excess may be measured by poking a ruler into the surface of the concrete in the Vebe test container once the container has been vibrated for at least 75 seconds more than the vibration time required for the Vebe test itself. The value of the AME percentage is determined as follows:

The height of container $\underline{H}$ is known: $\underline{H}$ = 199 mm. The clear height $\underline{h}$ and the depth to the aggregate $\underline{d}$ must be measured for each sample. The value $\underline{d}$ is taken as the mean of several measurements. The AME is then:

$$\text{AME \%} = \left[\frac{\underline{d}}{\underline{H} - \underline{h}} \right] \times 100\% \qquad \text{. . . equation 4.3}$$

Therefore, for a 100 mm cube mould, the AME is merely the depth $\underline{d}$ in millimetres, as the mould should be completely filled.

2. Theoretical Mortar Excess (TME)

A formula to give the theoretical mortar excess of a concrete mix will be derived below and will be used in these tests.

From the discussion on TME in Section 4.1.5.1, its value as a percentage will be given by:

$$\left[\frac{\text{volume of mortar - volume of voids of compacted stone}}{\text{bulk volume of compacted stone}} \right] \times 100\%$$

In Phase 1 testing it was found that the voids volume was equal to 39% of the compacted bulk volume for the 13.2 to 19.0 mm fraction of the recycled aggregate stockpile.

The volume of the packing voids therefore equals 0.39 * mass of the dry stone divided by the dry bulk density of the stone. In this particular case, the stone is wet-batched and so the the volume of voids equals 0.39 * mass of saturated stone divided by the saturated bulk density, which is known to be 1433 kg/m^3.

$$\text{voids volume} = 0.39 * \underline{SST} \ / \ 1433 \ m^3$$

where $\underline{SST}$ is the mass of the saturated recycled aggregate.

The volume of mortar (sand, cement and water) is then:

$$\text{mortar volume} = \left[\frac{\underline{W}}{1.00} + \frac{\underline{C}}{3.14} + \frac{\underline{S}}{2.64} \right] \div 1000 \ m^3$$

where the masses of $\underline{W}$, $\underline{C}$, and $\underline{S}$ are in kilogrammes.

The bulk volume of the compacted saturated recycled stone is equal to the mass of saturated stone (kg) divided by the saturated bulk ~~volume~~ (kg/m^3). Therefore equation 4.4 becomes:
density

$$\text{TME\%} = \left[\frac{\left(\frac{S}{2.64} + \frac{C}{3.14} + W \right) \div 1000 - 0.39 * \frac{SST}{1433}}{\frac{SST}{1433}} \right] \times 100\%$$

A calculator programme was written to produce the value of the TME upon entering the masses of each mix con~~t~~stituent.

Results:

(i) The test mixes were started off with the 1.50 water/cement ratio after a trial mix had shown that the 170 litres/m^3 initially used had produced a 100 mm slump rather than 60 mm. The water requirement was then reduced to 163 litres/m and the mix quantities recalculated as has been shown previously in this section. Details of this trial mix are under "MIX 13" in Appendix A6.

(ii) The mixes with the stone/sand ratio of 80:20 were found to be deficient in mortar and the casting of the cubes from such concrete was very difficult. Eventually, the mixes were no longer made with cement/water ratios greater than 2.25.

(iii) The mixes with low cement/water ratios (below c/w = 1.75) showed signs of segregation, especially when the sand content was low and the slumps higher than 50 mm. In the process of segregation, the coarser sand particles sink down through the mortar and collect at the bottom of the concrete mix, whereas the cement and water paste tends to gather at the top of the concrete. This is an undesirable situation as the cement/water ratio now varies across the depth of the concrete section to be cast. The richer cement/water ratios of over 2.00 did not segregate as the mortar was sufficiently sticky to prevent the sand particles from sinking.

(iv) The slumps measured in the mixes with a low sand content (20% and 30% of total aggregate) were found to be erratic as the stone particles lock against each other as there is not enough mortar lubrication between them. The situation sometimes arose where the slump would either be zero, or else the slump cone would simply collapse giving a high and unrealistic slump - this was for the same mix. In such cases, the "true" slump was estimated based on the manual handling of the mix and personal experience.

(v) The mixes with the 50% and 60% natural sand fractions produced very workable concrete in the broader sense of the term, that is, even if the slump was as low as 30 mm, it was still easy and pleasant to work with, did not segregate, and was of good consistency. This was especially so for the cement/water ratios of 1.75 and above. These concretes would be ideal for hand-placing and were very responsive to vibration. They were certainly somewhat oversanded - especially the 60% sand mixes - as their AME values show.

(vi) After a number of mixes had been made and their slumps adjusted to near 60 mm, it was found that the 163 litres/m^3 water requirement was somewhat off the mark for stone/sand ratios other than 50:50 and 60:40. When the batched quantities of the finally acceptable mix were brought to "per cubic metre" quantities by the method to be shown below, the more accurate water requirements were seen to be:

recycled stone/natural sand = 80:20 : between 120 and 130 litres/m^3

recycled stone/natural sand = 70:30 : between 130 and 160 litres/m^3

recycled stone/natural sand = 60:40 : between 150 and 170 litres/m^3

recycled stone/natural sand = 50:50 : between 160 and 170 litres/m^3

recycled stone/natural sand = 40:60 : between 170 and 190 litres/m^3

The lower value would apply to the lowest cement/water ratio and the higher value to the highest cement/water ratio of 3.00. The values shown in Table 4.3 were then recalculated and the adjusted quantities were entered on the test sheet for each of the mixes made - these results are in Appendix A6. Mixes 44 and 45 with a cement/water ratio of 3.00 were omitted as such oversanded and rich recycled concrete would seldom, if ever, be made.

(vii) Once a mix had been adjusted to the required range of slump, the per m^3 quantities were recalculated. The calculation is somewhat tricky this time though and it is because of the fact that the absorbed water inside the recycled stone pores does not contribute to the volume or yield of the mix.

The idea is to bring the saturated mass of stone to an equivalent mass of dry recycled stone by reversing the adjustment factor of 1.0677 that was used to establish the mass of wet stone that was batched. The bulk volume of the dry stone would then be the same as the bulk volume of the saturated stone and this is the volume in the mix that the stone fills.

Let the mass of saturated stone be $\underline{SST}$, the mass of the sand be $\underline{S}$, the mass of cement be $\underline{C}$, the mass of water be $\underline{W}$, the mass of dry stone be $\underline{DST}$ and the volume batched be $\underline{V}$.

Then: $$\underline{DST} = \underline{SST}/1.0677 \qquad \text{. . . equation 4.5}$$

$$V = \left[\frac{\underline{DST} + \underline{S}}{2.62} + \frac{\underline{C}}{3.14} + \underline{W}\right] \div 1000 \text{ m}^3 \qquad \text{. . . equation 4.1}$$

The "per cubic metre" quantities are then: (kg/m^3)

recycled stone : $\underline{SST}_1 = \left[\frac{\underline{DST}}{\underline{V}}\right] * 1.0677$

sand : $\underline{S}_1 = \underline{S}/\underline{V}$

cement : $\underline{C}_1 = \underline{C}/\underline{V}$

water : $\underline{W}_1 = \underline{W}/\underline{V}$

where the subscript of 1 refers to the quantity for one cubic metre of concrete.

A calculator programme was again written that produced these amounts per cubic metre (after the correction for the moisture content had been done - see the test sheets of the mixes.)

MIX CODE No.	BATCHED QUANTITIES (grammes)				QUANTITIES PER M^3 (kg / m^3)				MIX NUMBER	SLUMP (mm)	VEBE (sec.)	A.M.E. %	T.M.E. %	RELATIVE COST	DENSITY (kg/m^3)	WATER CEMENT R.	CEMENT WATER R.	$f_{cu}\left\{\frac{RHC}{7\,day}\right\}$ (MPa)
	St*	S	C	W	St*	S	C	W										
100-20	8500	1988	541	543	1884	441	120	120	1	150	1.0	-34.7	-14.3	52.72	N/T	1.00	1.00	N/T
100-30	10490	4210	812	816	1631	655	126	127	2	50	1.8	0.0	-2.5	51.03	2337	1.00	1.00	11.6
100-40	8480	5291	951	956	1344	839	151	152	3	60	2.0	8.1	16.2	50.70	2354	1.01	0.99	12.0
100-50	7000	6549	1014	1021	1103	1032	160	161	4	50	2.0	14.7	39.3	49.37	2338	1.01	0.99	13.1
100-60	6500	9121	1321	1327	861	1208	175	176	5	50	2.3	12.9	75.7	48.58	2331	1.00	1.00	12.1
125-20	8500	1989	706	566	1852	433	154	123	6	150	1.0	-24.0	-13.0	56.15	N/T	0.80	1.25	N/T
125-30	10492	4210	1075	862	1599	642	164	131	7	40	2.5	2.8	-0.8	54.88	2358	0.80	1.25	18.8
125-40	9143	5707	1237	995	1338	835	181	146	8	50	2.8	7.5	16.7	54.15	2357	0.80	1.24	15.4
125-50	7868	7370	1417	1137	1091	1022	196	158	9	60	2.2	10.1	40.8	53.38	2360	0.80	1.25	16.7
125-60	6785	9539	1685	1353	853	1199	212	170	10	50	1.8	12.1	77.2	52.78	2347	0.80	1.25	17.5
150-20	9354	2187	1226	819	1736	406	228	152	11	150	1.0	-7.6	-7.8	62.67	2348	0.67	1.50	15.7
150-30	9235	3831	1484	992	1483	615	238	159	12	30	8.2	3.6	6.2	61.40	2374	0.67	1.50	21.4
150-40	9000	5616	1731	1158	1273	794	245	164	13	52	4.7	9.3	22.1	60.25	2373	0.67	1.49	19.7
150-50	9000	8421	2076	1392	1061	993	245	164	14	60	2.6	10.3	44.5	58.43	2359	0.67	1.49	20.7
150-60	8500	11906	2540	1714	841	1178	251	170	15	45	2.4	15.0	79.6	57.04	2355	0.67	1.48	23.3
175-20	11060	2587	1451	833	1774	415	233	134	16	130	1.4	-14.0	-8.4	64.04	2337	0.57	1.74	19.9
175-30	8749	3509	1657	952	1471	590	279	160	17	90	2.0	5.1	7.0	65.86	2372	0.57	1.74	26.7
175-40	8000	4992	1898	1091	1238	773	294	169	18	35	2.6	13.9	25.3	65.29	2389	0.57	1.74	28.8
175-50	8500	7954	2320	1336	1043	976	285	164	19	50	2.8	11.5	46.8	62.73	2365	0.57	1.74	28.8
175-60	7500	10525	2861	1647	810	1137	309	178	20	70	1.8	15.7	86.1	63.03	2366	0.57	1.74	30.5
200-20	9000	2104	1316	660	1765	413	258	129	21	150	1.0	-12.6	-9.2	66.86	2339	0.50	1.99	21.8
200-30	8748	3505	1816	912	1469	589	305	153	22	50	2.0	4.4	7.2	68.93	2390	0.50	1.99	32.2
200-40	8000	4986	2119	1065	1230	767	326	164	23	65	4.3	9.3	26.1	68.93	2385	0.50	1.99	33.4
200-50	7500	7018	2383	1197	1025	959	326	164	24	55	3.5	10.2	49.2	67.16	2405	0.50	1.99	36.6
200-60	7000	9833	3133	1576	793	1114	355	178	25	65	2.0	15.2	89.8	68.01	2372	0.50	1.99	39.0
225-20	—	—	—	—	—	—	—	—	26	—	—	—	—	—	—	—	—	—
225-30	8500	3411	2121	943	1426	572	356	158	27	65	1.5	2.9	10.0	74.11	2363	0.45	2.24	32.4
225-40	8000	4996	2430	1083	1208	754	367	164	28	60	3.2	11.2	28.2	73.32	2402	0.45	2.24	35.6
225-50	7500	7019	2731	1218	1007	942	367	164	29	55	2.7	12.8	51.7	71.59	2391	0.45	2.24	40.8
225-60	7000	9811	3513	1567	784	1098	393	175	30	55	2.8	15.0	91.9	72.25	2379	0.45	2.24	45.4
250-20	—	—	—	—	—	—	—	—	31	—	—	—	—	—	—	—	—	—
250-30	8500	3406	2334	937	1412	566	388	156	32	60	3.0	2.0	11.1	77.64	2377	0.40	2.49	41.5
250-40	8000	4988	2723	1096	1189	742	405	163	33	60	2.9	8.4	30.1	77.42	2406	0.40	2.48	48.1
250-50	7500	7019	3094	1247	988	924	408	164	34	60	2.7	14.1	54.4	75.98	2396	0.40	2.48	50.3
250-60	6500	9122	3962	1597	750	1053	457	184	35	60	2.0	15.6	100.2	78.87	2392	0.40	2.48	52.8
275-20	—	—	—	—	—	—	—	—	36	—	—	—	—	—	—	—	—	—
275-30	8000	3210	2527	921	1377	552	435	158	37	60	1.7	2.2	13.6	82.51	2403	0.36	2.74	52.5
275-40	7500	4681	3048	1114	1145	714	465	170	38	55	3.0	6.3	34.7	83.55	2413	0.37	2.74	59.4
275-50	7000	6550	3322	1214	962	900	457	167	39	45	3.5	8.9	58.3	81.16	2415	0.57	2.74	61.7
275-60	6000	8425	4220	1539	728	1022	512	187	40	55	2.0	13.1	106.1	84.76	2380	0.36	2.74	61.8
300-20	—	—	—	—	—	—	—	—	41	—	—	—	—	—	—	—	—	—
300-30	7500	3006	2800	936	1326	531	495	165	42	60	1.9	2.9	17.6	88.58	2402	0.33	2.99	59.0
300-40	7000	4365	3329	1114	1104	688	525	176	43	45	4.1	7.1	39.4	89.75	2414	0.33	2.99	61.5
300-50	—	—	—	—	—	—	—	—	44	—	—	—	—	—	—	—	—	—
300-60	—	—	—	—	—	—	—	—	45	—	—	—	—	—	—	—	—	—

TABLE 4.4 : Summary of the parameters measured in the test mixes of Phase 2.

(viii) Table 4.4 appears overleaf and is the summary of all the parameters measured for each mix made. The batched quantities appear in grammes and these values are converted to per cubic metre amounts using the equations formulated above.

(ix) All the cubes cast were left to set for 24 hours under plastic sheeting before they were placed in water at 23^{0}C for a further six days. At seven days, they were dried for two hours before being weighed and then tested at the SABS-specified rate of 15 MPa per minute for 100 mm cubes. The results may be found in the test sheets in Appendix A6.

(x) Strength charts of cement/water ratio versus compressive strength are drawn for each of the five stone/sand ratios used and these follow in Figures 4.3 to 4.7.

(xi) A cost comparison of all the mixes made is done in Table 4.4 as well. These costs are based on the figures obtained from the course CE5G1: "Properties of Concrete" of 1985, and were used earlier in Section 4.2.1. - according to the Portland Cement Institute these prices were still valid for 1986. Natural coarse ~~sand~~ aggregate is priced at R25 per metric tonne, Klipheuwel sand at R10 a tonne and rapid-hardening cement at R6 per 50 kg pocket. The cost of the water is negligible.

(xii) An American researcher, Frondistou-Yannas (*8 and *9) believes that recycled aggregates will only be economically feasible if they are at least 15 percent cheaper than natural aggregates. She has shown, in a feasiblity study on the matter, that this is indeed possible. The major factor contributing to the lower cost is that the recyled aggregate seldom needs to be transported over as great a distance as the natural aggregates. Stone quarries are usually in rural areas, whereas rubble dumps are usually in, or near, urban areas. For this reason the cost of recycled aggregate is set hypothetically at the lower rate of R18 per tonne. Whether this price can be matched in South Africa is not known - as no commercial rubble-recycling plants exist -and is unfortunately beyond the scope of this thesis.

(xiii) It was subsequently noted that the yields of the mixes were usually higher than the volume calculated for the batched quantities. This feature can be explained by the fact that the Relative Density or Specific Gravity used for all the recycled aggregates was 2.62, whereas the actual RD or SG was found in Phase 1 testing to be 2.21. The difference exists because the SG of 2.62 would hold perfectly had the recycled aggregate been crushed to powder or had it been non-porous, whereas the porosity of the material causes the SG to drop to 2.21.

(xiv) By definition the absolute density is the mass of a particle divided by its absolute volume, whereas the relative density of a particle would be its mass divided by the outer or bulk volume divided by the density of water.

(xv) The mortar is not able to penetrate into the pores of the recycled aggregate, which means that these voids are either left filled with air or else with water. So, to calculate the yield of a concrete mix when the aggregate has been wet-batched, this fact must be taken into account, and it may be done in two ways:

Figure 4.3. : Strength chart for Recycled Concrete.

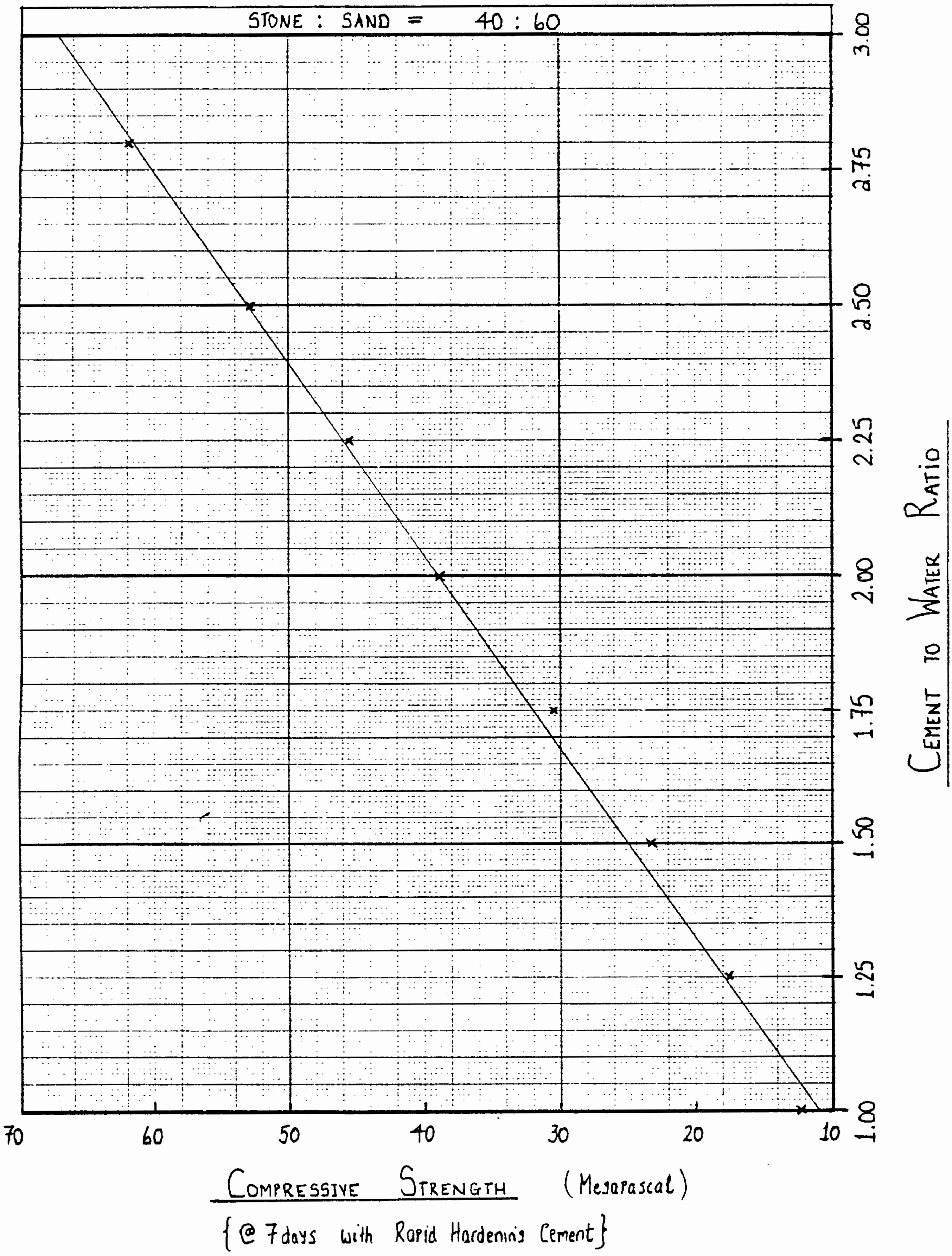
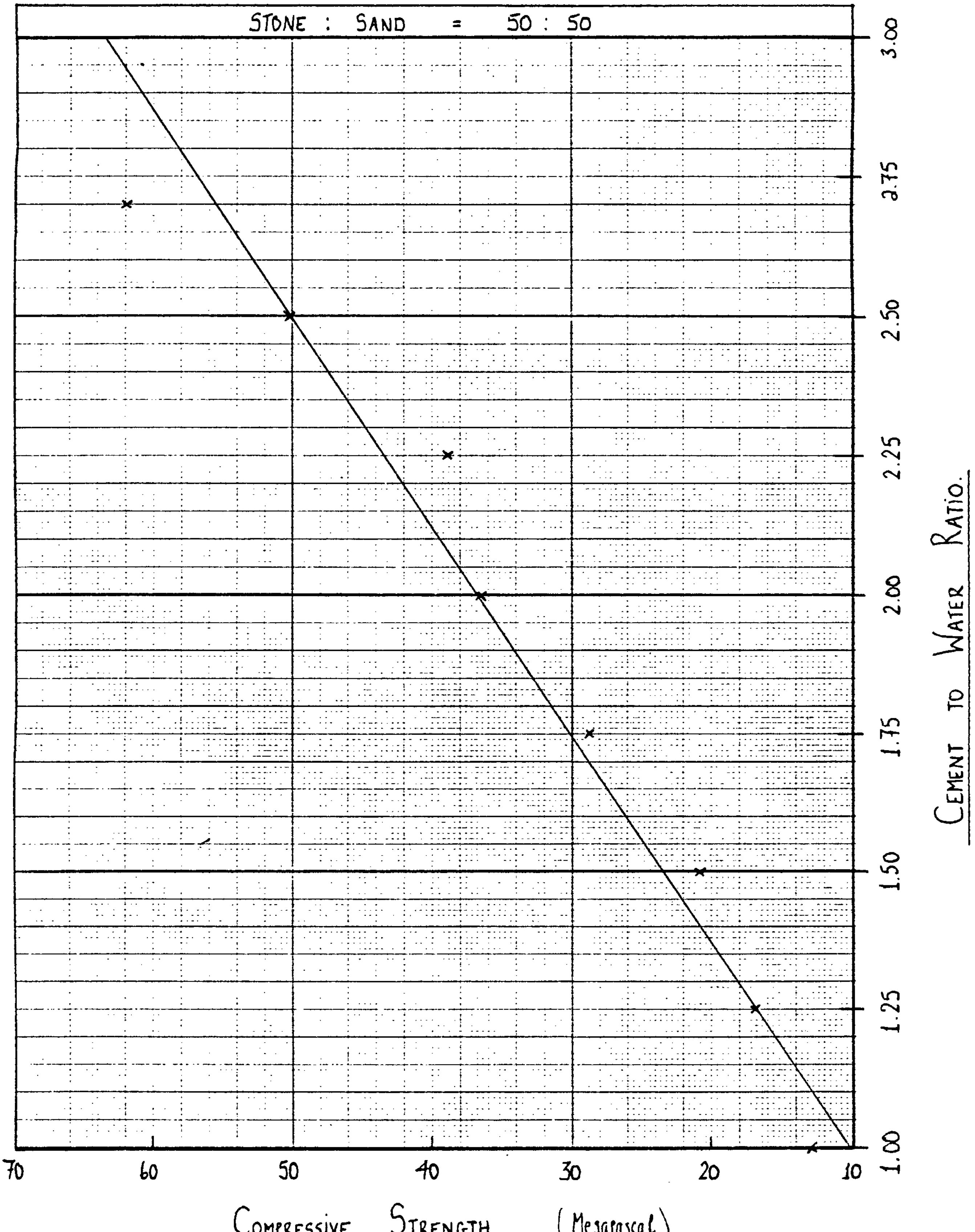


Figure 4.4 : Strength Chart for Recycled Concrete.



{@ 7 days with Rapid Hardening Cement}

Figure 4.5. : Strength Chart for Recycled Concrete.

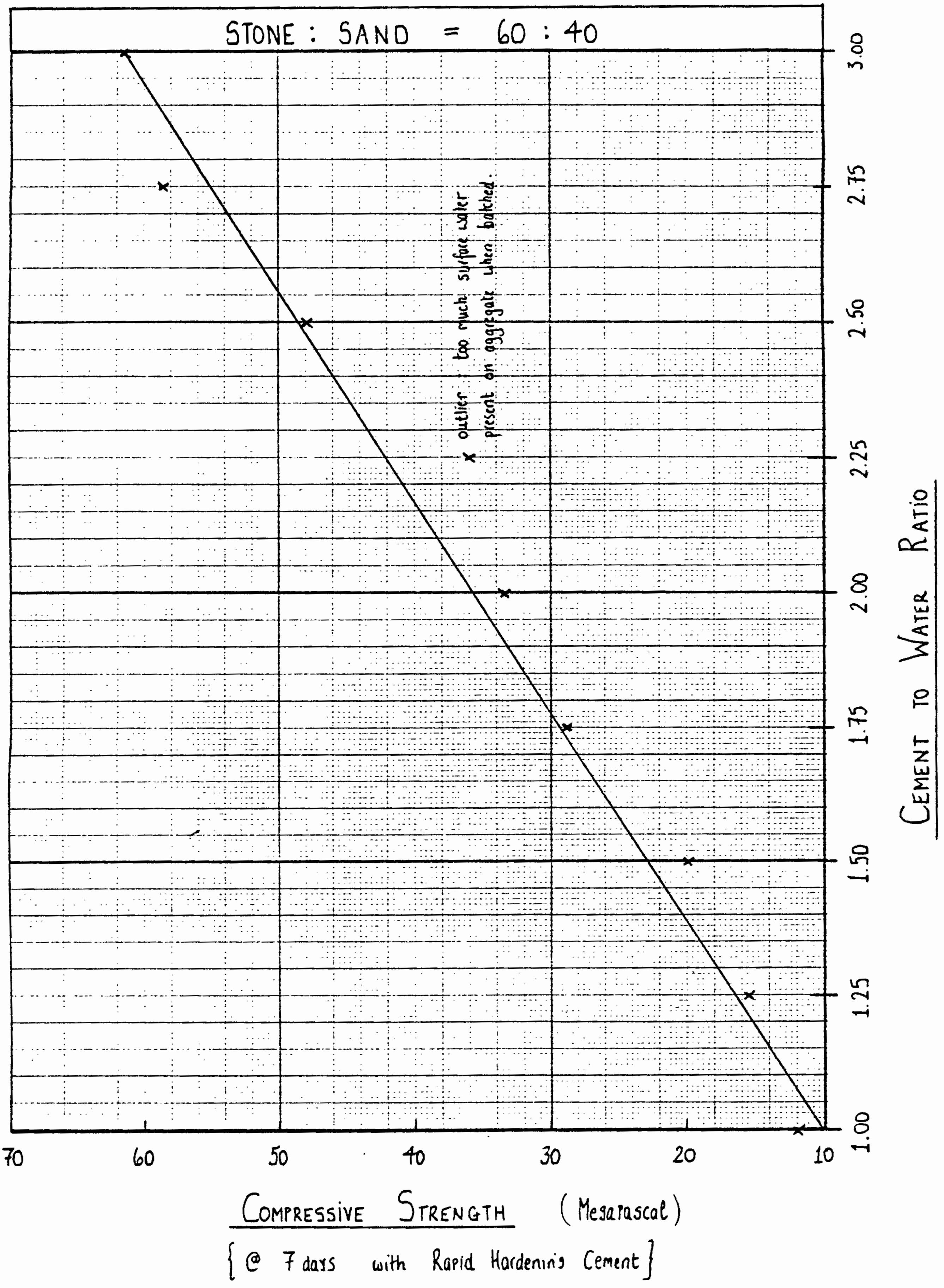
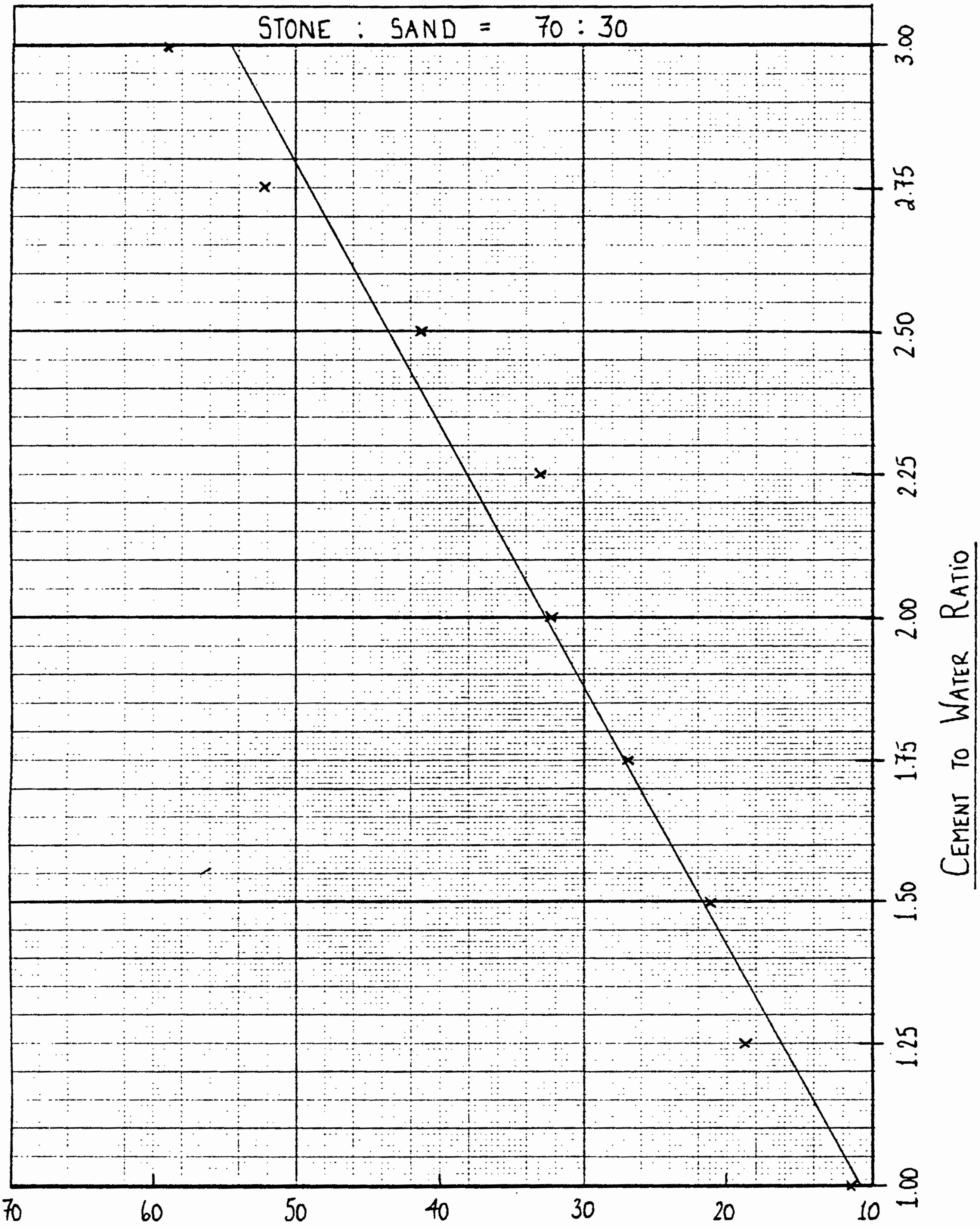


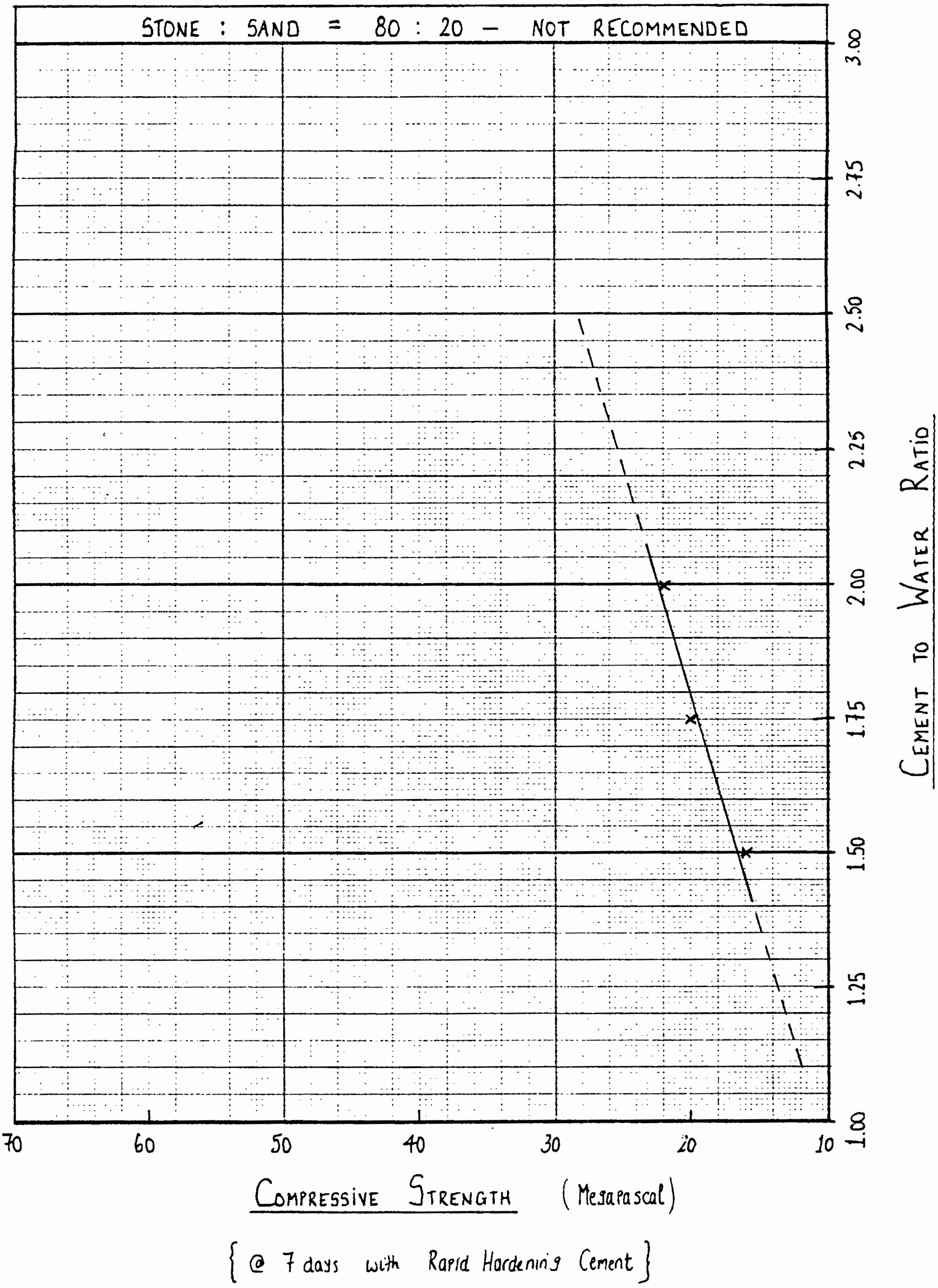
Figure 4.6. : Strength Chart for Recycled Concrete.



Compressive Strength (Megapascal)

{@ 7 days with Rapid Hardening Cement}

Figure 4.7 : Strength Chart for Recycled Concrete.



{@ 7 days with Rapid Hardening Cement}

1. The mass of the saturated recycled stone has to be converted to an equivalent mass of dry stone by using the factor mentioned previously.

   eg. if saturated stone = SST, dry stone = DST and the absorption coefficient of the aggregate is Ca% ;

   then $SST = (100\% + Ca\%) * DST$ . . . equation 4.6(a)

   so $DST = 100\ SST/(100 + Ca)$ . . . equation 4.6(b)

   These equations are more general than equation 4.5, which is specifically for the aggregate used in Phase 2 testing.

   The volume of the mix and the "per cubic metre" quantities are then calculated using the dry stone mass as calculated from equation 4.6(b) ignoring the volume of the water which is absorbed. The relevant equation to use is equation 4.1 using RD = 2.21 for this particular recycled stone.

2. An equivalent RD for the saturated stone could be calculated and so the mass of saturated recycled stone that was batched may be used directly in the yield equation.

   From the Phase 1 tests, the porosity of the stone is known as well as the porous specific gravity - for this stockpiled aggregate in the 13.2 to 19.0 mm fraction these two figures are 15% and 2.21. This means that if one cubic metre of this stone was saturated it would contain 15% of water by volume - that is $0.150m^3$ or 150 kg of water. In the dry state, the RD of 2.21 implies that the one cubic metre of dry stone would have a mass of 1000 x 2.21 = 2210 kg. The total mass of a cubic metre of saturated stone would therefore be 2210 kg plus 150 kg, which equals 2360 kg - meaning that the effective RD is 2.36.

   The general formula to perform this calculation is therefore:

   $$\text{RD saturated} = \text{RD dry} + \frac{\text{porosity}}{100} \qquad \text{. . . equation 4.7}$$

   The volume of the mix and the "per cubic metre" quantities are then calculated using the mass of the wet-batched recycled stone in equation 4.1 using the RD for the stone as calculated in equation 4.7.

(xvi) All the values shown in Table 4.4 were then recalculated using the second method shown above - the ratio of materials by mass does not change though, and so the stone/sand ratios are still valid. The data is shown in Table 4.5.

(xvii) It will be noted that the compressive strength for any particular cement/water ratio generally increases with increased sand percentages by mass in the mix. It then also happens that a particular compressive strength (f_{cu}) may be reached using two different cement/water ratios - for example compare Mix 35 with Mix 37.

MIX CODE No.	BATCHED QUANTITIES (grammes)				QUANTITIES PER M^3 (kg/m^3)				MIX NUMBER	SLUMP (mm)	VEBE (sec.)	A.M.E. %	T.M.E. %	RELATIVE COST	DENSITY (kg/m^3)	WATER CEMENT R.	CEMENT WATER R.	f_{cu} {RHC / 7 days} (MPa)
	St*	S	C	W	St*	S	C	W										
100-20	8500	1988	541	543	1677	392	107	107	1	150	1·0	-34·7	-14·3	45·03	N/T	1·00	1·00	N/T
100-30	10490	4210	812	816	1475	592	114	115	2	50	1·8	0·0	-2·5	44·47	2337	1·00	1·00	11·6
100-40	8480	5291	951	956	1237	772	139	139	3	60	2·0	8·1	16·2	45·25	2354	1·01	0·99	12·0
100-50	7000	6549	1014	1021	1031	964	149	150	4	50	2·0	14·7	39·3	44·90	2338	1·01	0·99	13·1
100-60	6500	9121	1321	1327	817	1146	166	167	5	50	2·3	12·9	75·7	45·15	2331	1·00	1·00	12·1
125-20	8500	1989	706	566	1652	387	137	110	6	150	1·0	-24·0	-13·0	48·16	N/T	0·80	1·25	N/T
125-30	10492	4210	1075	862	1448	581	148	119	7	40	2·5	2·8	-0·8	47·98	2358	0·80	1·25	18·8
125-40	9143	5707	1237	995	1231	769	167	134	8	50	2·8	7·5	16·7	48·48	2357	0·80	1·24	15·4
125-50	7868	7370	1417	1137	1020	955	184	147	9	60	2·2	10·1	40·8	48·83	2360	0·80	1·25	16·7
125-60	6785	9539	1685	1353	810	1139	201	161	10	50	1·8	12·1	77·2	49·17	2347	0·80	1·25	17·5
150-20	9354	2187	1226	819	1559	364	204	136	11	150	1·0	-7·6	-7·8	54·40	2348	0·67	1·50	15·7
150-30	9235	3831	1484	992	1352	561	217	145	12	30	8·2	3·6	6·2	54·44	2374	0·67	1·50	21·4
150-40	9000	5616	1731	1158	1176	734	226	151	13	52	4·7	9·3	22·1	54·29	2373	0·67	1·49	19·7
150-50	9000	8421	2076	1392	994	930	229	154	14	60	2·6	10·3	44·5	53·54	2359	0·67	1·49	20·7
150-60	8500	11906	2540	1714	799	1120	239	161	15	45	2·4	15·0	79·6	53·35	2355	0·67	1·48	23·3
175-20	11060	2587	1451	835	1589	372	208	120	16	130	1·4	-14·0	-8·4	55·47	2337	0·57	1·74	19·9
175-30	8749	3509	1657	952	1343	539	254	146	17	90	2·0	5·1	7·0	58·51	2372	0·57	1·74	26·7
175-40	8000	4992	1898	1091	1147	716	272	156	18	35	2·6	13·9	25·3	59·14	2389	0·57	1·74	28·8
175-50	8500	7954	2320	1336	978	915	267	154	19	50	2·8	11·5	46·8	57·68	2365	0·57	1·74	28·8
175-60	7500	10525	2861	1647	771	1083	294	169	20	70	1·8	15·7	86·1	59·11	2366	0·57	1·74	30·5
200-20	9000	2104	1316	660	1582	370	231	116	21	150	1·0	-12·6	-9·2	58·09	2339	0·50	1·99	21·8
200-30	8748	3505	1816	912	1341	537	278	140	22	50	2·0	4·4	7·2	61·34	2390	0·50	1·99	32·2
200-40	8000	4986	2119	1065	1140	710	302	152	23	65	4·3	9·3	26·1	62·56	2385	0·50	1·99	33·4
200-50	7500	7018	2383	1197	962	901	306	154	24	55	3·5	10·2	49·2	61·95	2405	0·50	1·99	36·6
200-60	7000	9833	3133	1576	756	1061	338	170	25	65	2·0	15·2	89·8	63·92	2372	0·50	1·99	39·0
225-20	—	—	—	—	—	—	—	—	26	—	—	—	—	—	—	—	—	—
225-30	8500	3411	2121	943	1305	524	326	145	27	65	1·5	2·9	10·0	66·36	2363	0·45	2·24	32·4
225-40	8000	4996	2430	1083	1121	700	340	152	28	60	3·2	11·2	28·2	66·70	2402	0·45	2·24	35·6
225-50	7500	7019	2731	1218	946	886	345	154	29	55	2·7	12·8	51·7	66·21	2391	0·45	2·24	40·8
225-60	7000	9811	3513	1567	747	1047	375	167	30	55	2·8	15·0	91·9	68·06	2379	0·45	2·24	45·4
250-20	—	—	—	—	—	—	—	—	31	—	—	—	—	—	—	—	—	—
250-30	8500	3406	2334	937	1293	518	355	143	32	60	3·0	2·0	11·1	69·58	2377	0·40	2·49	41·5
250-40	8000	4988	2723	1096	1105	689	376	151	33	60	2·9	8·4	30·1	70·64	2406	0·40	2·48	48·1
250-50	7500	7019	3094	1247	929	870	383	155	34	60	2·7	14·1	54·4	70·32	2396	0·40	2·48	50·3
250-60	6500	9122	3962	1597	717	1006	437	176	35	60	2·0	15·6	100·2	74·59	2392	0·40	2·48	52·8
275-20	—	—	—	—	—	—	—	—	36	—	—	—	—	—	—	—	—	—
275-30	8000	3210	2527	921	1264	507	399	145	37	60	1·7	2·2	13·6	74·26	2403	0·36	2·74	52·5
275-40	7500	4681	3048	1114	1066	665	433	158	38	55	3·0	6·3	34·7	76·58	2413	0·37	2·74	59·4
275-50	7000	6550	3322	1214	907	849	430	157	39	45	3·5	8·9	58·3	75·38	2415	0·37	2·74	61·7
275-60	6000	8425	4220	1539	696	978	490	179	40	55	2·0	13·1	106·1	80·31	2380	0·36	2·74	61·8
300-20	—	—	—	—	—	—	—	—	41	—	—	—	—	—	—	—	—	—
300-30	7500	3006	2800	936	1221	489	456	152	42	60	1·9	2·9	17·6	80·19	2402	0·33	2·99	59·0
300-40	7000	4365	3329	1114	1030	643	490	164	43	45	4·1	7·1	39·4	82·59	2414	0·33	2·99	61·5
300-50	—	—	—	—	—	—	—	—	44	—	—	—	—	—	—	—	—	—
300-60	—	—	—	—	—	—	—	—	45	—	—	—	—	—	—	—	—	—

TABLE 4.5 : Recalculated values of the parameters of the test mixes in Phase 2.

Mix 35: Code 250-60; the mix constituents in kg/m^3 were:

saturated stone = 717; dry sand = 1006
cement = 437; water = 176
the cement/water ratio was thus 2.48
the f$_{cu}$ at 7 days with RHC was 52.8 MPa

Mix 37: Code 275-30; the mix constituents in kg/m^3 were:

saturated stone = 1264; dry sand = 507;
cement = 399; water = 507
the cement/water ratio was thus 2.74
the f$_{cu}$ at 7 days with RHC was 52.5 MPa

(xviii) Both the above mixes had slumps of 60 mm although Mix 35 had the better workability because of all the sand - its measured mortar excess was 15.6% compared with the 2.2% of Mix 37.

(ixx) Looking at the cement factor, it is seen that Mix 35, code 250-60, had a cement content of 437 kg/m^3, whereas Mix 37, code 275-30, had a lower cement content of 399 kg/m^3. The lower cement content of Mix 37 may therefore appear to be the more economical altenative to produce recycled concrete of 52 MPa.

(xx) When comparing the cost of these two mixes, they oddly enough have almost the same cost/m^3 - Mix 35 @ R74.59 and Mix 37 @ R74.26. The common belief that lower cement contents produce cheaper concretes is then not valid in this case, and it should therfore be borne in mind that the aggregate cost is significant as well.

4.2.3: An Alternative Mix Design Method. (DRY BATCH)

The South African mix design method is based on the Water Demand Theory, where the water demands of various sands have been established and well documented, and the water demand of an impervious natural stone is negligible. The following relation holds:

water demand of a mix = water demand of sand + water demand of stone + water demand of cement

In general terms, the "water requirement" would be a better way to express this relationship, as "water demand" is a unique case mentioned before in Section 4.1.3.

Because of the porosity - and therefore significant absorption - of recycled coarse aggregate, the water requirement of the stone cannot be ignored. If it is overlooked, the concrete produced will be expensive because of the high cement content required. This is demonstrated below:

> If a recycled aggregate mix is designed based on the water demand of the sand to be used, then the mix will become very dry and unsuitable, resulting in a slump significantly lower than the designed value. This is due to the fairly large amount of water that the aggregate has absorbed into its pores from the mix water. To obtain the desired slump, the standard procedure would be to add more water and cement in the correct ratio. So the cement

content and cost of the mix increases quite significantly as a fairly large amount of water may be required to give equivalent slumps between recycled and natural coarse aggregates.

When the same recycled concrete is tested later for compressive strength, it will be found to be considerably stronger than what was expected and the concrete producer will realise that all the extra cement powder was not really needed.

The reason for this is that the absorbed water in the pores of recycled stone does not contribute towards the cement/water ratio of the mix - this was discovered by experimentation by this author in his BSc thesis (* 20).

The aim of this section is to establish a dry-batching mix design method where the absorption of the recycled aggregate is accounted for.

4.2.3.1: Dry-Batching using the Additional Absorption Coefficient.

In the BSc thesis, the "additional absorption coefficient" was defined by this author as the percentage of water over and above the water requirement of the mix needed to produce equivalence in strength and workability. This is then a measure of the amount of water absorbed by the porous recycled stone compared to the total mass of water in the mix.

The "absorption coefficient" on the other hand, is the percentage of water absorbed by the aggregate compared to its own mass.

The "Slump Adjustment Method" was developed in which the additional absorption coefficient could be measured. It was found that the additional absorption coefficients differed between equivalence in strength and equivalence in slump compared to a mix of control concrete made with natural coarse aggregate.

The procedure to measure these figures is as follows:

Two mixes - a control mix and a recycled mix - are made with identical amounts of material. The slumps of both mixes are measured and noted - the slump of the control mix will be the "design slump" and the slump of the recycled mix will always be much less than this design value. Cubes are cast from these two mixes. A third mix - identical to the recycled mix - is then made and its slump is adjusted until it reaches the design value. This adjustment is done with water only - no corresponding amount of cement is added. Again cubes are cast from this mix. The concrete is tested afer seven days. The additional absorption coefficients are then determined graphically from the plots of compressive strength or slump versus the additional percentage of water added.

The actual values in the test for the three mixes were:

MIX 1: Control mix:
Slump = 65 mm; fcu = 29.8 MPa
Constituents - (hornfels) stone: 1130 kg/m^3;
Cape Flats sand: 827 kg/m^3;
rapid-hardening cement: 294 kg/m^3;
water: 187 kg/m^3

MIX 2: Recycled Mix:
Slump = 10 mm; fcu = 35.8 MPa
Constituents - recycled stone: 1130 kg/m^3;
Cape Flats sand: 827 kg/m^3;
rapid-hardening cement: 294 kg/m^3;
water: 187 kg/m^3.

The batched quantity of water in both mixes was 1400 ml.

MIX 3: Recycled mix:
Constituents identical to MIX 2.
Initial slump again 10 mm; another 100 ml of water increased the slump to 20 mm; a further 100 ml of water increased the slump to 25 mm, and a final 100 ml of water brought the slump to 40 mm. Since the original water content of the mix was 1400 ml, these values represent percentages of 7.1, 14.3 and 21.4 respectively. The seven day fcu for this mix was found to be 26.64 MPa and the final "per cubic metre" quantities were:

recycled stone	:	1130 kg/m^3
Cape Flats sand	:	827 kg/m^3
rapid-hardening cement	:	294 kg/m^3
water	:	227 kg/m^3

The 21.4% increase in water in Mix 3 had actually caused the strength to drop below the control strength, but the correct amount that would have given strength equivalence is found graphically in Figure 4.8. The extra amount to give strength equivalence was determined as 14% and this is then known as the "strength-related additional absorption coefficient". This means that 187 * 1.14 = 213 kg/m^3 of water should have been used for the recycled mix to have the same strength as the control mix. The cement content would still have been calculated from the 187 litres/m^3 using the desired cement/water ratio - not from the 213 kg/m^3.

Figure 4.9 was constructed from the following information concerning MIX 3.

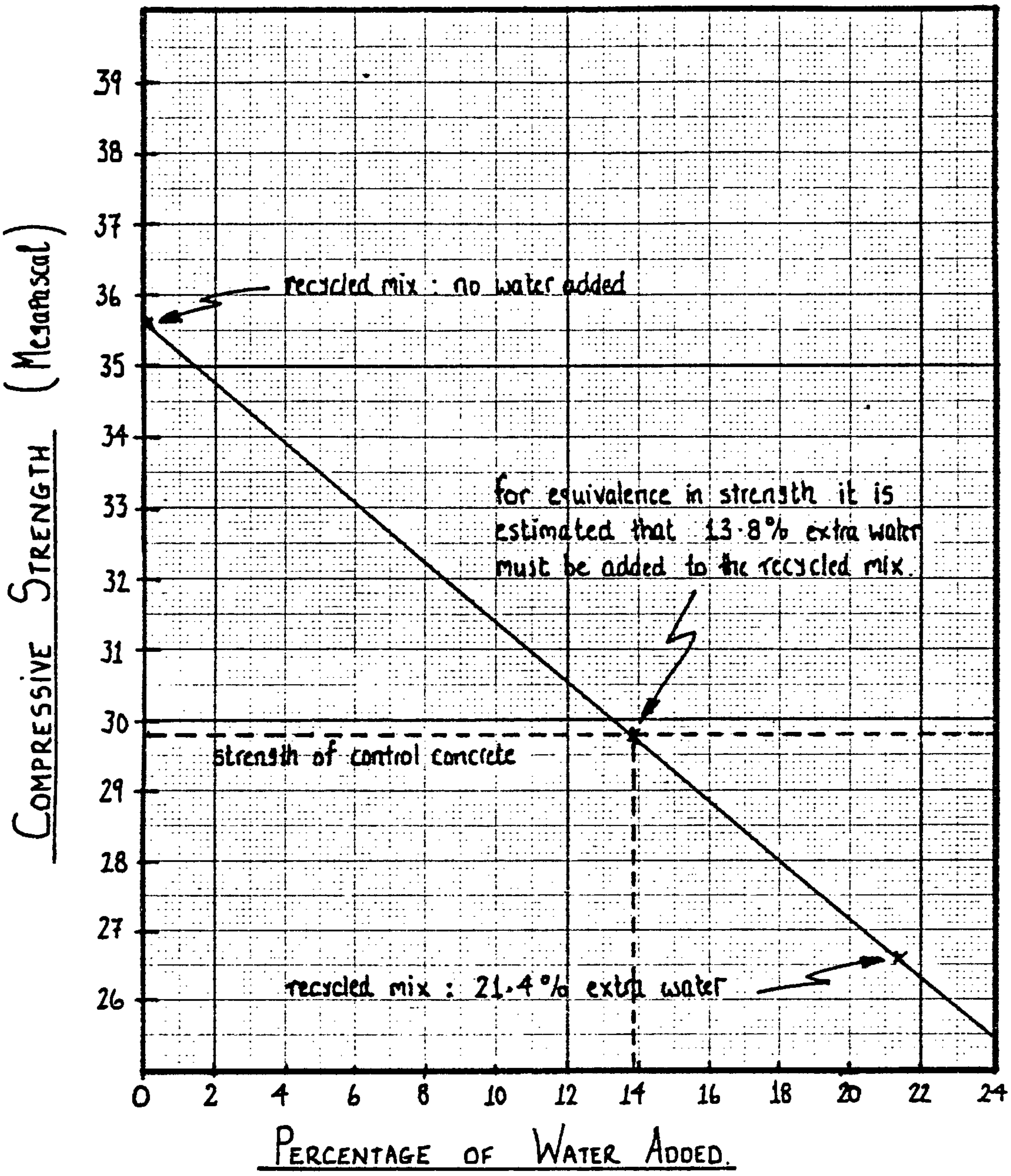
(deleted)

original slump with 1400 ml water was 10 mm (0% extra water);
added 100 ml water to give a slump of 20 mm (7.1% extra water);
added 200 ml water to give a slump pf 25 mm (14.3% extra water);
added 300 ml water to give a slump of 40 mm (21.4% extra water).

The amount of additional water to give equivalence in slump (65 mm) was extrapolated and found to be 39.4% - and it is known as the "slump-related additional absorption coefficient".

The large difference between the two additional absorption coefficients is due to the difference in surface texture and shape of the coarse aggregates - the recycled aggregates are rough-textured but more cubic than the smooth flaky hornfels stones. The slump test is also highly variable, especially with elapsed time (as was

FIGURE 4.8. : Determination of the Strength-related additional absorption coefficient.



The control mix had a slump of 65mm and a 7-day strength of 29·8 MPa. The first recycled mix had a slump of 10mm and a strength of 35.6 MPa. The second recycled mix was made and water only added to produce a similar slump to the control mix. The additional water % is plotted and also the strength of 26·6 MPa. See the construction.

the case here) and so it is recommended that use of the "slump-related additional absorption coefficient" be avoided and that it should remain of academic interest only.

However, the strength-related additional absorption coefficient is measured with far more accuracy, and its use may be of value to a concrete producer when recycled concretes are to be produced based on the technology of conventional concretes. This method may be considered unsatisfactory by certain parties (the author included) who will argue that dry-batched mix designs with recycled aggregates should be developed independently of control aggregates, that is, treating the recycled concrete as a material in its own right. This fact is essentially the difference between the BSc thesis and this thesis.

The design of a dry-batched recycled concrete then essentially follows the process of design for a conventional concrete with impervious natural stone. The additional absorption coefficient (AAC) is then used to adjust the cement content of the mix according to the effective amount of mix water.

Conventional strength charts of cement/water ratio versus f_{cu} for any variety of cement type, stone type or sand type may be used. The value of the AAC will then be determined via the Slump Adjustment Test and be applied to the mix design. The strength charts found for control mixes with 19 mm hornfels stone, Cape Flats sand and rapid-hardening cement at seven days are shown in Figure 4.10.

An example of mix design using the AAC is then as follows:

A strength of 30 MPa is required and from Figure 4.10 a cement/water ratio of of 1.63 is then needed. A trial mix shows that the water requirement for the desired slump with this particular sand and porous recycled stone is 225 lites/m^3. Notice that this is the water requirement of both the sand and the porous stone.

The Slump Adjustment Test produced the value of 15% for the strength-related AAC. So in calculating the cement content, it will not be necessary to use the full water requirement of the mix. The following relation will hold:

$$\text{effective mix water} = \left[\frac{\text{gross mix water}}{1 + \text{AAC}/100}\right] \qquad \text{. . . equation 4.8}$$

$$= 225/(1 + 0.15) \qquad = 196 \text{ litres/m}^3$$

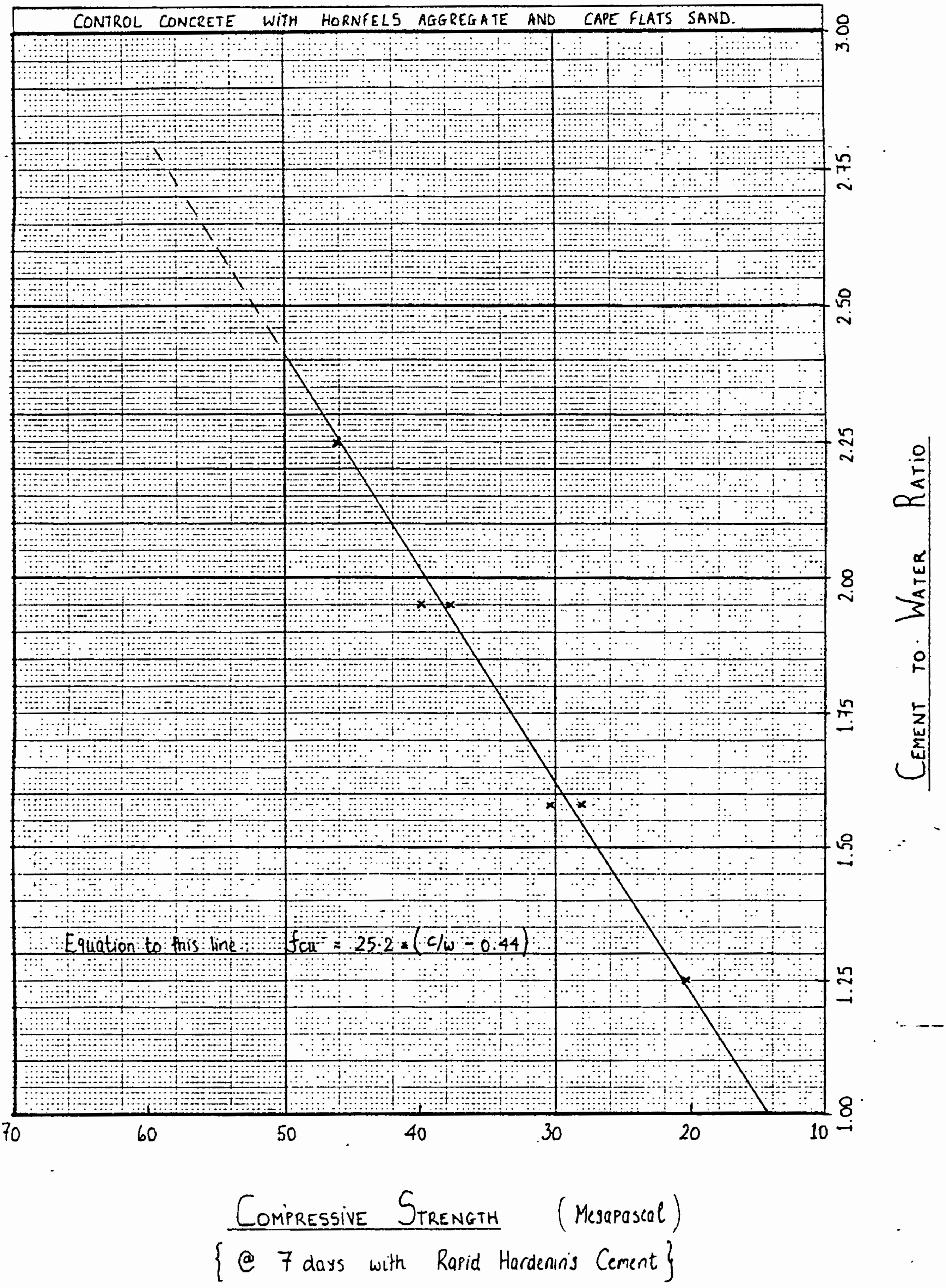
$$\text{cement content} \quad = 196 \times 1.63 \qquad = 320 \text{ kg/m}^3$$

$$\text{stone and water volume} = 1000 - (196 + 320/3.17) = 702 \text{ litres.}$$

The porous SG of the stone is 2.30 and for the natural sand 2.60, say. The desired stone/sand ratio is 60:40 by volume.

stone content = 0.60 x 702 x 2.30 = 969 kg/m^3
sand content = 0.40 x 702 x 2.60 = 730 kg/m^3

Figure 4.10 : Strength Chart for Conventional Concrete'.



The quantities to be batched are then:

dry recycled stone : 969 kg/m^3
dry sand : 730 kg/m^3
rapid-hardening cement : 320 kg/m^3
water : 225 kg/m^3
gross cement/water ratio : 1.42

But it is then assumed that only the following will partake in the volume and strength determination of the concrete:

dry recycled stone : 969 kg/m^3
dry sand : 730 kg/m^3
rapid-hardening cement : 320 kg/m^3
water : 196 kg/m^3
effective c/w ratio : 1.63

The 15% of water above the 196 litres (i.e. 29 litres) is assumed to be absorbed into the dry recycled stone and not to alter the effective cement/water ratio of 1.63 that was required.

4.2.3.2: Dry Batching using the Absorption Coefficient

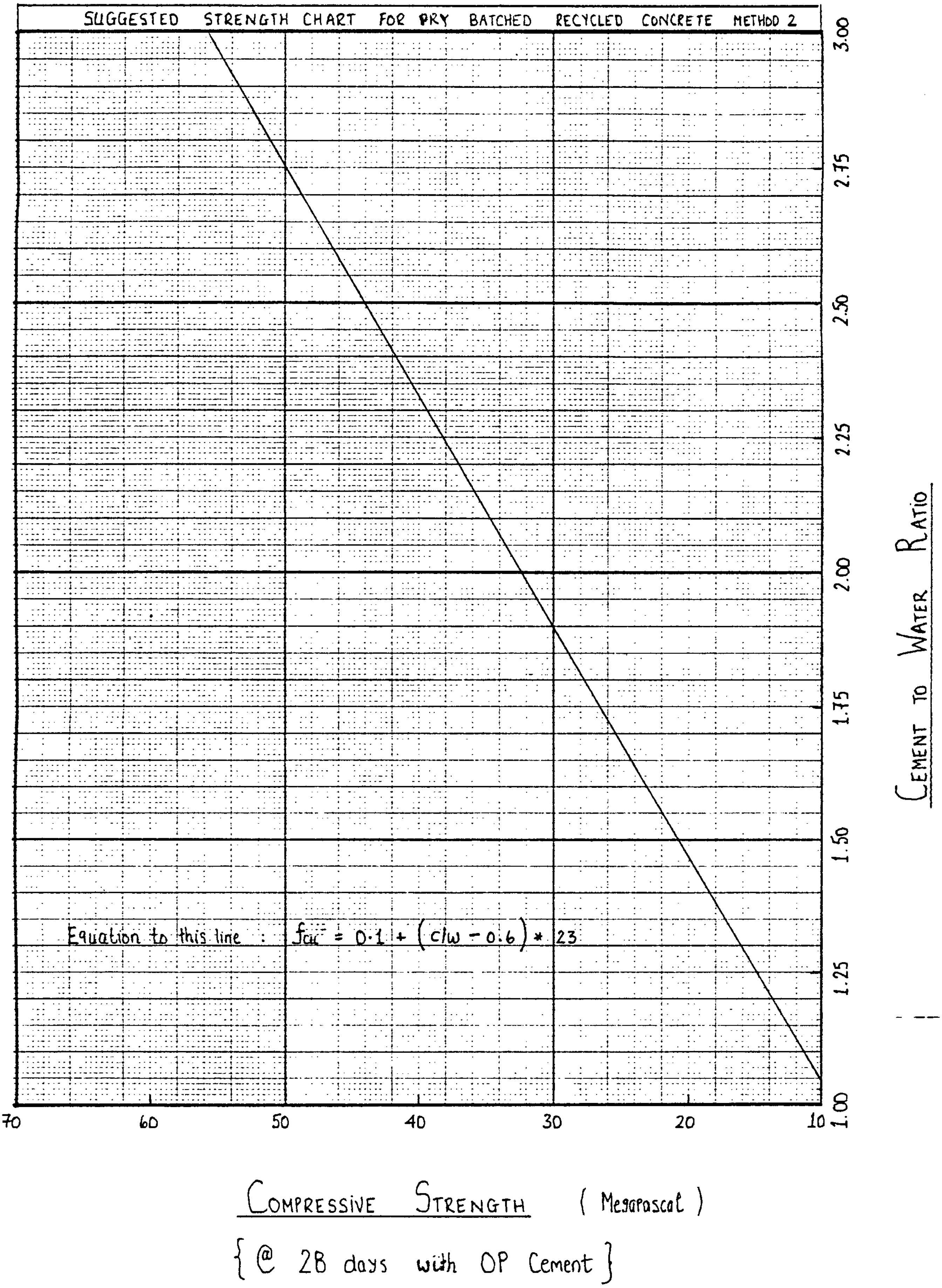
Just as the additional absorption coefficient (AAC) was used to design dry-batched recycled aggregate concrete in relation to control concrete with natural stone, so too is the absorption coefficient used. The value of the absorption coefficient (Ca) for a particular recycled aggregate should be determined by tests as in Phase 1 work.

This dry-batched mix design method is again based on the water demand of the sand to be used. The water requirement of the porous recycled stone is seen as its absorption potential. Strength charts for control concretes may again be used to determine required cement/water ratios for design strengths. It was found that in a trial mix that the strength chart in the Fulton and Crawford booklet (* 21), as shown in Figure 4.11 and drawn for ordinary Portland cement at 28 days, works well for an OPC mix. Ideally a strength chart based on this design method should be constructed from a series of test mixes, so that greater accuracy may result. As this wet-batching method is suggested as an afterthought, experimental work was thus not possible.

The standard mix design procedure is again followed to the point where the constituents have been mixed and the resulting slump is very low because of the absorption that occurs. An amount of water equal to the absorption of the recycled stone may now be added to the mix without the addition of any cement powder. This water then accounts for the "water requirement" of the porous stone. If, by some chance, the slump is still too low, then water, as well as the corresponding quantity of cement powder, must be added to maintain the designed cement/water ratio.

It was found by experimentation (* 20) that the mix water absorbed into the pores of the recycled stone is lost to the setting and hardening of the cement paste, thereby causing an increase in the effective cement/water ratio and consequently the strength. It is therefore assumed that the extra water added is equivalent to the water lost into the pores. However, the water demand test in Section 4.2.1 showed that the water consumed by the sand (natural or recycled) is not lost to the cement/water ratio, but in fact determines this ratio in the mortar paste.

Figure 4.11 : Strength Chart for a Dry-batched Recycled Aggregate Concrete.



The following example will demonstrate this mix design method:

A recycled aggregate concrete with a 28-day strength of 20 MPa is required and the desired slump in the freshly-mixed state is 75 mm. The 19 mm nominal stone to be used has an absorption coefficient of 6.7% and the Klipheuwel sand used has a water demand of 165 litres/m . (This is for 75 mm slump, 19 mm stone and ordinary Portland cement.) A stone /sand ratio of 70:30 by volume is required.

From Figure 4.11, the cement/water ratio needed for the 20 MPa strength at 28 days with OPC is found to be 1.47. The water requirement of the mix is taken as 165 litres/m and the cement content is therefore 165 * 1.47 = 243 kg/m^3.

$$\text{volume of sand and stone} = 1000 - \left[\frac{243}{3.14} + 165\right] = 758 \text{ kg/m}^3$$

mass of dry stone = 0.70 * 758 * 2.21 = 1173 kg/m^3
mass of dry sand = 0.30 * 758 * 2.64 = 600 kg/m^3

Equation 4.1 may be used to check that 1 m of concrete will be yielded.

$$\left[\frac{1173}{2.21} + \frac{600}{2.64} + \frac{243}{3.14}\right] + 165 \;/\; 1000 = 1.000\text{m}^3$$

Upon mixing these constituents, a very low slump is certain to result, but now the crux of the method - 1173 * 0.067 (that is, 78 litres, or 6.7% of the stone content by mass) of water may be added freely to the mix to attain the desired 75 mm slump. No cement powder is needed, but if the mix requires any further addition of water, then cement would be added in the cement/water ratio of 1.47.

The extra water added behaves in a manner similiar to an admixture to improve workabil~~it~~ity. The use of admixtures with recycled concretes will be mentioned in Phase 3.

4.2.3.3: Dry-Batching Independent of Control Concretes

The previous two methods of dry-batched mix designs using: firstly, the additional absorption coefficient, and secondly, the absorption coefficient of the recycled aggregate, depend on the strength charts and data available for conventional concretes with impervious stone. The additional absorption coefficient (AAC) and the absorption coefficient (Ca) are then used to adjust the recycled aggregate concrete to become like the control concrete.

In the method about to be presented, no reference to conventional concrete is required and so the method is independent of control mixes.

This method is also based on the Water Demand Theory and is identical to the design of conventional concretes - except that a different strength chart, based on the gross cement/water ratio of the mix, will be used. In this strength chart the strengths are generally 15 to 20% higher than the control strengths for the same cement/water ratio. This is because mix water is absorbed into the aggregate pores, thereby increasing the strength, since the effective cement/water ratio has been increased. The strength chart found for this design method is shown in Figure 4.12 (from BSc thesis: * 20).

It should be noted, however, that the slumps of these mixes were all rather low - from 15 to 30 mm - and so adjustments with water and cement powder would be required for increased slump values.

Water requirements for these mixes may be found by trial mixes and are bound to be over 200 litres/m^3 since it will include the requirement for both the sand and the stone. This means that a high cement content will consequently result, but this method uses a lower cement/water ratio for a particular strength than any of the other design methods. This can be seen by comparing the control line to the design line of strengths in Figure 4.12.

As an example, an attempt will be made to design the same concrete that was designed in the previous example in Section 4.2.3.2.

A recycled concrete with a seven-day strength of 20 MPa and a slump of 75 mm was required. The recycled stone was of 19 mm nominal size and had an absorption coefficient of 6.7% and a porous SG of 2.21. The Klipheuwel sand to be used had a water demand of 171 litres/m^3 (for 75 mm slump, 19 mm stone size and rapid-hardening cement) and a stone/sand ratio of 70:30 by volume was required.

The 171 litre/m^3 of water is certain to produce a slump below 20 mm and the water requirement of the mix is then estimated to be 190 litres/m to increase the slump. From Figure 4.12, the cement/water ratio needed for 20 MPa strength at seven days with RHC is found to be a mere 1.13 and the cement content required is then 190 * 1.13 = 215 kg/m^3.

$$\text{volume of sand and stone} = 1000 - \left[\frac{215}{3.14} + 190\right] = 742 \text{ litres}$$

mass of dry stone = 0.70 * 742 * 2.21 = 1147 kg/m^3
mass of dry sand = 0.30 * 742 * 2.64 = 587 kg/m^3

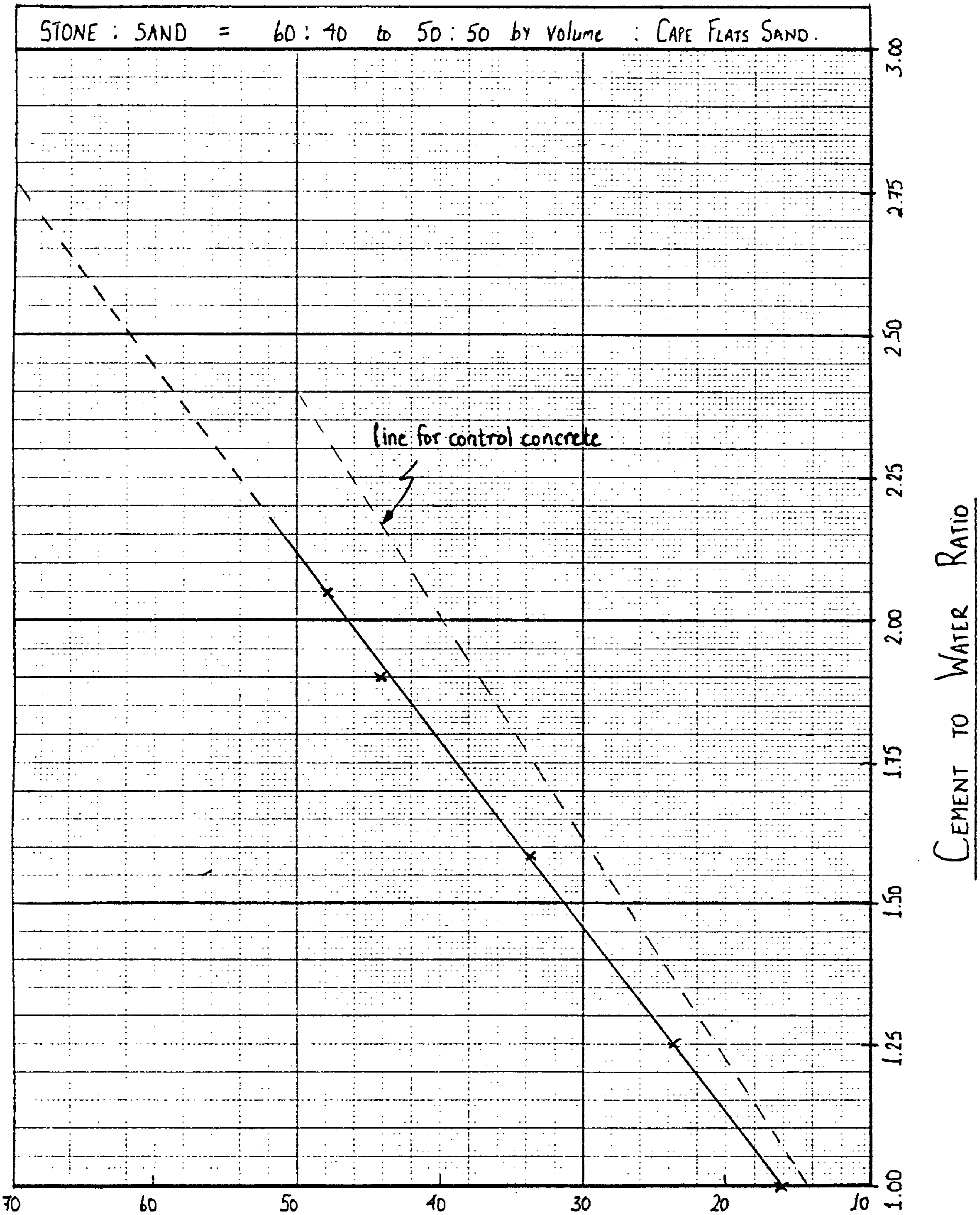
Since a certain percentage of mix water will be absorbed into the pores of the recycled stone (assume that it is equal to 6.7% by mass of stone), the yield or volume of the mix will be lower than the 1.0 m^3 calculated. The quantities may then be readjusted to 1m^3 as follows:

The 1147 kg/m of stone will absorb 1147 * 0.067 = 77 litres of water. The yield of the above mix will therefore be only 1000-77 = 923 litres, that is 0.923 m^3, and so all the calculated amounts should be multiplied by the inverse of 0.923, that is, 1.0834. The "per cubic metre" amounts are then:

dry recycled stone = 1243 kg/m ; dry sand = 636 kg/m^3;
rapid-hardening cement = 233 kg/m ; water = 206 kg/m^3.

If the slump is still below the required value, then adjustment with both cement powder and water would be required in the design ratio of 1.13.

FIGURE 4.12 : Strength Chart for Recycled Concrete Independent of Control Concrete based on the gross c/w ratio.



COMPRESSIVE STRENGTH (Megapascal)

{@ 7 days with Rapid Hardening Cement}

4.2.4: Comparison of the Proposed Batching Methods.

Briefly, the two methods that were proposed in Sections 4.2.2 and 4.2.3. are:

1. WET-BATCHING of the recycled coarse aggregate.

   The advantage of this method is that it can be executed easily under site conditions as no moisture checks are needed on the stockpiled recycled stone. It produces mixes of good workability and the mixes generally do not stiffen or lose slump prior to placing.

   The disadvantage of this method is that it is essential to achieve a constant surface wetness throughout a series of batches otherwise there will be variation in concrete strength as can be seen in Figures 4.3 to 4.7. Some standard procedure should be established so that this uniformity may be achieved - and it may be advantageous to actually dry the aggregate surface - as long as the workablity does not suffer.

2. DRY-BATCHING of the recycled coarse aggregate.

   Three different methods of dry-batched mix designs were presented.

   The advantages of these methods are that high early workablities result and then the effective cement/water ratio increases as the water is absorbed. Furthermore, there is no problem in keeping the moisture condition constant, and so the resulting strengths will be very close to those in the appropriate strength charts.

   The disadvantages of these methods are that, although it is also suited to site conditions, daily checks on moisture condition of both the sand and the recycled stone would be required and adjustments made to the amounts of mix water. The other problem is that the mixes lose workability rather quickly as they stiffen up due to mix water being lost into the aggregate pores.

For all of these methods, it is essential that the properties of the recycled coarse aggregate be known - for example, the porosity percentage by volume, the absorption coefficient by mass, and the relative density of the material. Also note that the use of recycled fine aggregate is not recommended.

Two mixes of identical constituents were made to demonstrate these two methods. The recycled stone that was used came from the stockpile and from the 9.5 to 13.2 mm size fraction. The SG of the stone was 2.04, its absorption coefficient was 9.1% and its porosity was 18.5% (These values were found in the Phase 1 tests). A cement/water ratio of 1.25 was selected, Klipheuwel sand and ordinary Portland cement were be used (as no RHC was available at the time), 60 mm of slump was required and a 2:1 stone/sand ratio by volume.

The water requirements for wet batching was found by a trial mix to be 160 litres/m^3 for the stone/sand ratio of approximately 66:34.

4.2.4.1: Design of the WET-batched Mix:

water requirement = 160 litres/m³
cement content = 200 kg/m³

$$\text{volume of stone} = 1000 - \left[\frac{200}{3.14} + 160\right] = 776.3 \text{ litres}$$

+ sand

mass of dry stone = 0.66 x 776.3 x 2.04 = 1045 kg/m³
mass of dry sand = 0.34 x 776.3 x 2.64 = 697 kg/m³

mass of wet stone = 1045 * 1.091 = 1140 kg/m³

The following quantities were batched and 60 mm slump tested:

saturated stone : 7000 g
Klipheuwel sand : 4278 g
ordinary Portland cement : 1225 g
water : 981 g

Four 100 mm cubes were cast and tested at 28 days to produce results of 17.3, 17.5, 17.7 and 17.5 MPa - the mean fcu was thus 17.5 MPa. The expected strength from Figure 4.3 was 18.0 MPa, but this was for rapid-hardening cement.

The following calculation is to show how the quantities would be converted to "per cubic metre" amounts.

Firstly, the effective SG of the saturated stone must be found from equation 4.7:

$$\text{RD wet} = \text{RD dry} + \left[\text{porosity\%} / 100\right]$$

$$= 2.04 + 18.5 / 100$$

$$= 2.225$$

Secondly, calculate the volume of the batch made:

$$V = \left[\frac{7.000}{2.225} + \frac{4.278}{2.64} + \frac{1.225}{3.14} + 0.981\right] \div 1000\text{m}^3$$

$$= 0.006138\text{m}^3$$

The conversion factor is therefore V^{-1}, i.e. 162.93 per kg.

The "per cubic metre" quantities are then:

saturated stone : 1140 kg/m³
Klipheuwel sand : 697 kg/m³
OP cement : 200 kg/m³
water : 160 litres/m³

slump = 60 mm
fcu = 17.5 MPa

4.2.4.2: Design of the DRY-batched Mix:

The water demand of Klipheuwel sand for a 75 mm slump and 9.5 to 13.2 mm stone was found in Section 4.2.1 to be 181 litres/m^3. This time ordinary Portland cement will be used, which means that the slump will increase, and since only 60 mm of slump is now required, the water requirement of the sand is now taken as 171 litre/m^3.

The mix will be designed via the third DRY-batch method described earlier and an attempt made to equal the expected strength of the WET-batched mix. The previous cement/water ratio was 1.25 and the strength expected was 18 MPa. From Figure 4.12, the cement/water ratio required for this strengths 1.07. Remember that 1.25 is an effective ratio and the 1.07 a gross cement/water ratio.

The cement content is then 171 * 1.07 = 183 kg/m^3

$$\text{volume of sand and stone} = \left[1000 - \frac{183}{3.14} + 171\right] = 771 \text{ litres}$$

mass of dry stone = 0.66 * 771 * 2.04 = 1038 kg/m^3
mass of dry sand = 0.34 * 771 * 2.64 = 692 kg/m^3

The following quantities were batched and the initial slump was a lowly 15 mm as no allowance had been made for the "water demand" of the stone.

	INITIAL	FINAL
dry recycled stone	7000 g	7000 g
Klipheuwel sand	4667 g	4667 g
O P cement	1234 g	1469 g
water	1150 g	1370 g

Cement and water were then added in the ratio of 1.07 until a slump of near 60 mm was reached - 220 ml of water and 235 g of cement powder was added.

Four 100 mm cubes were cast and tested at 28 days. The four strength results were: 18.7; 19.3; 19.0 and 18.9 Mpa - the mean f_{cu} was thus 19.0 Mpa, against the expected strength of 18 Mpa.

The final batched quantities may be converted back to "per cubic metre" amounts as follows:

The 7000 g of recycled stone will absorb 9.1% of its own mass in mix water, i.e. 7000 * 0,091 = 637 ml. This amount of water then does not participate in the volume yield of the mix.

The resulting volume using the final batched quantities is then:

$$V = \left[\frac{7.000}{2.04} + \frac{4.667}{2.64} + \frac{1.496}{3.14} + (1.370 - 0,637)\right] = 6.40 \text{ litres}$$

$$= 0.0064 \text{ m}^3$$

The conversion factor is therefore V^{-1}, i.e. 156.25 per kg

The "per cubic metre" quantities are:

dry recycled stone : 1094 kg/m^3
Klipheuwel sand : 729 kg/m^3
0 P cement : 230 kg/m^3
water : 214 litres/m^3

slump = 60 mm
f_{cu} = 19.0 MPa

Comments:

Both the design methods produced satisfactory results in terms of expected strengths and concrete workability. The disadvantages of the two methods - namely the problem with the surface wetness of the wet-batch method and the problem of mix adjustment and moisture control of the dry-batch method, should be traded off against each other and the concrete producer should make his/her own decision on which to employ. The author, however, recommends the wet-batch method as he has had good results with it.

4.3: DISCUSSION OF RESULTS.

4.3.1: The Water Demand of Fine Recycled Aggregate.

To summarize the results obtained in the Section 4.2.1 test, the water demands of a Klipheuwel sand and a recycled sand were determined by making two concrete mixes of medium strength to the standard slump of 75 mm.

Details of each sand were then as follows:

1. Klipheuwel sand:
   fineness modulus = 2.13
   specific gravity = 2.64
   water demand = 171 litres/m^3

2. Recycled sand:
   fineness modulus = 3.18
   specific gravity = 2.65
   water demand = 258 litres/m^3

These water demands are for 75 mm of slump in conjunction with a 13.2 to 19.0 mm stone and rapid-hardening cement. If ordinary Portland cement was to be used then each of the water demand figures may be reduced by approximately 6 litres/m^3. This is because ordinary Portland cement generally requires less water than rapid-hardening cement and consequently produces slumps between 30 and 40 mm higher than would rapid-hardening cement.

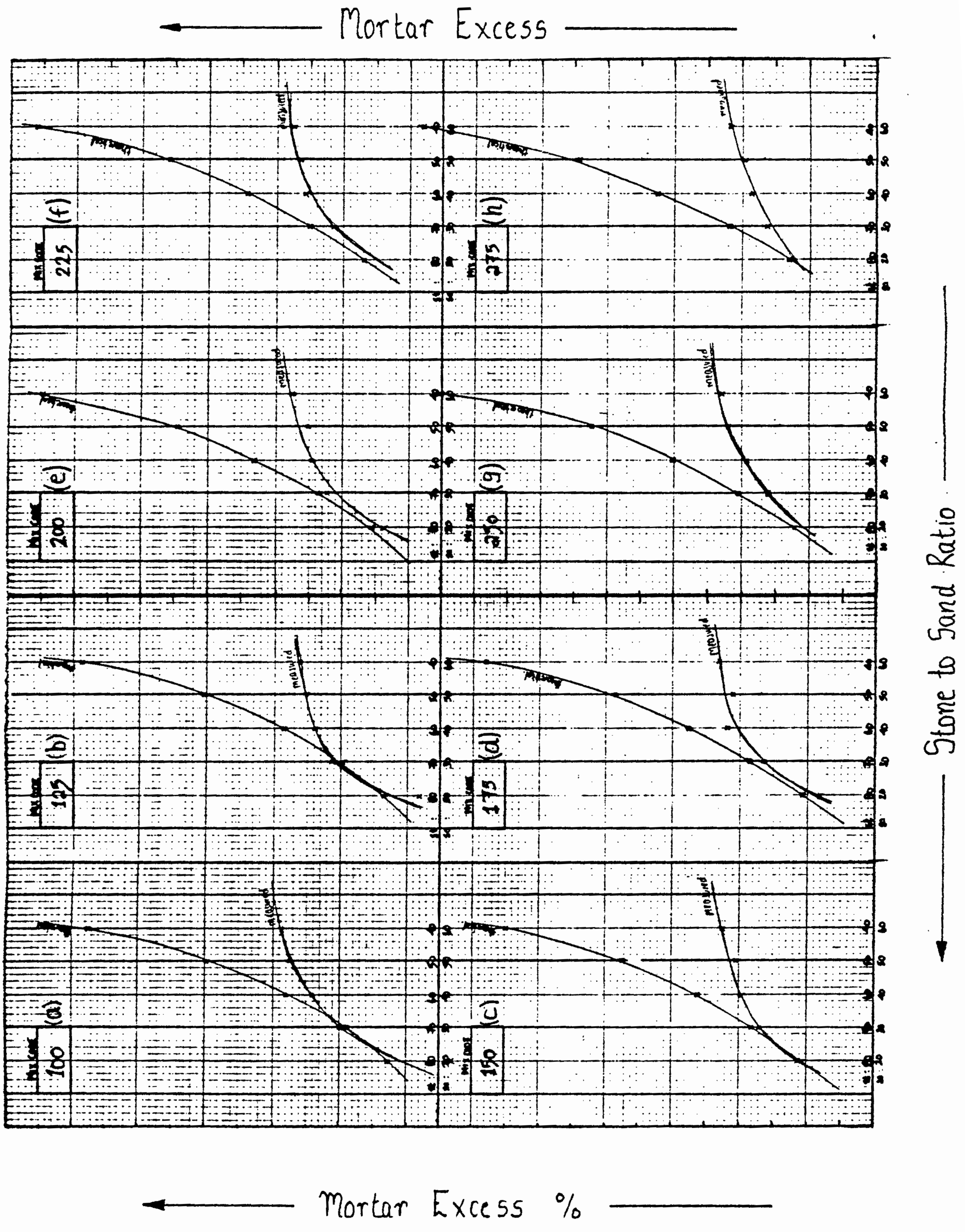
Fulton (*17) has suggested that sands with a water demand in excess of 220 litres/m^3 be avoided as they push up the cement content required to maintain the desired cement/water ratio. Recycled sand should therefore be avoided if structural concrete is to be made because of its high water demand, but also since it may have contaminants that could cause degradation of the concrete at a later stage. It may be noted that none of the recycled sands tested in Phase 1 contained any deleterious substances and therefore the use of these sands in low-strength plain concretes, and especially mass concretes, is acceptable.

4.3.2: WET-batching Method of Mix Design for Recycled Aggregates.

The testing done in Section 4.2.2 was as follows: Forty-five recycled aggregate mixes were made whereby the coarse recycled aggregate was presoaked in water and then wet-batched into the mixes. The mixes were made with variations in the stone/sand ratio by volume and also the cement/water ratio. The slump aimed for was 60 mm and all the mixes, with the exception of the 80:20 stone/sand mixes, were brought to slumps of 50 to 70 mm. The mortar excess or deficiency was measured and the Vebe test performed for each mix. Cubes were cast from these concretes and they were tested in compression at seven days of age, as rapid-hardening cement had been used.

4.3.2.1: Mortar Excess

The actual mortar excess (AME) was measured for each mix and the theoretical mortar excess (TME) was calculated according to the mix constituents and equation 4.4. Both the AME and TME results are listed in Tables 4.4 and 4.5.



Figures 4.13 (a) to (h) : Plots of the actual and theoretical mortar excess versus the stone/sand ratios used.

For each cement/water ratio used the TME and AME is plotted against the stone/sand ratio in Figures 4.13(a) to 4.13(h). Note how the AME values are almost always less than the TME values and that the two curves seldom intersect. The values of TME rise rapidly with increasing sand content, whereas the AME curve flattens out with increasing sand content. This is because the large proportion of sand has disrupted the packing of the coarse aggregate in the mortar - the stones do not sink or pack as tightly, especially in richer mixes, and so the trend is more pronounced. Even in the lean mixes where segregation usually occurs, the coarser particles of sand sink down in the mortar and upset the tight packing of the coarse aggregates, and so the AME values are then always much less than the TME values.

An attempt was then made to correlate the AME against the TME by performing a linear regression analysis on all of the mortar excess values in Tables 4.4 and 4.5.

The linear regression equation has the form $Y = a + bx$

where $a = y - bx$ . . . equation 4.9

$$b = \left[\frac{Sxy}{Sxx}\right] \qquad \text{. . . equation 4.10}$$

where y = mean value of samples y

x = mean value of samples x

$$Sxx = x - \frac{(\ \ x)}{n} \qquad \text{. . . equation 4.11(a)}$$

$$Syy = y - \frac{(\ \ y)}{n} \qquad \text{. . . equation 4.11(b)}$$

$$Sxy = xy - \frac{x * \ \ y}{n} \qquad \text{. . . equation 4.11(c)}$$

where n = the number of sets of variables.

The correlation coefficient $\underline{r}$ will indicate how good the "linearity" or "correlation" of the data sets are. The nearer $\underline{r}$ is to +1 or -1, the better the correlation, and if $\underline{r}$ is near zero, there is no correlation.

$$\underline{r} = Sxy\ /\ \mathrm{SQRT}\ (Sxx * Syy) \qquad \text{. . . equation 4.12}$$

The linear regression is performed in Appendix A6. The calculation was performed on a calculator with statistics capabilities by entering the sets of values as shown.

The values of the parameters were found to be:

$a = 21.615$; $b = 2.278$; $r = 0.7350$

The equation of the line that was fitted is then:

$TME\% = 2.278\ AME\% + 21.615$

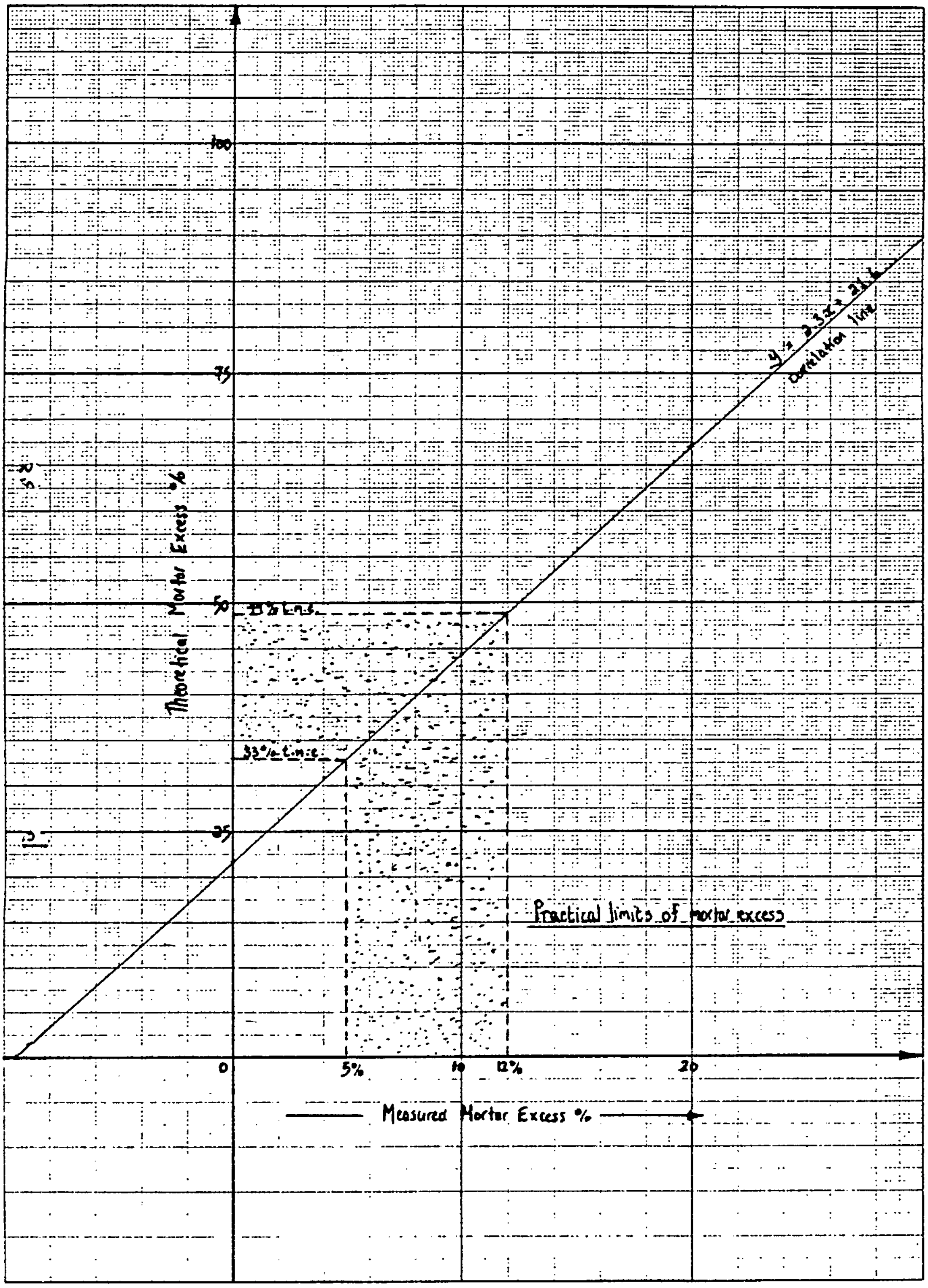


Figure 4.14 : Practical limits of mortar excess and the line of correlation that was found.

or more practically, it may be reduced to:

$$TME\% = 2.3\ AME\% + 21.615 \quad \ldots \text{equation } 4.13$$

$$AME\% = 0.44\ TME\% - 9.5 \quad \ldots \text{equation } 4.14$$

The correlation coefficient r equals 0.735, which indicates that some correlation certainly exists even though it is not markedly so.

Figure 4.14 is then drawn and it shows how the practical limits of actual mortar excess may be comapared by means of the regression equation to corresponding values of TME. This figure also shows the regression equation on a plot of TME versus AME.

In Section 4.1.5 the practical limits of AME were established as 6% to 10%, but Figure 4.14 shows these limits as 5 to 12% and the corresponding TME values were then 33 to 49%.

The implication of this envelope in Figure 4.14 is that a mix designer may calculate the TME of a mix by equation 4.4 and then, if need be, adjust the mix constituents so that a convenient AME will result.

4.3.2.2: Workability and Stone/Sand ratio.

The concretes that were made demonstrated a large range of workability - from the harsh 80:20 stone/sand mixes that were difficult to work with, through to the richer 40:60 mixes of stone/sand that were a pleasure to work with. Again it is stressed that "workabliity" is a more complex term than would be imagined, and although it is "measured" by the slump test, this test cannot fully account for workability.

The mixes with lower cement/water ratios - that is, from 1.00 to 1.50 - allowed the fresh concrete to segregate. The coarser sand particles would sink to the bottom, leaving the sloppy cement-water mortar to accumulate at the top of the mix. The cement/water ratio would then vary across the depth of a cast section, causing a variation in strength. The mixes with cement/water ratio of 1.75 and above did not permit this segregation to occur as the mortar becomes more sticky and prevents the particles from sinking or floating in the mix.

The 40:60 stone/sand mixes were very pleasant to work with, but were visibly oversanded - this could be seen from the mortar excess as well. Such mixes would not really be made in practice - especially if the sand was expensive (not in Cape Town), or the high sand content was likely to induce excessive shrinkage in the concrete.

The 50:50 stone/sand mixes were also very good in terms of workability, consistency and placeability - and although slightly oversanded, use of such concretes would be recommended.

The best mixes in terms of mortar excess, higher stone content, and lower sand content are the 60% stone and 40% sand mixes. The workability of these mixes was also pleasing. Actual mortar excess values measured were between 2.8 and 11.2%, so this concrete could be used widely and good surface finishes also obtained.

The 70:30 stone/sand mixes were prone to segregation and because of the low sand content were not all that responsive to slump adjustments, as the stones could not slide or roll over each other easily due to their rough surface texture. Once the higher cement/water ratios above 2.00 were reached, these mixes become much more workable.

The 80:20 stone/sand mixes were distinctly lacking in workablility and suffered from severe mortar deficiency. It was very difficult to make cubes from these concretes and their slumps could not be measured with any great accuracy at all, because the slump cone would either topple or remain unmoved even though the mortar (very little of it) would be watery. These mixes also suffered in strength compared to the other sand/stone ratios and are to be avoided.

4.3.2.3: Compressive Strength and Stone:Sand Ratio.

From Tables 4.4 and 4.5 and the strength charts in Figures 4.3 to 4.7 it will be noticed that the compressive strength for the same cement/water ratio increases as the sand content increases. As the sand content increases, so does the water content of the mixes, and therefore the cement content too, in order to maintain the cement/water ratio.

The increase in f_{cu} with increasing sand percentage is probably due to the higher cement content that results, and which produces better adhesion between the particles in the mix.

The higher strength potential of the oversanded concretes must be traded off against their high mortar excesses and shrinkage potential, and so the 50:50 stone/sand and 60:40 stone/sand mixes would again be the most feasible for practical use.

4.3.2.4: Slump and Vebe Measurement.

The slump and Vebe seconds measured for the mixes were found to have very little correlation - this was actually expected since the same was found by Fulton (*29) in his work. Fulton's plot of Vebe seconds versus slump is shown in Figure 5.16 below.

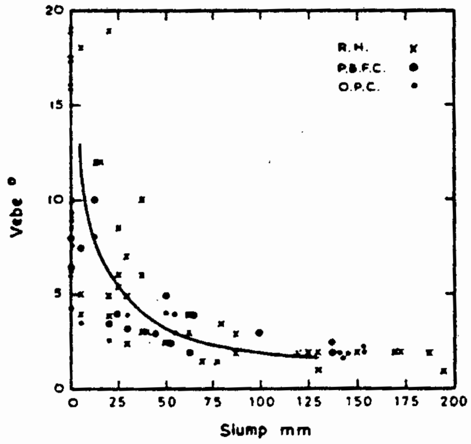


Figure 5.16: Slump versus Vebe (from Fulton).

The problem was that for the range of slumps produced (>50 mm), the Vebe times are so short that it becomes an insensitive test - the shorter the Vebe time, the higher the percentage of human error. For stiff concretes of between 10 and 50 mm, say, the Vebe correspondence would probably be better - although the slump test again becomes insensitive for slumps below 25 mm and over 100 mm.

It would probably be better for a concrete manufacturer to use the tests independently as both tests would still be of great assistance in attempting to produce concrete of consistent workability.

4.3.2.5: Mix Calculations.

A problem was encountered with the process of converting batched mix constituents to "per cubic metre" amounts - this was due to a misinterpretation of the coarse aggregate properties as found in Phase 1.

The specific gravity (SG) of these recycled stones were given as one value for the material in its porous state, and as a second value for the material had it been completely solid. For example, the recycled stone used in Phase 2 in the 13.2 to 19.0 mm fraction had the following:

SG as porous material = 2.21
SG as solid material = 2.60

To calculate the yield of a concrete mix, the porous SG should be used, and Table 4.4 had to be recalculated into Table 4.5.

A further problem is whether to take the absorbed water in the pores of the recycled stone into account - this water contributes to the mass of the mix, but not the volume, as the SG of the stone has already accounted for its volume. An effective SG for saturated porous stone was then found, whereby the porosity fraction of the stone is simply added to the SG (porous). The calculation was derived in Paragraph (xvii) of the results in Section 4.2.2.

An example is as follows:

> The recycled stone has a porous SG of 2.21 and a porosity of 15% - the effective SG is then 2.36.

A conversion to "per cubic metre" calculation can be seen in Section 4.2.4 - this calculation is for wet-batching of recycled aggregate.

4.3.3: Dry-Batching Methods for Recycled Aggregates.

Three different methods of designing dry-batched recycled concrete were proposed:

1 By using the strength-related additional absorption coefficient.

2. By using the absorption coefficient of the recycled aggregate.

3. By using a strength chart of gross cement/water ratio which ignores the water absorption by the porous aggregate.

The first method is entirely dependent on control concrete made from natural stone and an attempt was then made to match the recycled concrete to the control concrete in terms of strength. This is done by using the additional absorption coefficient, which is determined by the Slump Adjustment Test. Additional water and cement powder would in all likelihood be required to increase the slump of the recycled concrete to that of the control. The method is based on the Water Demand Theory and the strength chart applicable would be for known conventional concretes such as that shown in Figure 4.10.

The second method is also dependent on control concrete and an attempt is then made to account for the "water demand" of the recycled stone. It is assumed that the porous stone requires an amount of water equal to its absorption; that is, an amount of water equal to its mass multiplied by its absorption coefficient. No extra cement is added when this additional amount of water is added for the stones' absorption. It will be found that the full absorption figure contributes too much extra water to the mix and that strengths lower than those plotted in Figure 4.10 will result.

This method is likely to produce equivalence in slump between the control and recycled concrete, with the control strengths somewhat higher. Ideally a series of mixes with different cement/water ratios should be made and a complete strength chart prepared from these results, but it was however found that the strength chart in Figure 4.11 gave satisfactory results using ordinary Portland cement. The calculation of mix quantities again follows the water demand theory.

The third method is independent of control concretes - it is a method also based on the water demand theory, but a strength chart of total water/cement ratio versus strength is drawn up. In this way the absorption of the stone is turned into a strength gain rather than attempting to account for it with additional water. The effective cement/water ratio is not of consequence here. The total water demand of the mix should be used - it is the demand of the sand as well as the porous stone - otherwise slumps of less than 20 mm or less will result. For 19 mm stone, about 20 litres/m^3 may be added to the sand's water requirement to account for the stone. For 13 mm nominal stone a figure of 30 litres/m may be used, because the absorption potential increases as the stone size decreases, as found in Phase 1. A strength chart such as that shown in Figure 4.12 would be used to determine the required cement/water ratios.

If all three strength charts are drawn on one diagram, as in Figure 4.15, then the difference in the required cement/water ratio for a particular strength can be seen. The cement contents and water requirements are the highest for Method 3 and lowest for Method 2. Thus, the economy of the three methods is fairly similiar.

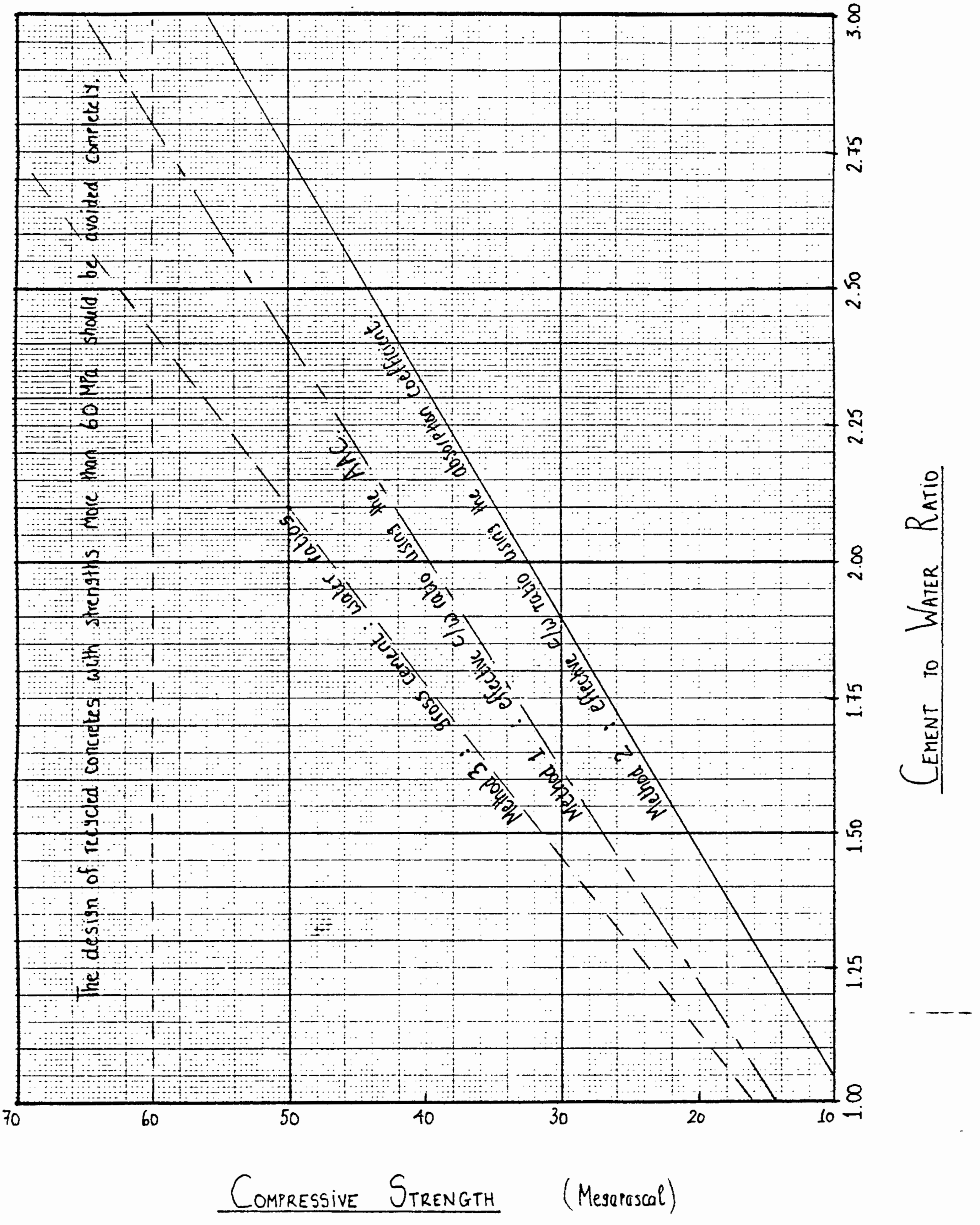
4.3.4: Selecting a Method of Batching and Design.

Four methods of mix design/batching have been presented; a WET-batch and three-DRY batch methods. In Section 4.2.4 the two methods for which the most data was available were compared. These were the WET-batched methods from Section 4.2.2 and the third DRY-batched method from Section 4.2.3.3. These are the two methods that would then be recommended for practical use -

although the concrete producer would be free to select the method which he/she finds the most suitable.

The other two DRY-batch methods would also be viable once further testing is done and more reliable strength charts developed for selection of required cement/water ratios.

FIGURE 4.15: Comparison of the Strength Charts for the "Dry-batch" methods of Mix Design.



PHASE 3: THE MECHANICAL PROPERTIES OF RECYCLED CONCRETE.

5.1: Introductory Theory and Literature Survey.

The earliest findings concerning the properties of recycled concrete come from Gluzhge (*1) in 1946. He concluded that:

i) A recycled concrete will be no better than the waste concrete that was used as the aggregate;

ii) the use of concrete fines or sand requires an undue increase in the cement content of the mix;

iii) the compressive strengths of recycled concretes are lower than their control mixes of normal concrete;

iv) the specific gravity of crushed concrete aggregates is lower than that of natural aggregates;

v) for equal compressive strengths, the recycled concretes have higher flexural strengths, and

vi) prior to curing, the recycled concrete mixes stiffen rapidly, but consolidate well with vibration.

Gluzghe's work is still valid, though Buck (*30) has shown that a recycled concrete can be made to have a higher strength than the parent concrete that was crushed to yield the aggregate.

In the subsections that follow, the mechanical properties of recycled concrete are compared to control concretes. The information was obtained from various literature sources dating up to 1977, which are appropriately referenced.

It should be borne in mind that the recycled concretes were all made using a similiar method as described in Phase 2, namely the wet-batched method in which the recycled coarse aggregate is pre-soaked before use. In the case of compressive strength, the researchers find that the recycled concrete produces lower strengths than the control mixes. It is important to remember that this does not imply that the recycled concrete is necessarily inferior to the control concrete, but rather that the effective cement/water ratios were not the same, thereby inducing the difference in strength.

5.1.1: Compressive Strength.

Buck (*30) has found that for identical mix quantities, but with a correction made for the water absorbed by the control and recycled aggregates, the strength of the recycled concrete was up to 8 MPa weaker. The strength of the recycled concrete could be between 64 and 100 percent that of the control.

Frick (*20), however, found that if no correction was made for the water absorption of the porous recycled stone, then the recyled concrete would be 15 to 25 % stronger than the control. The workability of the recycled mixes would unfortunately be very low, and large additions of water and cement powder would be required to improve it.

All the researchers into the subject (* 1, 5, 7, 20, 30, 31) agree that better strengths result when only the recycled coarse aggregate is used. The recycled fines are not used because of their high water demands, which lead to expensive concretes, and also since they may contain deleterious materials such as gypsum.

5.1.2: Aggregate-Mortar Bond Strength.

Frondistou-Yannas (*5) studied the bond strength between the concrete mortar and the coarse aggregate particles by making mortar briquettes according to ASTM C190. The test specimen, containing a single 19 mm aggregate particle, was designed to ensure that the applied tensile load would be transmitted through the aggregate only.

The results showed that this bond strength would be at least 88% that of the control, if the recycled particle contained primarily natural stone from the parent concrete. If the recycled particle consisted mainly of the old mortar, then the bond strength would be at least 55% that of the control. By "control" it meant that a clean natural 19 mm stone (granite) was used in a briquette.

Hester (*32) is of the opinion that the bond strength - that is, the "grip" that the cement paste forms on the aggregate particle - may be improved by using rather liquid mixes with slumps typically between 120 and 150 mm. Such runny mixes are prone to segregation and bleeding, but he advocates the liberal use of admixtures to remedy these problems. Hester is not a researcher into recycled concrete, but is a specialist in the design of high-strength concretes for use in slender prestressed applications. He is, however, of the belief that the same principle would apply to recycled concrete (*32).

5.1.3: Tensile Strength.

The tensile strength of a concrete is usually determined in one of two ways:

i) the flexural tensile strength may be obtained by the loading to fracture of "prisms" or "beamlets", or
ii) the flexural splitting strength may be obtained by the "splitting" of cylinders in a compressive testing machine.

These two tests will be described in greater detail in Section 5.2.

Attempts have been made to relate the tensile and flexural strengths of a concrete to its compressive strength, but the relationship is neither specific nor simple. This is because factors such as cement/water ratio, curing conditions, age, mix proportions and properties of the aggregate do not affect the two strengths to the same degree. Kaplan (*46) also found that the rate of gain in strengths (tensile and compressive) are not the same. Also, the ratio of tensile/compressive strength is higher at an early age than a later ages. Kaplan (*46) also found that incomplete consolidation has a greater negative effect on compressive strength than on tensile strength.

The following formulae have been proposed: The CEB-FIP Committee (*38) recommended, for the direct tensile splitting strength, that:

$f_{ts} = 0.24 * \mathrm{CUBROOT}(f_{cu})$ . . . equation 5.1

where f_{ts} = tensile splitting strength in MPa at 28 days
f_{cu} = cube strength of concrete in MPa at 28 days.

For the range of compressive strengths of 15 to 20 MPa, a good approximation to equation 5.1 is:

$f_{ts} = 0.78 + 0.05 * f_{cu}$ . . . equation 5.2

Packard (*47) of the Portland Cement Association uses the following formula - developed from the design of concrete road and airport pavements - which is based on the flexural strength of the concrete (also at the age of 28 days):

$f_{tf} = 0.68 * \mathrm{SQRT}(f_{cu})$ . . . equation 5.3

where f_{tf} = flexural tensile strength of concrete in MPa.

Research into high early-strength lightweight concretes by Swamy (*42), using ultra-fine cement and expanded slate aggregates with a 67% sand replacement, (i.e.the fine, artificially-produced expanded slate "sand" is replaced by a natural sand) yielded the following two formulae for wet-curing of the concrete:

$f_{tf} = 0.75 * \mathrm{SQRT}(f_{cu})$ . . . equation 5.4

$f_{ts} = 0.56 * \mathrm{SQRT}(f_{cu})$ . . . equation 5.5

Since the recycled aggregates are porous and less dense than natural aggregates, the relationships for lightweight concretes may prove more relevant to recycled concretes.

Malhotra (*31) found that the flexural strength of the recycled concrete was between 80 and 100% that of the control. His findings are based on the fracture of concrete beamlets to give the flexural tensile strength. Gluzghe (*1) had previously shown that for equal compressive strengths, the recycled concretes had higher flexural strengths than the control - this result was established in 1946 and has not been disputed since.

5.1.4: Elastic Modulus.

The elastic modulus of a concrete depends primarily on the modulus of elasticity of the aggregate present and its volume fraction, and so too on the the elastic modulus of the concrete matrix and its volume fraction. Numerous investigators such as Pomeroy (*33), Kaplan (*34), Hansen (*35), Powers (*36) and Hobbs (*37) have found this to be the case, and attempts have been made to formulate expressions whereby the theoretical E-modulus of a concrete may be calculated.

Furthermore, it was found by Hansen (*35) and Powers (*36), amongst others, that the elastic modulus, as well as the compressive strength, is highly dependent on the air content or porosity of the concrete.

Hansen (*35) derived a formula to relate the modulus of the concrete to the moduli of the component materials and their respective volume concentrations. The following expression was found to produce sufficiently accurate results for normal concretes:

$$1/Ec = Vm/Em + Va/Ea \qquad \text{. . . equation 5.6}$$

where Ec, Em and Ea = modulus of elasticity of the concrete, mortar and coarse aggregate respectively, and

Vm and Va = fractional volume of the mortar and the coarse aggregate respectively.

This equation is from the Reuss Model, whereby the paste and the aggregate are subjected to equal compressive stresses when a compressive load is applied.

Another model, known as the Voigt Model, exists whereby both the paste and the aggregate are subjected to equal strain when a compressive load is applied. The formula (*33) for this model is:

$$Ec = Va.Ea + Vm.Em \qquad \text{. . . equation 5.7}$$

The Voigt Model is the upper bound value for the elastic modulus of a two-phase material, whereas the Reuss Model gives the lower bound value.

Hobbs (*37) derived a relationship from considerations of the bulk modulus of a composite in which the aggregate and the concrete matrix retain contiguity. The equation is as follows:

$$Ec = \left[\frac{(Ea - Ep)Va + (Ea + Ep)}{(Ea + Ep) + (Ep - Ea)Va} \right] * Ep \qquad \text{. . . equation 5.8}$$

This equation has been found to represent experimental observations very satisfactorily for both high- and low-modulus aggregates. From these equations it will be seen that, the greater the modulus of the concrete aggregate, the greater will be the elasticity modulus of the resulting concrete. Similiarly, the greater the volume concentration of the coarse aggregate, the greater the elastic modulus of the concrete.

If the concrete is porous, then the equations should be adapted to account for the negative effect of such porosity. Hansen's (*35) semi-empirical equation is as follows:

$$Ep = Es * (1 - p) / (1 + 2p) \qquad \text{. . . equation 5.9}$$

where Ep = modulus of the porous material, and
Es = modulus of the pore-free solid material.
p = porosity

Powers (*36) had also fitted the following equation to his observed measurements:

$$Ep = Es * (1 - p)^3 \qquad \text{. . . equation 5.10}$$

A similar equation is attributed to Hansen (*35) in Chapter 8 of Fulton's "Concrete Technology" (*17) and is:

$$Ep = Es * (1 - p)^4 \qquad \text{. . . equation 5.11}$$

Pomeroy (*33) has found that normal dense aggregates have elastic moduli that exceed the moduli of the hardened cement paste (HCP) by a factor of five or more. The modulus of the HCP is typically 10 to 20 GPa, whereas the modulus for natural stone is usually in the region of 80 GPa. It follows, therefore, that the stiffness of most dense aggregate concretes will be greater than that of the matrix.

In practice, it is difficult to apply the equations that have been presented because of moduli of the aggregates are seldom known. Consequently, attempts are then made to relate the modulus of elasticity of a concrete to its compressive strength, which is more readily determined. The predictive equations that will be given are empirical and there is still debate regarding the most acceptable ones.

The CEB-FIP recommendations of 1970 and 1978 (*38) proposed the following formula:

$$E = 6.6 * SQRT(f\underline{cy}) \qquad \text{. . . equation 5.12}$$

where E = elastic modulus in GPa, and
$f\underline{cy}$ = cylinder strength of the concrete in MPa.

For lightweight concrete, the CEB-FIP equation is:

$$E = 0.0018 * SQRT(W^3 f\underline{cy}) \qquad \text{. . . equation 5.13}$$

where E = elastic modulus in GPa;
W = weight density of the concrete in kN/m , and
$f\underline{cy}$ = cylinder strength in kPa.

Another set of formulae, proposed by the CEB in 1976, is:

$$E = 9.5 * CUBROOT(f\underline{cy} + 8) \qquad \text{. . . equation 5.14}$$

$$E = 9.5 * CUBROOT(f\underline{cy} + 8) * (m/2400)^3 \qquad \text{. . . equation 5.15}$$

where equation 5.14 would apply to dense aggregate concrete and equation 5.15 to lightweight aggregate concretes with m = the mass density of the concrete in kg/m^3.

Teychenne, Pomeroy and Parrott (*39) used test results of concretes with widely-varying mix proportions and concluded that the E-modulus of concretes at any age $\underline{t}$ could be estimated by the equation:

$$Et = Co + 0.2 * f\underline{cu}_t \qquad \text{. . . equation 5.16}$$

where $f\underline{cu}_t$ = cube strength at time $\underline{t}$ in Mpa;
E = modulus of elasticity in GPa at time $\underline{t}$, and
Co = a linearly-related constant (approximately 20).

the constant Co depends very much on the aggregate used and a test mix should be made to determine its value.

Using various South African aggregates and covering a wide range of strengths, Davis (*28) developed the following equation for the E-modulus of a concrete:

$E = 4.9 * SQRT(f_{cu})$ . . . equation 5.17

Up to this point it is seen that the equations shown use both the cylinder strength f_{cy} and cube strength f_{cu} of the concretes. The cube strength of a concrete is always slightly more than the corresponding cylinder strength. In general, the following relation holds:

$f_{cy} = 0.80 * f_{cu}$ . . . equation 5.18a

or $f_{cu} = 1.25 * f_{cy}$ . . . equation 5.18b

Furthermore, all the E-modulus values used up to now have all been the "static" modulus of elasticity which differs from the "dynamic" elastic modulus. The dynamic E-modulus is found by electro-dynamic methods which may be found in BS 1881; 1970 (*40) or ASTM C215-60 (*41). The dynamic modulus is usually higher than the static modulus and various relationships between the two have been presented, but are not relevant to this work.

The ever-growing technology of lightweight concrete has produced several formulae which produce satisfactory results. Due to the similiarity between lightweight and recycled aggregates, namely that both are porous, it might be found that these formulae could be applied to recycled concretes. The equations and their proponents are as follows:

Swamy (*42): $E = 0.97 * m^3 * SQRT(f_{cu})$ . . . equation 5.19

Pauw (*43): $E = 0.0043 * SQRT(w f_{cu})$ . . . equation 5.20

Schaffler (*44): $E = 0.00006 * SQRT(m f_{cu})$ . . . equation 5.21

where w = the weight density in kN/m^3, and
m = the mass density in kg/m^3

The Poisson's Ratio of lightweight concretes was found by Swamy (*42) to be:

$\nu \cancel{\#} = (0.16 * E + 20 * f_{cu}) / E$ . . . equation 5.22

where E = static modulus of elasticity of the concrete in MPA, and
f_{cu} = compressive cube strength in MPa.

The Elastic Modulus of Recycled Concrete.

The recycled aggregates obtained from crushed concrete will obviously have a lower modulus of elasticity than will a natural coarse aggregate, and therefore the E-modulus of a recycled concrete will also be lower than that of a control concrete. This has been verified by various researchers: Fondistou-Yannas (*5) has shown that recycled concretes have elastic moduli between 60 and 100% that of the control concretes. Hansen and Boegh (*45) found the E-moduli of recycled concretes to be 15 to 30% lower than those of conventional concretes.

5.1.5: Density and Water Absorption.

All the researchers have shown that recycled concrete is less dense than conventional concrete. This is due to the porosity of the recycled aggregates, which are in turn less dense than conventional aggregates. Figure 5.1 shows the densities of conventional and recycled concretes as found by Frick (*20). This figure also shows that the percentage difference in concrete density decreases as the cement content, the cement/water ratio or the compressive strength increase.

The water absorption of recycled concretes is higher than that of conventional concretes. This is again attributable to the porosity of the recycled coarse aggregate. Kreijger (*48) has quoted figures of 4 to 8% for coarse recycled aggregates and 8 to 12% for recycled fine aggregates. The absorption of natural stone is very low - between 0 and 2% by mass.

5.1.6: Workability.

Workability - a property of the fresh concrete mix - is a very important aspect of concreting. This was discussed in detail in Phase 2 of this work, but a brief mention of it is again made here in Phase 3 to widen the scope of this section on the properties of recycled concretes.

Researchers have found that the workablitiy of recycled concrete is fully comparable with conventional concrete, provided that the water absorption of the porous recycled coarse aggregate is accounted for. Gluzghe (*1) has stated that recycled concrete mixes lose their workability more rapidly with time. If the recycled aggregate is not fully saturated before use, it will continue to absorb water from the mix and thereby cause the concrete to stiffen. Frick (*20) found that recycled and conventional concretes of "seemingly identical workability" would not produce the same slump values because of the difference in shape and surface texture of the coarse aggregate.

5.1.7: Durablity.

To an American, it would appear that durability means primarily the resistance of the concrete to cycles of freezing and thawing; secondly, its resistance to sulphate attack, and resistance to the expansive reactions between siliceous and carbonaceous aggregate with the alkalis in the concrete. South Africans would also consider a property such as abrasion resistance to be part of a concrete's durability.

The process of freezing and thawing of water contained in the pores of a concrete is a very strenuous one to the concrete. The water expands as it freezes and creates severe internal stresses in the concrete, which can cause cracking. For lightweight concrete it has been said that the pores in the coarse aggregate act as minute cushions which allow some of the freeze-thaw stresses to dissipate, and it therefore has a better durability than normal concrete in this respect. The aggregates used in lightweight concrete may be very porous, but their matrix material is usually impervious to water, such that the inner pores contain air, which is compressible and allows the "cushioning effect". The inner pores of a recycled aggregate may well contain water since its matrix is not impervious, and this water also freezes and thaws to place stresses in the concrete.

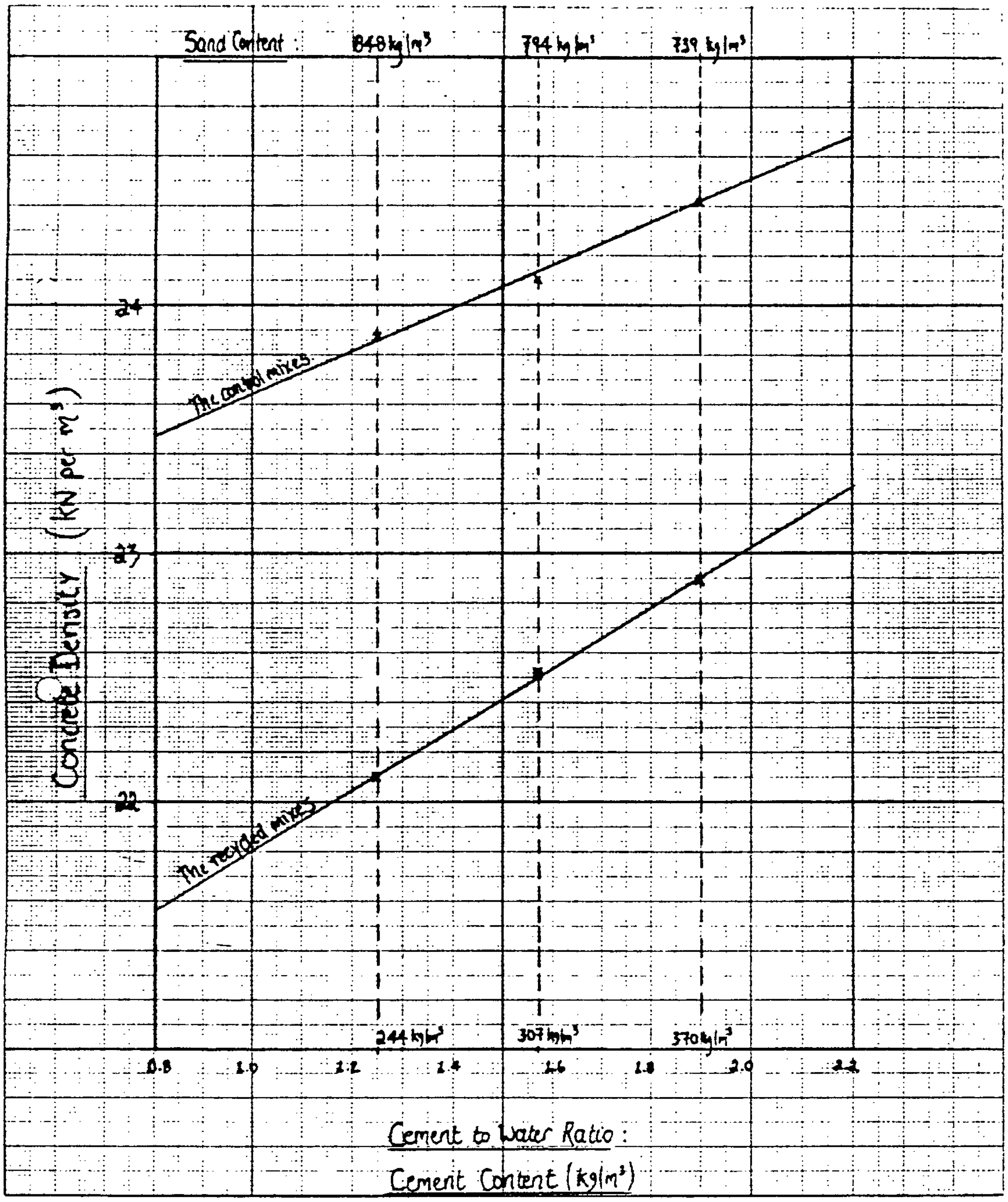

Sand Content :
848 kg/m³
794 kg/m³
739 kg/m³
24
23
22
Concrete Density (kN per m³)
The control mixes
The recycled mixes
244 kg/m³
307 kg/m³
370 kg/m³
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
Cement to Water Ratio :
Cement Content (kg/m³)

FIG 5.1

Several researchers (*5,30) have found the freeze-thaw resistance of recycled concrete to be comparable to that of standard concrete, although Buck (*30) found a substantial improvement against frost attack in the recycled concrete that contained chert gravel in the aggregate.

The presence of an excess amount of sulphate in a concrete instigates two harmful chemical reactions in the concrete matrix. Firstly, the calcium hydroxide is converted to calcium sulphate, and secondly, the calcium aluminate is converted to calcium sulphoaluminate. Both these reactions produce more than double the solid volume, and so the large expansion causes great disruption in the concrete, which leads to serious cracking. An effective defence mechanism against sulphate attack is the imperviousness of a concrete, which means that recycled concrete, by its porous nature, may be more vulnerable to it. Young (*7) has found that the chemical durability of recycled concretes is lower than for normal concretes if no attempt is made to remove contaminants from the rubble. This means durability against frost-attack and the interaction of alkalis with siliceous and carbonaceous aggregates.

The wear or abrasion resistance of a recycled concrete may well be lower than that of normal concrete because of the more friable and weaker stone, but sufficient wear resistance is possible by selecting a recycled aggregate that complies with code restrictions. In Phase 1 tests were done to determine the 10% fines crushing value of various recycled aggregates and it was found that these aggregates have sufficient strength to pass the 110 kN 10% FACT value specified in SABS 1083 (*14) for concrete subject to abrasion.

5.1.8: Shrinkage and Creep.

The shrinkage and creep of concrete is too extensive a subject to be discussed in full detail here and will be dealt with in a brief manner.

Different types of shrinkage occur in a concrete. Firstly, there is a plastic shrinkage which is due to bleeding and the fine particles in the concrete. It is therefore a mode of settlement which may be considered to be beneficial to the concrete, but it may be countered by revibration of the concrete before it has set. Secondly, there is autogenous shrinkage, which occurs in zones of the concrete where there is insufficient water. It is also called self-dessication and would occur, for example, at the centre of mass concrete. Thirdly, there is the most common and problematic drying shrinkage, which occurs due to an excess of water in the fresh concrete. This water would be required to give the concrete workabililty and for curing purposes, but when the curing stops, this water starts to evaporate, and induces the shrinkage in the concrete. The fourth type of shrinkage that occurs is carbonation shrinkage, which occurs especially in thin sections where CO_2 can penetrate into the concrete. This is a process of chemical decomposition which takes place over a long period of time, and in magnitude may be equal to about half the drying shrinkage, and may be alleviated by precarbonation.

The stiffness of the aggregate provides resistance to the shrinkage, which occurs as the hydrating cement paste loses water - but it is the proportion of the aggregate in the concrete that is of the greater importance. So, the higher the percentage of coarse aggregate that is attained in the concrete mix, the less will be the shrinkage. Recycled aggregates have less stiffness than natural stone aggregates and so the shrinkage potential of a recycled concrete is greater than that of a normal concrete.

The total deformation of concrete subjected to sustained stress may be regarded as composed of two principal components.

i) instantaneous elastic deformation, and
ii) time-dependent deformation - creep and shrinkage.

Creep is defined as stress-induced, time-dependent strain. Usually it will be observed as a steadily-increasing loading. On the other hand, it may be seen as a reduction in the stress in concrete that has been restrained against deformation in some way; this is often called "stress relaxation" and is an important aspect in the design of prestressed concrete members. Generally, creep is an important consideration in the behaviour assessment and serviceability assessment of concrete structures.

Several theories have been advanced to explain the physical processes involved in the creep of concrete. Mallows (*49) summarized these proposed theories into three broad groups, based on the work of Mindness and Young (*50):

5.1.8.1: Thermally-Activated Creep Theory.

The basic premise of this theory is that the time-dependent strains in concrete - namely, shrinkage and creep - result from thermally-activated processes which can be described by process rate theory. Creep strains originate through deformations of a micro-volume of paste when energy is added to the system by external sources. The rate of the deformations are dependent on temperature, applied stress and change in moisture content within the concrete system. It should be noted that creep recovery is explained by regarding the removal of load as the application of a negative stress.

5.1.8.2: Distribution of Absorbed Water Theory.

This approach considers the presence of absorbed water layers to be the underlying factor in the creep of concrete. Absorbed water is assumed to diffuse under stress, causing microstrains within the concrete system. The amount of absorbed water is assumed to be a function of the ambient relative humidity with which the system is in equilibrium.

When an external stress is applied, the stress exerted on the water in the micropores is increased. To maintain equilibrium, the thickness of the absorbed water layer must be decreased to compensate for the effective increase in the adjoining pressure. Thus water diffuses from the micropores to the larger capillary pores where no stresses exist.

5.1.8.3: The Interlayer Theory.

This theory proposes that external stress tends to densify the chemical assembly of the particles in concrete. It is suggested that under load, water is redistributed and the particles (which are like laminae) are densified and ordered. Hence the external stress modifies the existing interlayer spacings.

Further reading of the following publications is recommended: "Creep and Shrinkage in Concrete Structures" by Bazant and Wittman (*51) and "Creep of Concrete"; Neville (*52).

There are many factors that affect the creep and shrinkage of concrete; these will not be discussed as they are well covered by authors such as Wolhuter (*53), Neville (*52), Mallows (*49) and Bozant (*51). The one factor which should be mentioned is the influence of the aggregate used as it is essentially the only difference between recycled and normal concrete.

The coarse aggregate in a concrete is assumed to be volumetrically stable and thus to have a restraining effect on the strains caused by shrinkage and creep. Increasing the aggregate content by volume fraction of a concrete mix will therefore reduce the creep and shrinkage potential of the hardened concrete. This restraining effect of the aggregate is further affected by the stiffness or elastic modulus of the coarse aggregate - the higher the E-modulus, the lower the creep ~~of~~ or shrinkage rate.

If a concrete aggregate itself is prone to creep or shrinkage, then the creep and shrinkage potential of the resulting concrete will be greatly increased. Certain natural stone aggregates are renowned for their shrinkage potential - for example dolerite from Scotland and fine-grained sandstone from South Africa. Very few natural aggregates used for concrete manufacture have been found to exhibit any creep potential, but recycled concrete aggregates that are still relatively young may certainly be liable to creep. By "relatively young" it is meant a few years, as about 90% of the total creep in a concrete will occur in the first five years, by 10 years of age 95% of the creep will have occurred, and possibly after 25 to 30 years, no further creep will occur.

The porosity of a recycled aggregate will tend to decrease the shrinkage and creep potential of a concrete because water is removed from the cement paste by the aggregate's absorption. At the same time, this porosity of the aggregate reduces the E-modulus of the resulting concrete as discussed in Section 5.1.4, thereby offsetting the effect of the absorption. Thus the creep and shrinkage potential of a recycled aggregate remains higher than that of a normal concrete.

Methods of predicting the magnitudes of creep and shrinkage according to the CEB-FIP will be presented in Section 5.3.4 when the values found for the two different recycled concrete mixes will be compared to the predicted values.

5.2: The Tests Performed on the Recycled Concrete.

The following properties of the recycled concretes were investigated in this series of tests:

i) Compressive strength gain with time;
ii) tensile strength: flexural and splitting tests;
iii) elastic modulus, and
iv) creep and shrinkage.

CONCLUSION

Two different recycled concrete mixes were made, from which a sufficient number of the various specimens required for the tests were cast. Consideration of various factors was required to design the two appropriate mixes - the design of the two mixes is shown below in Section 5.2.1.

5.2.1: The Design of the Two Recycled Concrete Mixes.

Different factors were considered in the design of the two mixes to investigate typical properties of recycled concrete. The fact that the creep behaviour was to be tested was perhaps the most important of these factors. The considerations were:

i) Recommended Stress Levels for Creep Testing.

Pomeroy and Illston (*54), in their recommendations for a standard creep test for the United Kingdom, suggest that applied stress should be 25% of the mean cube strength at age of loading. The American standard for creep testing, ASTM C512-76 (*55), requires that the applied stress should not be more than 40% of compressive strength of the concrete.

Two mixes, one weak and one strong, were made since the UCT creep rig is only capable of applying a common pressure value - even though it has 12 load rigs that can take two cylinders each. The load pressure that was to be applied was therefore equal to 40% of the weaker compressive strength and also equal to 25% of the stronger compressive strength.

If the applied load pressure is P, the weaker compressive strength is $f\underline{\underline{cu}}_1$ and the stronger $f\underline{\underline{cu}}_2$, then:

$$P = 0.40\ f\underline{\underline{cu}}_1 = 0.25\ f\underline{\underline{cu}}_2 \qquad \text{. . . equation 5.23}$$

ii) Sand Content.

The Cape sands often dominate the creep and shrinkage behaviour of concretes produced in this region. It was therefore desireable that the concrete mixes had low sand contents to permit the coarse aggregates to have a greater effect on the shrinkage and creep. The aim was then to have a sand content of 40% by mass of the total aggregate mass.

iii) Concrete Strengths at Loading.

Due to an insufficient number of moulds, the two mixes had to be cast on successive days. The weaker mix was cast first and then loaded at eight days age. The stronger mix was cast the day after the weaker and loaded at seven days. It should be remembered that rapid-hardening cement was to be used.

From Table 4.5 in Phase 2, it was seen that Mix 200-40, or Mix Number 23, had the seven-day comparative strength of 33 MPa - this was for a cement/water ratio of 2.0 and a sand fraction of 40% by mass of total aggregate. This mix was used as the stronger mix.

$f_{cu_2} = 33$ MPa

$f_{cu_1} = 0.25/0.40 * 33 = 20.6$ MPa

From Table 4.5 it is again seen that Mix 150-40 (Number 13) may be used for the weaker mix. It has a 40% sand fraction, a cement/water ratio of 1.50 and a seven-day strength of about 20 MPa.

iv) Absorption Coefficient of the Aggregate.

The stone size to be used was 9.0 to 13.2 mm and the absorption coefficient for this fraction was found from Phase 1 testing to be 9.1%. The porous specific gravity of this size fraction was similarily found to be 2.04.

The constituents in kg/m^3 of the two mixes 150-40 and 200-40, based on the absorption coefficient of 7.66% and the porous specific gravity of 2.21 for the 13.2 - 19.0 mm stone size, were as follows:

	MIX 150-40	MIX 200-40
Saturated stone	1176	1140
Dry Klipheuwel sand	734	710
Rapid-hardening cement	226	302
Water	151	152

The mix quantities shown above need to be adjusted to account for the higher absorption of the smaller stone size and the lower specific gravity. The calculation to give the "per cubic metre" quantities was discussed in Phase 2 and is as follows:

The mass of the dry stone, DST = SST/(1 + Ca) kg/m^3, where SST is the mass of the saturated stone and Ca is the absorption coefficient - which is 0,091 for this particular aggregate.

The batched volume is then:

$$Vb = \left[\frac{DST}{2.04} + \frac{S}{2.64} + \frac{C}{3.14} + W\right] \div 1000 \text{ m}^3 \quad \text{. . . equation 5.24}$$

The "per cubic metre" amounts are then:

$SST_1 = SST/Vb$

$S_1 = S/Vb$

$C_1 = C/Vb$

$W_1 = W/Vb$

The mix quantities for Mixes 200-40 and 150-40 were then used as input values for the above calculation and the adjusted amounts of constituents in kg/m^3 are then as follows:

	WEAK MIX	STRONG MIX
Saturated stone	1142	1107
Dry Klipheuwel sand	713	690
Rapid-hardening cement	220	293
Water	147	148

The weaker mix was known as MIX 1 and the stronger mix as MIX 2, and the constituent amounts calculated were to be used in the making of the mixes.

5.2.2: Production of Mix 1.

Based on the mix quantities calculated in Section 5.2.1, the following amounts of materials were batched into the mixer:

Saturated stone	109.5 kg	
Dry Klipheuwel sand	68.3 kg	+ 9.0 kg
Rapid-hardening cement	21.0 kg	
Water	14.1 kg	

The slump was very high, approximately 150 mm, and the mix also appeared to be deficient of mortar. Sand only was added gradually until the slump had been reduced to 80 mm - 9.0 kg of extra sand was added.

Sixteen 100 mm cubes, twelve 105 mm diameter cylinders and six 100 x 100 x 500 mm beamlets were cast from this concrete mix. The moulds were stripped after 24 hours of curing beneath waterproof sheeting and the concrete specimens were then placed under water at 24°C until they were required for testing.

Because of the additional sand, the "per ~~square~~ cubic metre" quantities had to be recalculated. The same calculation as before is done:

MIX 1 - "weaker mix"

saturated stone = 1103 kg/m^3
dry Klipheuwel sand = 779 "
rapid-hardening cement = 212 "
water = 142 l/m^3

saturated stone/sand = 1.416
mass fraction of sand of total dry aggregate = 43.5%
effective cement/water ratio = 1.493
expected strength at eight days = approx. 22 MPa
volume fraction of sand of total aggregate = 37.3%

5.2.3: Production of MIX 2.

The mix quantities calculated previously for MIX 2 in Section 5.2.1 were revised because the sand/stone ratio had changed.

The quantities were:

	PREVIOUS	ADJUSTED
saturated stone	1107 kg/m^3	1107 kg/m^3
dry Klipheuwel sand	690 "	782 "
rapid-hardening cement	293 "	293 "
water	148 "	148 "

The stone/sand ratio was thus 1107/690 = 1.6043, whereas the final stone/sand ratio for MIX 1 was 1103/779 = 1.4159. Using the same stone content for MIX 2 of 1107 kg/m as before, the required sand content to maintain the new ratio of 1.4159 was therefore 1107/1.4159 = 782 kg/m^3. The adjusted quantities are then shown in the second column above, but these produced more than one cubic metre of concrete, and the batch volume calculation was again performed to bring these amounts to "per cubic metre" quantities. The final quantities of mix constituents can be seen in the highlighted table of data for MIX 2 overleaf.

The following amounts of materials were then batched into the mixer:

saturated stone = 100.0 kg
dry Klipheuwel sand = 70.6 kg
rapid-hardening cement = 26.5 kg
water = 13.35 kg

The slump that resulted was exactly 60 mm and the concrete mix was very pleasant to work with - it did not segregate, was easy to compact and handle, and required no adjustment.

Again sixteen 100 mm cubes, twelve 105 mm diameter cylinders and six 100 x 100 x 500 mm beamlets were cast. After 24 hours of curing under a waterproof sheeting, the moulds were stripped and the concrete specimens placed under water at 24°C until they were required for testing.

The final data for concrete of MIX 2 was then:

MIX 2 - "stronger mix"

saturated stone = 1070 kg/m^3
dry Klipheuwel sand = 755 "
rapid-hardening cement = 284 "
water = 143 l/m^3

saturated stone/sand ratio = 1.417
mass fraction of sand to total dry aggregate = 43.5%
volume fraction of sand of total aggregates = 37.3%
effective cement/water ratio = 1.986
expected strength at seven days = approx. 34 MPa

5.2.4: Proposed Testing to be done.

Firstly, the aim was to test the strength versus time of the comp-ressive strength of recycled concrete. Cubes were therefore to be crushed in the testing machine at one day, three days, seven days, eight days, 14 days and 28 days.

Secondly, the tensile strength of the recycled concrete was to be tested. The flexural tensile strength was to be found at seven and 28 days by the centre-point loading to fracture of the 100 x 100 x 500 mm beamlets. The splitting strength was to be found at seven and 28 days as well. The specimens to be used for this test were the 105 mm diameter cylinders that were cut into two lengths of approximately 150 mm each.

Thirdly, the elastic modulus of the recycled concrete was to be determined at seven and 28 days as well. Two cylinders from each mix were capped in the appropriate manner with a high-strength paste made from rapid-hardening cement and fine-grained sand.

The fourth series of tests on these recycled concretes were to determine their creep and shrinkage behaviour. Four cylinders from each mix were capped and loaded into the creep rig at eight days for MIX 1 and seven days for MIX 2. Two cylinders from each mix were to be used as the shrinkage control specimens, and the ends of these cylinders were covered with a sanding sealer to give them the same degree of surface exposure as the creep specimens.

Each specimen was weighed prior to testing so that the concrete density would be available for use in the empirical formulae used to estimate the elasticity modulus and flexural strengths of concretes.

5.2.5: Results of the Compression Strength Testing.

Two hours before their testing, the concrete cubes were taken from the water and left out to dry. Their masses were determined and they were then crushed in the Amsler testing machine at a rate of 15 MPa per minute.

The results of the cube fractures and their densities are given in Table 5.1.

5.2.6: Results of the Tensile Strength Testing.

Two methods were used to determine the tensile strength of the recycled concrete, namely the Brazilian cylinder-splitting test and the tensile-flexural test done on small concrete beams.

5.2.6.1: Brazilian Splitting Test.

The 300 x 105 mm diameter cylinders were each sawn in half so that more results would be available. The diameter and length of each

Concrete Age (days)	Number of cubes tested	Dimensions of cubes	Average mass (gram)	Mean Density (kg/m³)	Mean fcu. (MPa)
MIX 1					
1	2	all 100 x 100 x 101 mm	–	–	9.3
3	3		–	–	16.3
7	4		2337	2314	21.3
8	2		–	–	21.6
14	2		–	–	23.5
28	3		2365	2342	26.0
MIX 2					
1	2	all 100 x 100 x 101 mm	–	–	12.2
3	3		–	–	23.8
7	3		2367	2344	31.4
8	2		–	–	32.9
14	3		–	–	37.2
28	3		2376	2352	41.7

TABLE 5.1. : Results of the Compressive Strength Testing of the Recycled Concretes.

Details of Mix	Cylinder number	age (days)	length (mm)	diameter (mm)	mass (gram)	splitting force (N)	splitting strength (MPa)	density (kg/m^3)
MIX 1:	1	7	149.0	105	—	50 000	2.03	—
	2	7	148.0	105	—	53 000	2.17	—
	3	7	146.5	105	—	48 000	1.99	—
mean f_{ts} 7days = 2.04 MPa	4	7	147.0	105	—	48 000	1.98	—
f_{ts} 28days = 3.17 MPa	5	28	149.0	105	3003	78 000	3.17	2328
	6	28	145.0	105	2964	71 000	2.97	2315
mean density = 2342 kg/m^3	7	28	149.0	105	2987	81 000	3.30	2361
	8	28	146.0	105	2987	78 000	3.24	2363
MIX 2:	1	7	148.0	105	—	94 000	3·85	—
	2	7	148.0	105	—	94 000	3·85	—
	3	7	147.0	105	—	94 000	3·88	—
mean f_{ts} 7days = 3.85 MPa	4	7	149.0	105	—	94 000	3·83	—
f_{ts} 28days = 4.32 MPa	5	28	146.0	105	2992	116 000	4.82	2367
	6	28	148.0	105	3010	104 000	4.26	2349
mean density = 2354 kg/m^3	7	28	149.0	105	3010	102 000	4.15	2333
	8	28	144.0	105	2949	96 000	4.04	2365

TABLE 5.2. : Results of the Tensile Splitting Testing of the Recycled Concretes.

specimen was measured, as well as its mass to permit determination of its density.

The cylinders were carefully aligned in the Amsler compression testing machine between two pieces of hardboard and the force then applied until a splitting fracture occurred. The compressive force was applied along two diametrically-opposed lines in the "Brazilian" method as proposed by Carneiro and Barcellos (*56).

The tensile strength is then calculated from the following equation:

$$f_{ts} = 2P/\pi dl \qquad \text{. . . equation 5.25}$$

where P = applied force to cause failure
d = diameter of cylinder
l = length of cylinder

The density of the concrete is calculated as follows:

$$\rho \; \cancel{p} \; = 4m/\pi d^2 l \qquad \text{. . . equation 5.26}$$

where m = mass of the cylinder.

The results of the Brazilian splitting tests are shown in Table 5.2.

5.2.6.2: Flexural Tensile Test.

The concrete beamlets, which are approximately 500 mm long, were placed symmetrically on two supports (one fixed and one roller) 450 mm apart. A knife-edge load was applied at the centre point of the beamlet's span and its magnitude increased until the concrete specimen failed.

The tensile strength of the concrete is considered to be the stress at failure in the bottom fibre of the beamlet. The tensile flexural strength of each specimen may be calculated from equation 5.27 below, which was derived in Figure 5.2:

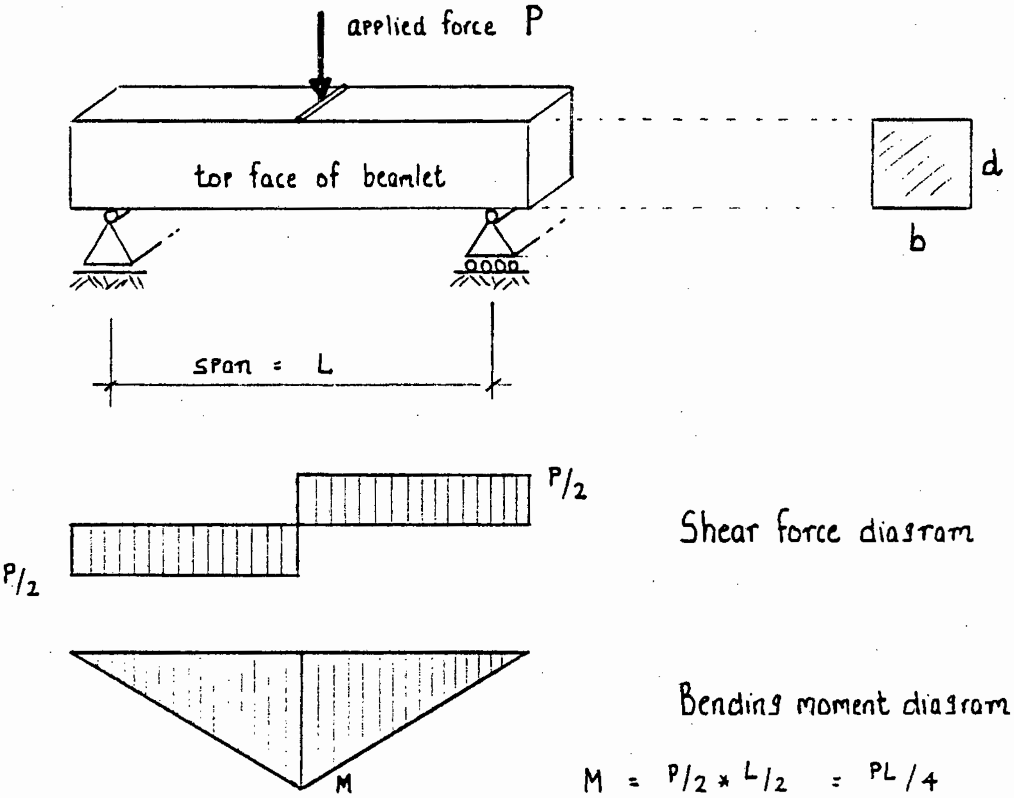
$$f_{tf} = 6P.L/4.b.d^2 \qquad \text{. . . equation 5.27}$$

where P = force applied to cause failure
L = span of beamlet = 450 mm
d = depth of section = 100 mm
b = breadth of section (variable)

The results of these tests are tabulated in Table 5.3.

5.2.7: Results of the Elastic Modulus Testing.

Two cylinders from each mix were prepared for testing according to the method described in BS 1881, Part Five of 1970 (*40). The method is described fully in Appendix A7. Each cylinder was capped with a strong mor-



$M = P/2 * L/2 = PL/4$

$I = b.d^3/12$ and $y = d/2$

$\sigma_{bending} = M.y/I$ with $Z = I/y = b.d^2/6$

$\therefore$ maximum tensile stress $= \frac{M}{Z} = \frac{PL}{4} \div \frac{b.d^2}{6}$

$\therefore f_{tf} = \frac{6PL}{4b.d^2}$ -------- equation 5.27

Figure 52 : Derivation of the Tensile Strength in Flexure of a Concrete specimen.

Details of Mix	Beamlet number	Age (days)	Length (mm)	Depth (mm)	Breadth (mm)	Mass (gram)	Span (mm)	Fracture Force (N)	Tensile Strength (MPa)	Density (kg/m^3)
MIX 1:	1	7	500	100	101	11 837	450	5100	3.41	2344
	2	7	498	100	101	11745	450	5000	3.34	2335
mean f_{tf} 7day = 3.39 MPa	3	7	498	100	103	12038	450	5200	3.41	2347
f_{tf} 28day = 4.26 MPa	4	28	500	100	102	11926	450	7200	4.76	2338
mean density = 2337 kg/m^3	5	28	500	100	101	11770	450	6000	4.01	2331
	6	28	495	100	104	11973	450	6200	4.02	2326
MIX 2:	1	7	500	100	103	12042	450	7900	5.18	2338
	2	7	497	100	104	11984	450	7400	4.80	2319
mean f_{tf} 7day = 5.00 MPa	3	7	497	100	101	11827	450	7500	5.01	2356
f_{tf} 28day = 5.16 MPa	4	28	500	100	102	11878	450	8000	5.29	2329
mean density = 2345 kg/m^3	5	28	498	100	104	12145	450	8100	5.26	2345
	6	28	495	100	103	12160	450	7500	4.92	2385

TABLE 5.3 : Results of the Tensile Flexural Testing of the Recycled Concretes.

tar and targets for the demountable mechanical (DEMEC) strain gauge were affixed to the concrete specimens with an epoxy glue. This was done in accordance with BS 1881 specifications.

5.2.7.1: Elastic Modulus of MIX 1 at Seven Days.

The mean cube strength of the recycled concrete from MIX 1 was found to be 21.3 MPa. Therefore the code value of C, which is one third of the cube strength, was then 7 MPa.

The diameter of the cylinder was found to be 104 mm, which means that the cross-sectional area was 8495 mm². This meant that 8495 newtons or 8.50 kN of force needed to be applied per megapascal of stress. The stress increments were then marked off on the force gauge of the testing machine. The convention was adopted that the capped surface of a cylinder would be placed on the bottom plate of the Amsler testing machine.

Cylinder 1.1 required no adjustment when the preliminary loading was performed and the E-modulus could then be taken from the first attempt - which apparently is a fairly rare occurence. Cylinder 1.2 required five attempts before the cylinder was centred properly and the readings for the E-modulus determination could be taken. The eccentricity of the second cylinder was measured and noted for use when the 28-day testing was to be done.

The results of these readings and the plots of the stress versus strain may be found in Appendix A7. BS 1881 requires that the best straight line be drawn through the points and the elasticity modulus then found from the mean slopes yielded by the front and back gauges on the cylinder. It was felt that a numerical fit of a line by a regression analysis would be more accurate. This same linear regression analysis, which is a preset programme on several pocket calculators, was discussed in Section 4.3.2.1 under equations 4.9 to 4.12.

For Cylinder 1.1:

E (front) = 24.558 GPa; $\underline{r}$ = 0.994
E (back) = 20.803 GPa; $\underline{r}$ = 0.997

where $\underline{r}$ is the correlation coefficient, which indicates how linear the data was - the closer it is to unity, the better the fit of the line.

The mean value of E-modulus = 24.561 GPa.

The difference in elastic modulus of the two cylinders was fairly high and it can only be assumed that the second cylinder might have had some internal flaws such as air bubbles.

However, the mean elastic modulus for MIX 1 at seven days age with rapid-hardening cement was then 22.8 GPa.

5.2.7.2: Elastic Modulus of MIX 1 at 28 Days.

The mean cube strength at age 28 days for MIX 1 was found to be approximately 24 MPa and the value of C was therefore 8 MPa. Again the load required per megapascal of stress was 8.50 kN.

Cylinder 1.1 required seven attempts at centring the cylinder before the elastic modulus loading could be performed. Cylinder 1.2 was placed in the testing machine at the same eccentricity that had been measured at seven days and no adjustments were required before the final loading was done.

For Cylinder 1.1

E (front) = 24.763 GPa; r = 0.998
E (back) = 25.128 Gpa; r = 0.999

mean value of E-modulus = 23.422 GPa.

For Cylinder 1.2:

E (front) = 22.971 GPa; r = 0.998
E (back) = 23.872 GPa; r = 0.999

mean value of E-modulus = 23.422 GPa.

It will be noticed that the previous disparity in elastic modulus that existed between the two cylinders at seven days had now diminished, and the 28-day modulus of elasticity of recycled MIX 1 was then 24.2 GPa.

5.2.7.3: Elastic Modulus at Seven Days.

The mean cube strength of MIX 2 at age seven days was found to be approximately 31 MPa and the value of C could have been taken as 10 MPa, but a value of 8 MPa was used instead which is within the requirements of BS 1881. The diameter of the cylinders was again 104 mm and so a load of 8.5 kN was required for one megapascal of stress.

Cylinder 2.1 was centred succesfully on the first attempt, but Cylinder 2.2 required eight attempts before it was centred and the final loading and measurement could be done. The results are shown in Appendix A7.

For Cylinder 2.1:

E (front) = 26.616 GPa; r = 0.994
E (back) = 29.493 GPa; r = 0.999

mean value of E-modulus = 28.040 GPa.

For Cylinder 2.2
E (front) = 28.305 GPa; r = 0.991
E (back) = 27.819 GPa; r = 0.996

mean value of E-modulus = 28.062 GPa.

These two cylinders produced exceptionally similiar results for their modulus of elasticity, although there was a 10% difference from front to back in the first cylinder, which is within the 15% limit permitted by the code.

The mean modulus of elasticity for MIX 2 at seven days with rapid-hardening cement was therefore 28.05 GPa.

5.2.7.4: Elastic Modulus of MIX 2 at 28 Days.

The mean cube strength of the concrete at age 28 days was found to be about 41 MPa, and so the value of C was taken at 13 MPa. Again the load required per megapascal of stress was 8.5 kN.

Cylinder 2.1 was again centred sucessfully on the first attempt. The eccentricity of cylinder 2.2 at seven days had been measured and here at 28 days it was again applied, but two further attempts were required to centre the cylinder before the test could be performed. The results are shown in Appendix A7.

For Cylinder 2.1:

E (front) = 28.742 GPa; $\underline{r}$ = 0.999
E (back) = 27.945 GPa; $\underline{r}$ = 0.999

mean value of E-modulus = 28.344 GPa

For Cylinder 2.2:

E (front) = 28.551 GPa; $\underline{r}$ = 0.999
E (back) = 30.297 GPa; $\underline{r}$ = 0.999

mean value of E-modulus = 29.424 GPa.

The mean value of the elastic modulus of MIX 2 at age 28 days was therefore 28.9 GPa.

The results of the modulus of elasticity tests will be discussed in Section 5.3.3 and they will be compared to the values produced by the formulae given in Section 5.1.4.

Note: When a cylinder is placed in the testing machine and the preliminary loading performed, the specimen will be considered as "centred" if the deflections of the front and rear are within 10% of each other. It is very often the case that the one side of the cylinder will deflect more than the other, and it is required that the specimen be recentred to try and produce the same deflection between both sets of targets. The side that deflects the most is then assumed to take too much of the stress and should be moved away from the centre of the bearing plates of the testing machine.

5.2.8: The Creep and Shrinkage Testing.

Four 105 mm diameter cylinders from each mix were placed in the hydraulically-controlled UCT creep rig. Two further cylinders from each mix were also placed in the controlled-humidity creep room to serve as shrinkage control specimens.

5.2.8.1: Calibration of the Creep Rigs.

The creep frame that was to be used was the CEB hydraulic type which is shown in Figure 5.3. The UCT creep rig holds twelve of these frames, which in turn can accomodate two 105 mm diameter cylinders each. The axial load to each frame is applied by means of a hydraulic ram which has its pressure regulated by the central hydraulic system.

Firstly, it was required that the desired stress to be applied to the recycled concrete specimens be determined. At the intended time of loading, the compressive strengths of the two concretes - a weaker and a stronger - were estimated as:

f_1, the weaker, was 22 MPa

f_2, the stronger, was 33 MPa

The required stress was therefore (from previous discussion in Section 5.2.1) 40% of the weaker strength and also 25% of the stronger strength.

P reqd = 0.40 * 22 = 8.8 MPa

or = 0.25 * 33 = 8.2 MPa

An average stress value of 8.50 MPa was therefore to be applied.

The average diameter of the cylinders was measured to be 104.5 mm and the cross-sectional area therefore 8577 mm^2.

The required force on the cylinders was therefore found to be:

F reqd = 8577 mm^2 * 8.50 N/mm^2 72 900 newtons.

The Philips load cell that had previously been used to calibrate the creep apparatus had a capacity of 10 tonnes, which is 10 000 kilogramme-force (kgf). The 72.9 kN of applied force is therefore equivalent to 72 900/9.81 = 7432 kgf. This meant that the creep rig would have to be loaded to 74.3% of the capacity of the Philips 10T cell.

In 1982, the creep frame was calibrated using the abovementioned load cell, whereby the "pounds-per-square-inch" pressure values from the dial gauges (positioned in the hydraulic system of the frame) were compared to the "kilogramme-force" readings from the load cell. The layout of the creep frames in the UCT creep room is shown in Figure 5.4.

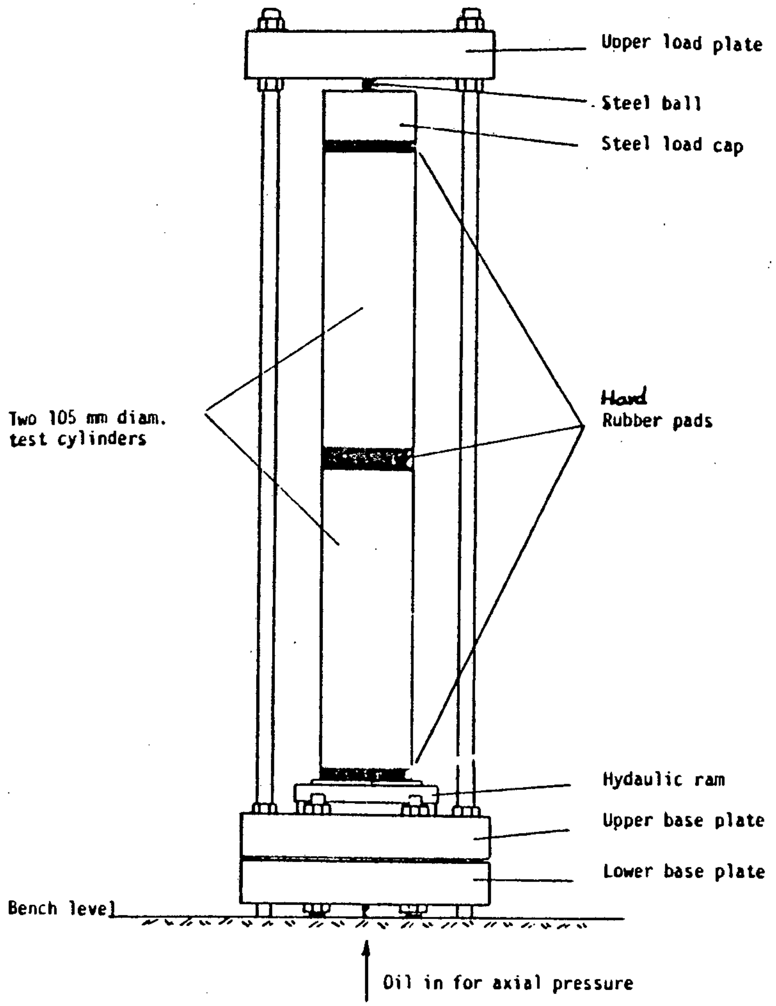

Upper load plate
Steel ball
Steel load cap
Two 105 mm diam. test cylinders
Hard Rubber pads
Hydaulic ram
Upper base plate
Lower base plate
Bench level
Oil in for axial pressure

FIG 5.3

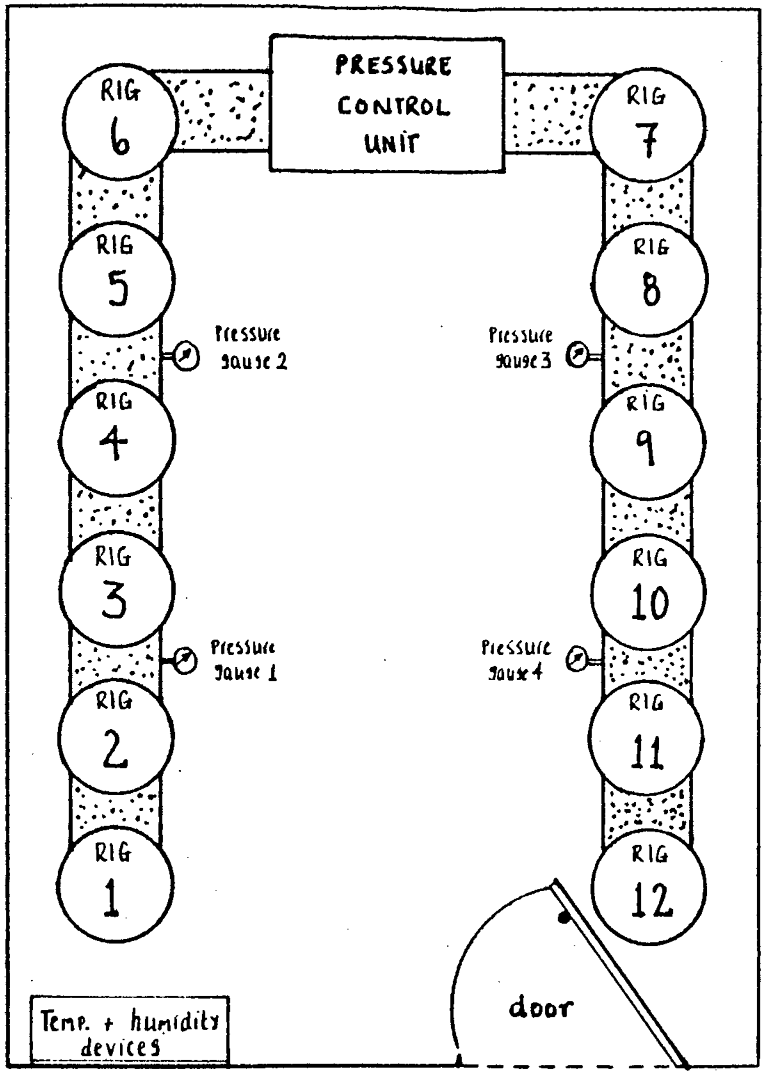

PRESSURE CONTROL UNIT
RIG 6
RIG 7
RIG 5
RIG 8
Pressure gauge 2
Pressure gauge 3
RIG 4
RIG 9
RIG 3
RIG 10
Pressure gauge 1
Pressure gauge 4
RIG 2
RIG 11
RIG 1
RIG 12
door
Temp. + humidity devices

FIG 5.4

For each creep frame (1 to 12), the gauge pressure in pounds per square inch was found from the available calibration charts that corresponded to 74.3% of the Philips load cell's capacity. These calibration charts are included in Appendix A8. The gauge pressure values for the twelve creep frames were then as follows:

CREEP FRAME No	GAUGE PRESSURE (lb/in^2)
1 *	16 540 *
2 *	16 650 *
3 *	16 450 *
4	17 000
5	16 450
6 *	16 500 *
7	16 720
8	16 940
9	not available
10	16 240
11	not available
12	16 105

Since only four creep frames were needed to test the eight specimens of recycled concrete, it was decided that the frames marked with an asterisk (*) above would be used. The average pressure to supply 74.3% of the 10 tonnes force using frames 1, 2, 3 and 6 was therefore 16 535 lb/in^2.

5.2.8.2: Procedure of Testing.

The intention had been to load the concrete specimens when MIX 1 was eight days old and MIX 2 seven days old, but the compressor controlling the hydraulic system of the creep rig broke down on the target day. When it had been fixed, the specimens were then loaded into the creep frames - but two days had elapsed - and MIX 1 was therefore loaded at 10 days and MIX 2 at nine days.

Two sets of targets for the strain gauge were glued to each cylinder parallel to its axis, and diametrically opposed. The strain gauge used was a demountable mechanical device (DEMEC) which had been set to a 6-inch gauge length. Each division on the strain gauge, when set to its usual 8 inch-gauge length, was equal to a strain of 1.02 x 10^{-5} - and for the 6-inch gauge length, the strain would then be 1.36 x 10^{-5} per division.

The strain gauge was calibrated throughout the test using an inert metal bar, known as an INVAR bar, and the DEMEC gauge was found to be consistent.

The Creep Room has a controlled temperature and humidity which needs to be mentioned to allow accurate comparison of creep and shrinkage results. The temperature was 23°C ± 1°C and the relative humidity 50% ± 4%. This was monitored each time readings were taken.

The creep and shrinkage strains were measured at regular intervals throughout the duration of the test (60 days), as can be seen from the charts in Appendix A8. After the load had been activated initially, the readings were taken at short intervals for the creep specimens only.

5.2.8.3: Processing of Results.

The readings taken from all the concrete cylinders may be found in Appendix A8. The results from each pair of cylinders loaded by a particular creep frame are processed together to give the total creep plus shrinkage strains, as well as the elastic shortening strain on application of the load.

On a seperate sheet, the mean shrinkage strains and the mean total deferred strains (creep plus shrinkage) of the two creep frames per mix were then combined to give the overall mean creep and shrinkage strains for each of the two recycled concretes. The creep strain of the concrete was taken to be the total deferred strain measured less the shrinkage strain measured from the control specimens.

Finally, for each of the two mixes, the specific creep strain (to be defined below in Section 5.2.8.4) was calculated up to the age of 60 days.

5.2.8.4: Representation of Creep.

The simplest way in which the creep of concrete could be measured would be by relating the actual creep strain measured against time under load. This is known as "creep strain" and is denoted by the symbol C.

A second fairly simple way to represent creep is by using the concept of "specific creep" - denoted by Csp. It is defined as the creep strain divided by the applied stress, and it therefore permits the comparison of creep results obtained from different stress levels in the concrete. The stress level, on the other hand, is the applied stress divided by the compressive strength of the concrete.

So far the following symbols have been defined:

C = creep strain in the concrete;
P = the applied stress causing creep;
f_{cu} = the compressive strength of the concrete;
Csp = the specific creep (strain per unit stress), and
SL = the stress level in the concrete.

Therefore, the following equations hold:

$$Csp = C/P \quad \text{strain per MPa} \qquad \ldots \text{ equation 5.28}$$

$$SL = P/f_{cu} \times 100\% \qquad \ldots \text{ equation 5.29}$$

Concrete researchers and engineers favour the use of the specific creep approach, but the more recent international design codes such as the CEB-FIP 1978 model code, the CEB code of 1970 and the Australian code prefer to use either a "creep coefficient" denoted by ϕ, or else a "creep function" denoted by 0.

Creep coefficient : $\phi = C/\varepsilon_{el}$ . . . equation 5.30

Creep function : $\Phi = \phi/Ec$ . . . equation 5.31

where ε_{el} = the elastic strain due to the load.
Ec = the elastic modulus of the concrete.

Equations 5.29 and 5.30 may be combined to yield the following expression recognising that Ec = "stress over strain" or P/ε_{el}.

Creep coefficient : $\phi = Csp.Ec$ . . . equation 5.32

Debate exists, however, on which value of the Young's modulus Ec should be used on the above equation. Both the CEB code of 1970 and the CEB-FIP code of 1978 require the use of the 28-day elastic modulus, irrespective of the concrete's age upon loading. The Australian code AS*14881, (*57) suggests that it should be the value at the time of loading. In his work, Mallows (*49), followed the CEB-FIP recommendations and used the 28-day E-modulus, and so too, the creep factors in this thesis will be found using the 28-day modulus of elasticity.

If the 28-day E-modulus is not known, then it may be calculated as follows using the equation given in the CEB code of 1970 (*58):

$$\frac{E_{28}}{E_0} = \sqrt{\frac{f_{28}}{f_0}}$$ . . . equation 5.33

where E_{28} = elastic modulus at 28 days;
E_0 = elastic modulus at loading;
f_{28} = compressive strength at 28 days, and
f_0 = compressive strength at loading.

Mallows (*49) then derived the following formula for converting from specific creep to a creep factor which he called the "unbiased creep factor".

$$\phi = Csp.E_0 \sqrt{f_{28} / f_0}$$ . . . equation 5.34

In this work, the compressive strength and elastic moduli were known for both the age at loading and at 28 days. They were:

MIX 1:
f_0 = 22 Mpa
f_{28} = 26 MPa (loaded at 28 days)
E_0 = 23 GPa
E_{28} = 24 GPa

MIX 2:
f_0 = 33 MPa
f_{28} = 42 MPa (loaded at 28 days)
E_0 = 28 GPa
E_{28} = 29 GPa

Mallows then also attempted to convert his experimental data, by means of the CEB-FIP creep factors, to a standard set of conditions from which he determined his "normalized 300-day creep factor" for various South African aggregates. (By "normalizing" the creep factors, an attempt is made to bring these concretes to a common, standard composition. This was then his basis of comparison for these different aggregates.)

The CEB-FIP code of 1970 (*58) has the following theoretical formulation for the creep factor:

$$\phi_t = Kc \;.\; Kd \;.\; Kb \;.\; Kc \;.\; Kt \qquad \text{. . . equation 5.35}$$

where Kc depends on the environmental conditions;
Kd depends on the hardening of the concrete at the age of loading;
Kb depends on the composition of the concrete;
Ke depends on the theoretical thickness of the member, and
Kt depends on the development of the deferred deformation with time.

The full method of estimating the CEB creep factor is included in Appendix A9. The standard set of conditions for the creep factor as defined by Mallows (*49) from this creep formulation shown above was then as follows:

(i) the concrete is loaded at 28 days of age (Kd = 1);
(ii) the cement/water ratio is 2.50; (Kb = 1)
(iii) the cement content is 500 kg/m^3;
(iv) the relative humidity is 50%, and
(v) the effective specimen thickness is 52.5 mm.

All creep tests conducted in the UCT Creep Room using the hydraulically-controlled creep rig would require 104-105 mm diameter cylinders with an effective specimen thickness of 52.5mm. Secondly, the relative humidity in the Creep Room is kept constant at 50%, and so only the factors Kd and Kb would need to be applied to UCT creep results to "normalize" them.

Mallows' final equation for the "normalized creep factor" was then as follows:

$$\phi n = Csp \;.\; E_0 \;.\; \sqrt{\frac{f_{28}}{f_0}} \Big/ Kd \;.\; Kb \qquad \text{. . . equation 5.36}$$

Since the 28-day elastic moduli are known for the two recycled concretes, equation 5.36 simplifies to the following for this thesis:

$$\phi n = \frac{Csp \;.\; Ec}{Kd \;.\; Kb} \qquad \text{. . . equation 5.37}$$

This equation will permit the comparison of the creep of the recycled concrete to the creep of concretes made from various other natural aggregates. The values of Kd and Kb are found from the figures in the CEB creep estimation method of 1970, which is shown in Appendix A8.

5.2.8.5: Results of the Creep and Shrinkage Tests.

As much data as possible for the two recycled concretes will be presented in this section and the final 60-day "unbiased" and "normalized" creep factors will be found.

MIX 1: Loaded at 10 days of age;
fcu at loading = 22 MPa;
E-modulus at loading = 22.8 GPa, and
E-modulus at 28 days = 24.2 GPa.

Initial elastic strain upon load = 39.0 x 10^{-5}
(this is the mean of eight strain-gauge readings)

Applied stress = $\mathcal{E}_{el}$.Ec = 22.8 x 10^{3} * 39.0 x 10^{-5}
= 8.892 MPa

Stress level = applied stress/fcu = 40.4%

60-day shrinkage strain = 29.2 x 10^{-5}
60-day creep strain = 76.0 x 10^{-6} per MPa
60-day specific creep = 85.5 x 10^{-5}

60-day "unbiased" creep factor = 85.5 x 10^{-6} * 24.2 x 10^{3}
= 2.09

the creep correction factors are: Kd = 1.0
Kb = 1.0

60-day "normalized" creep factor = 2.09

The fact that rapid-hardening cement was used and that the concrete was loaded at 10 days produces the correction factor of 1.0 for Kd. The water/cement ratio of 0.67 and the cement content of 212 kg/m^3 gives the value of 1.0 for Kb.

MIX 2: Loaded at nine days of age
fcu at loading = 33 MPa
E-modulus at loading = 28.05 GPa
E-modulus at 28-days = 28.90 GPa

Initial elastic strain upon loading = 29.8 x 10^{-5}

Applied stress = $\mathcal{E}_{el}$.Ec = 28.05 x 10^{3} * 29.8 x 10^{-5}
= 8.359 MPa

Stress level = applied stress/fcu = 25.3%

60-day shrinkage strain = 28.6 x 10^{-5}
60-day creep strain = 51.1 x 10^{-5} per MPa
60-day specific creep = 61.1 x 10^{-6}

60-day "unbiased" creep factor = 61.1 x 10^{-6} * 28.90 x 10^{3}
= 1.77

The creep correction factors are: Kd = 1.05
Kb = 0.84

60-day "normalized" creep factor = 1.77/(1.05 * 0.84)
= 2.01

The use of rapid-hardening cement and the loading of the concrete at nine days produces the value of 1.05 for Kd, whereas the value of 0.84 for Kb was found using the water/cement ratio of 0.50 and the cement content of 284 kg/m^3.

Note: It was initially attempted to load the recycled concrete cylinders to a stress of 8.50 MPa - this was translated into a gauge pressure of 16 535 pounds per square inch - but the pressure gauges attached to the creep rig do not have divisions fine enough to permit accurate loading. It was felt that by using the concrete strains measured upon load application, and the known moduli of elasticity, a more accurate applied stress value would be found. In so doing, the average stress applied to the concrete on MIX 1 was 8.892 MPa, and to MIX 2 was 8.359 MPa.

5.3: DISCUSSION OF THE TEST RESULTS

5.3.1: Compressive Strength of Recycled Concretes.

The work in Phase 2 has shown that fairly high strengths of up to 60 MPa may be attained in recycled aggregate concretes, although it is recommended that 50 MPa should be considered as the "ceiling strength" of these concretes.

In Phase 3 the strength-development with time of the recycled concretes was investigated. Table 5.4 below shows the compressive strengths of the two recycled concretes at different ages. The effective cement/water ratio of MIX 1 was 1.49, and for MIX 2 it was 1.99. For rapid-hardening cement the standard-age-strength is assumed to occur at seven days, and each of the strengths in Table 5.4 is therefore expressed as a percentage of the 7-day strength.

CONCRETE AGE (days)	MIX NUMBER 1 Mean f_{cu} (MPa)	 % of 7-day strength	MIX NUMBER 2 Mean f_{cu} (MPA)	 % of 7-day strength
1	9.3	43.7	12.2	38.9
3	16.3	76.5	23.8	75.8
7	21.3	100.0	31.4	100.0
8	21.6	101.4	32.9	104.8
14	23.5	110.3	37.2	118.5
28	26.0	122.1	41.7	132.8

Table 5.4: The compressive strengths of the two recycled concretes with time

A plot of these values may be seen in Figure 5.5. Figure 5.6 was taken from Fulton (*17) and shows the compressive strength/age relationship for normal concretes made with rapid-hardening cements. The two curves on this diagram in Figure 5.6 that corresponded most closely with the 7-day strengths of the two recycled mixes were used to determine the strength percentages that follow:

Fulton's mix, similiar to MIX 1:	AGE IN DAYS	f_{cu} IN MPa	% OF 7-DAY f_{cu}
	3	21	68
	7	31	100
	14	38	123
	28	43	139
Fulton's mix, similiar to MIX 2	3	13	62
	7	21	100
	14	26	124
	28	31	148

Taking the average values of the "percentage of 7-day strength" figures, that is, 66% at three days, 100% at seven days, 123% at 14 days and 143% at 28 days, the estimated strength gain of conventional concretes made with rapid-hardening cement is drawn in on Figure 5.5.

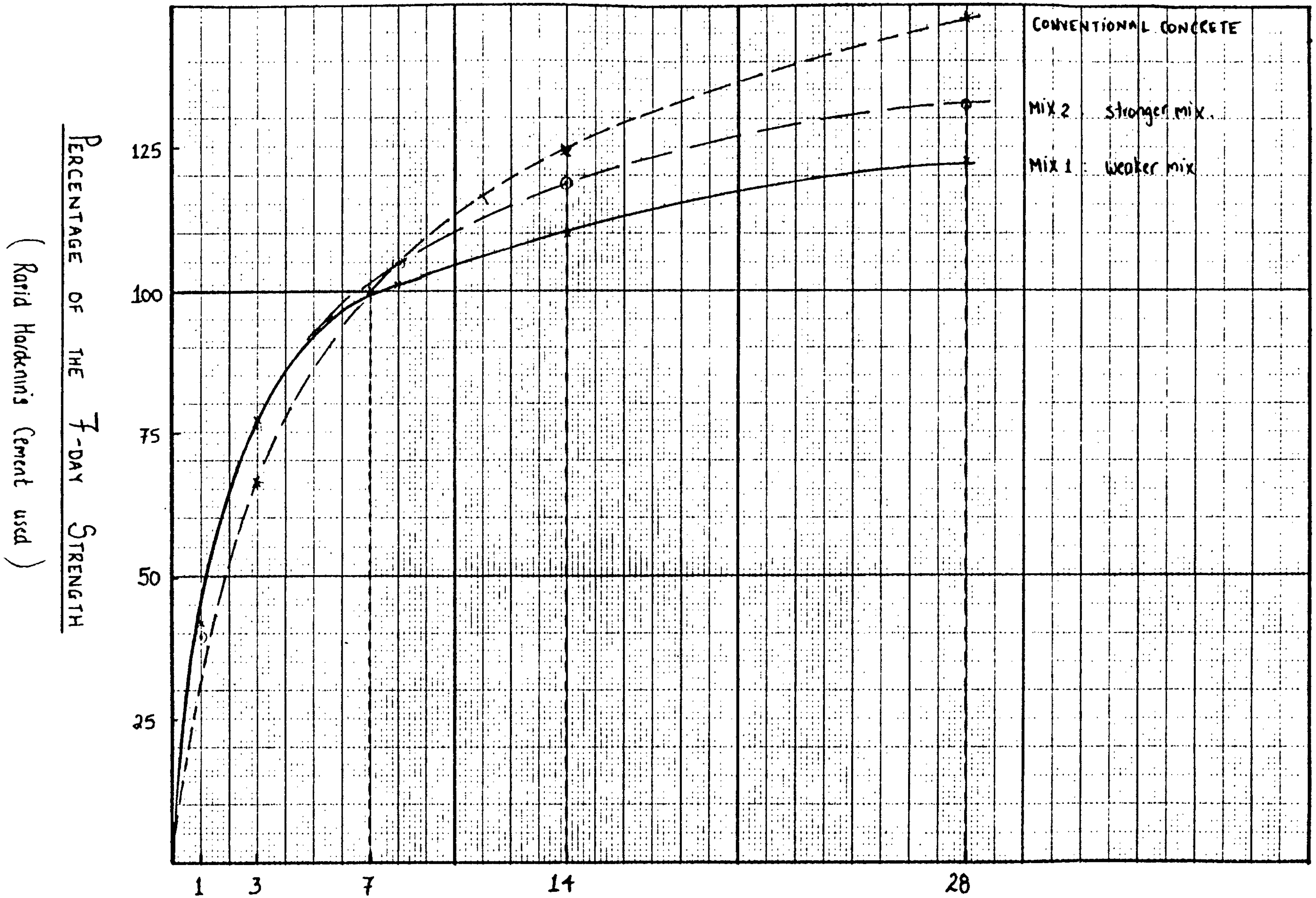


Fig 5.5 Concrete Age (Days)

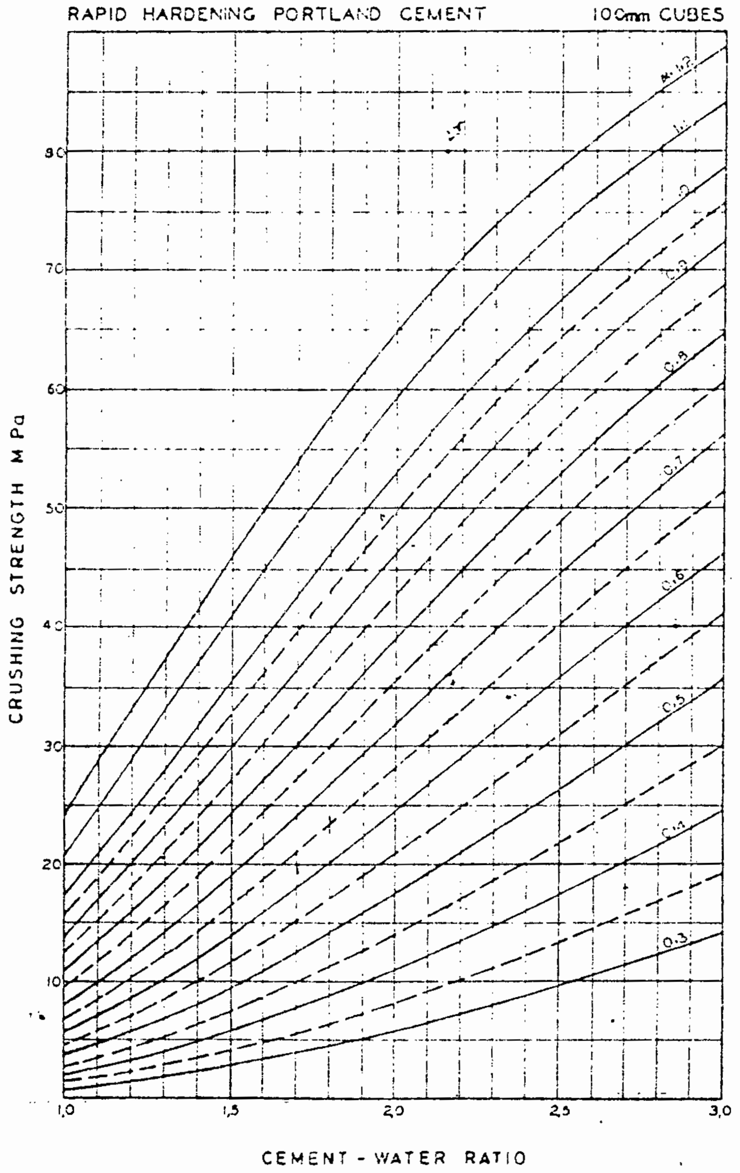

RAPID HARDENING PORTLAND CEMENT
100mm CUBES
CRUSHING STRENGTH MPa
80
70
60
50
40
30
20
10
1,0
1,5
2,0
2,5
3,0
CEMENT - WATER RATIO
1,2
1,1
1,0
0,9
0,8
0,7
0,6
0,5
0,4
0,3

FIG 5.6

From Figure 5.5 it is then seen that the recycled concrete appears to mature slightly faster than its normal concrete counterpart, that is, the 7-day strength is closer to the long-term strength for recycled concrete.

5.3.2: Tensile Strength of Recycled Concrete.

Flexural tensile strength: f_{tf}

The flexural tensile strength of the two recycled concretes was found by the centre-point loading of the small concrete beams, or "beamlets" as they were called previously. The resulting data, also shown in Table 5.3, was as follows:

	MIX 1	MIX 2
effective cement/water ratio	1.49	1.99
flexural tensile strength at 7 days (MPa)	3.39	5.00
flexural tensile strength at 28 days (MPa)	4.26	5.16

For MIX 1, the gain in strength from day 7 to day 28 was 26%, whereas for MIX 2 it was only 3% - this should not be seen as significant because it is felt that this test is prone to error and will produce results that vary.

Packard's equation (*49) relating the flexural strength of a concrete to its compressive strength was presented in Section 5.1.3 as equation 5.3. Packard found this strength to be approximately equal to 68% of the square-root of the compressive strength for ordinary Portland cement at the age of 28 days. Applying this equation to the avaliable data for the recycled concretes, the following figures are obtained:

MIX 1:	f_{cu} at 7 days	:	21.3 MPa	
	f_{tf} at 7 days (estimate)	:	3.14 MPa	. . . (1)
	f_{tf} at 7 days (actual)	:	3.39 MPa	
	f_{cu} at 28 days	:	26.0 MPa	
	f_{tf} at 28 days (estimate)	:	3.47 MPa	. . . (2)
	f_{tf} at 28 days (actual)	:	4.26 MPa	
MIX 2:	f_{cu} at 7 days	:	31.4 MPa	
	f_{tf} at 7 days (estimate)	:	3.81 MPa	. . . (3)
	f_{tf} at 7 days (actual)	:	5.00 MPa	
	f_{cu} at 28 days	:	41.7 MPa	
	f_{tf} at 28 days (estimate)	:	4.39 MPa	. . . (4)
	f_{tf} at 28 days (actual)	:	5.16 MPa	

The actual flexural tensile strengths of the two recycled concretes were therefore consistently higher than Packard's equation would suggest. The general form of Packard's equation is:

$$f_{tf} = K * SQRT(f_{cu}) \qquad \text{. . . equation 5.38}$$

For each of the four actual results, the value of the coefficient K in equation 5.38 would then be:

(1) K = 0.73
(2) K = 0.84
(3) K = 0.89
(4) K = 0.80

There is therefore no unique value for this coefficient K, although it may then be stated that the flexural tensile strength of recycled concrete will be between 73% and 89% of the square-root of its compressive strength at any age. The average value for K was, however, 0.82.

The values for K at 28 days with rapid-hardening cement were 0.84 and 0.80, which is a much narrower range than the above one, and the mean value of K was again 0.82 for 28-day results only.

For the flexural tensile strength of lightweight concrete, Swamy (*42) developed an equation of the same form as equation 5.38 - where the value of the coefficient K in his formulation was 0.75 - which is somewhat closer to the value of 0.82 that was found above for recycled concrete.

Tensile Splitting Strength: f_{ts}

The tensile strength of the two recycled conretes was found by the splitting of cylinders under compressive loading - known as the "Brazilian" splitting test. The resulting data, also shown in Table 5.2, was as follows:

	MIX 1	MIX 2
effective cement/water ratio	1.49	1.99
splitting strength at 7 days (MPa)	2.04	3.85
splitting strength at 28 days (MPa)	3.17	4.32

For MIX 1, the gain in strength from seven to 28 days was 55%, whereas for MIX 2 it was again lower at only 12%. The splitting test produced a much narrower range of results, as will be seen from the comparison of Table 5.2 and Table 5.3, than did the flexural test. The stronger mix, namely MIX 2, therefore definitely matures quicker than the weaker mix with respect to flexural or tensile strength. The opposite of this applied with compressive strength.

The CEB-FIP formula (*38) relating the tensile splitting strength of a concrete to its compressive strength was presented in Section 5.1.3 and is:

$$f_{ts} = C * \mathrm{CUBRT}(f_{cu}^{2}) \qquad . . . \text{ equation 5.1}$$

the value used for estimates of the coefficient C is 0.24.

The application of this formula to the data found for the two recycled concretes is as follows:

MIX 1 - at 7 days:
f_{cu} = 21.3 MPa
f_{ts} (estimate) = 2.11 MPa
f_{ts} (actual) = 2.04 MPa
corrected value of C = 0.27

- at 28 days:
f_{cu} = 26.0 MPa
f_{ts} (estimate) = 1.84 MPa
f_{ts} (actual) = 3.17 MPa
corrected value of C = 0.36

MIX 2 - at 7 days:
f_{cu} = 31.4 MPa
f_{ts} (estimate) = 2.39 MPa
f_{ts} (actual) = 3.85 MPa
corrected value of C = 0.39 MPa

- at 28 days:
f_{cu} = 41.7 MPa
f_{ts} (estimate) = 2.89 MPa
f_{ts} (actual) = 4.32 MPa
corrected value of C = 0.36

The actual splitting strengths of the recycled concretes are again consistently higher than the CEB-FIP equation would suggest - in fact they are significantly greater, at between 11 and 61% above the estimated strengths. Using the general form of equation 5.1, the values of the coefficient C were between 0.27 and 0.39 for recycled concrete with rapid-hardening cement at any age.

From the two 28-day values, the value of the coefficient C was 0.36 in both instances. This fact indicates that, although rapid-hardening cement may be used to achieve high early compressive strengths, the maturity of the concrete in tension or flexure is maintained at a later age, namely 28 days.

In his work with lightweight concretes, Swamy (*42) again used an equation of the same form as equation 5.38, namely:

f_{ts} = K * SQRT(f_{cu}) . . . equation 5.38

this time his value of the coefficient K was 0.56.

For each of his four actual results, the value of K in this equation would then be:

(1) K = 0.44
(2) K = 0.62
(3) K = 0.69
(4) K = 0.67

Again there is no unique value for the coefficient K as it has a range of 0.44 to 0.69 and a mean value of 0.61 for rapid-hardening cement at any age. As expected, the range narrows considerably when only the 28-day values are used, namely 0.62 to 0.67, and the mean value for K at 28 days is then 0.64. Swamy's formulation for lightweight concrete is again more accurate than the other methods proposed to estimate the flexural or tensile strength of recycled concrete.

In general, it may therefore be stated that no shortfall of flexural or tensile strength will occur in recycled concrete - a fact that has been echoed by other researchers such as Gluzghe (*1) and Malhotra (*31).

5.3.3: Modulus of Elasticity of Recycled Concrete (Static Modulus).

Young's modulus of elasticity of each of the two recycled concretes was determined at the ages of seven and 28 days following the standard method of BS 1881, Part Five of 1970 (*40).

The data obtained for the two recycled concretes was then as follows:

	MIX 1	MIX 2
effective cement/water ratio	1.49	1.99
E-modulus at 7 days	22.80 GPa	28.05 GPa
E-modulus at 28 days	24.20 GPa	28.90 GPa

For the weaker concrete of MIX 1, the gain in stiffness from days seven to 28 was 6.1% and for MIX 2, the stronger concrete, the gain was again lower at only 3.0%. So, just as was the case with the flexural or tensile strengths, the recycled concrete with the higher cement/water ratio, or for that matter, cement content, matures further with respect to elastic modulus than does the concrete with the lower cement/water ratio.

In Section 5.1.4 numerous equations were presented which express the elastic modulus of a concrete as a function of its cube strength, cylinder strength and sometimes density. The following ones will be used as a comparison with the results found for the two recycled concretes:

(i) the CEB-FIP recommendation (*38):

$$E = 6.6 * \text{SQRT (cylinder strength)} \quad \text{. . . equation 5.12}$$

(ii) Davis' equation for South African aggregates (*28):

$$E = 4.9 * \text{SQRT (cube strength)} \quad \text{. . . equation 5.17}$$

(iii) the CEB formula of 1976 (*58):

$$E = 9.5 * \text{CUBRT (cylinder strength + 8)} * \left[\frac{\text{mass density}}{2400}\right]^3 \quad \text{. . . equation 5.15}$$

The "cylinder strength" and "cube strength" of a concrete is not the same, but researchers have found that the cylinder strength ($f\underline{cy}$) is approximately equivalent to 80% of the cube strength ($f\underline{cu}$) - as was shown in equations 5.18 (a) and (b) of Section 5.1.4.

The CEB-FIP equation, number (i) above, therefore becomes:

$$E = 6.6 * \text{SQRT}(0.8\ f\underline{cu}) = 5.9 * \text{SQRT (cube strength)}$$

which produces a somewhat larger value for E than does Davis' equation.

The general form of the first two equations is therefore:

$$E = Ke * \text{SQRT}(f\underline{cu}) \quad \text{. . . equation 5.39}$$

Another set of equations estimating the E-modulus are found from the technology of lightweight concrete - which appears to be similiar to that of recycled concrete in many respects. They are:

(iv) CEB-FIP (*38):

$$E = 0.0018 * \mathrm{SQRT}(w .f_{cy}) \qquad \ldots \text{ equation 5.13}$$

$$\therefore E = 0.0016 * \mathrm{SQRT}(w .f_{cu}) \qquad \ldots \text{ equation 5.13 (a)}$$

(v) Pauw (*43) (ACI equation):

$$E = 0.043 * \mathrm{SQRT}(w .f_{cu}) \qquad \ldots \text{ equation 5.20}$$

(vi) Schaffler (*44):

$$E = 0.000\ 06 * \mathrm{SQRT}(m^3.f_{cu}) \qquad \ldots \text{ equation 5.21}$$

(vii) Swamy (*42):

$$E = 0.97\ m\ * \mathrm{SQRT}(f_{cu}) / 10^6 \qquad \ldots \text{ equation 5.19}$$

where m is the "mass density" of the concrete in kg/m^3 and w is the "weight density" in kN/m^3. The f_{cu} in these equations is expressed in megapascal, but for equation (iv) it is in kPa.

The general form of these equations for lightweight concrete is then:

$$E = Ce * \mathrm{SQRT}(m^3.f_{cu}) \qquad \ldots \text{ equation 5.40}$$

Table 5.5 overleaf shows the comparison of the actual elastic moduli with those calculated by methods (i) to (vii) presented above. It will be seen that these equations generally overestimate the stiffness of the two recycled concretes, although Davis' equation 5.17 for natural South African aggregates, and Pauw's ACI equation 5.20 for lightweight concretes produce the closest results to the actual E-modulus values.

Using the two "general-form" formulae in equations 5.39 and 5.40, the values of the coefficients Ke and Ce were calculated corresponding to the actual values of the E-moduli of the recycled concretes. This was also done in Table 5.5.

Equation 5.39 depends only on the compressive cube strength of the concrete and a MPa value for f_{cu} results in a GPa value for E. In equation 5.40, both the f_{cu} and density of the concrete is considered and the units to be used are kg/m^3 for the density (m) and MPa for both the f_{cu} and elastic modulus.

The range found for the coefficient Ke in equation 5.39 at any age was 4.48 to 5.01 with an average value of 4.80. The ranges become narrower if Ke is considered only at one particular age of the concrete, that is, at seven days with rapid-hardening cement it is between 4.94 and 5.01 with a mean value of 4.97. For a 28-day determination the range of Ke is 4.48 to 4.75, with a mean value of 4.61.

The same trend applies to the coefficient Ce in equation 5.40: at any stage the range is 0.039 to 0.044 with a mean of 0.042; at seven days with rapid-hardening cement the values are almost identical at 0.043, and at 28 days the range is very narrow, namely 0.039 with a mean value of 0.040.

PARTICULARS OF EACH CONCRETE	MIX 1		MIX 2	
	at 7 days	at 28 days	at 7 days	at 28 days
Actual cube strength (MPa)	21.3	26.0	31.4	41.7
Actual mass density (kg/m^3)	2337	2365	2367	2376
Actual weight density (kN/m^3)	22.93	23.20	23.22	23.31
Actual E-modulus (GPa)	22.8	24.2	28.0	28.9
Estimates of E-moduli				
(i) E (GPa)	27.2	30.1	33.1	38.1
(ii) E (GPa) (Davis)	22.6	25.0	27.5	31.6
(iii) E (GPa)	27.3	29.8	31.3	34.2
(iv) E (GPa)	25.6	28.8	31.7	36.8
(v) E (GPa) (Pauw)	21.8	24.5	27.0	31.2
(vi) E (GPa)	31.3	35.2	38.7	44.9
(vii) E (GPa)	24.5	27.7	30.5	35.4
Recalculated coefficient values:				
for K_e	4.94	4.75	5.01	4.48
for C_e	0.044	0.041	0.043	0.039

TABLE 5.5 : Comparison of the actual E-moduli of the recycled concrete with various estimated values.

The use of the following two equations is then recommended for the determination of the modulus of elasticity in recycled concretes:

1. If only the compressive strength of the concrete is known:

   $E = Ke * SQRT\ (f_{cu})$ . . . equation 5.39

   where Ke = 4.97 for rapid-hardening cement at 7 days, and
   Ke = 4.61 for rapid-hardening cement at 28 days.

2. If the mass density of the concrete is also known, then the following formula would be preferred:

   $E = Ce * SQRT\ (\ M^3.f_{cu}\ )$ . . . equation 5.40

   where Ce = 0.043 for rapid-hardening cement at 7 days, and
   Ce = 0.040 for rapid-hardening cement at 28 days.

In general, it does however appear that for equal compressive strengths, the recycled aggregate has a lower modulus of elasticity than does the normal concretes, which is evident from the stiffness comparisons in Table 5.5. This is in accordance with the findings of other concrete researchers such as Fondistou-Yannas (*5) and Hansen (*45). But again it is evident that no shortfall in stiffness results with the recycled concretes, and using the "ceiling strength" of 50 MPa mentioned before, the maximum E-modulus that may be used in a recycled concrete from equation 5.39 is 35 GPa, and from equation 5.40 is 36 GPa.

5.3.4: The Shrinkage and Creep of Recycled Concrete.

From each of the two recycled concretes that were made, four cylinders were tested in the hydraulic creep rig and two cylinders were placed unloaded with those loaded for a duration of 60 days. The unloaded specimens served to monitor the drying shrinkage that would have occurred over those 60 days.

The shrinkage strains of the two recycled concretes that resulted after the 60 days in an atmosphere of temperature 23 ° C ± 1 °C and relative humidity of 50% ± 4% were very similiar in magnitude - the weaker mix, MIX 1, showed a strain of 29.2×10^{-5} and the stronger mix, MIX 2, a shrinkage of 28.6×10^{-5}.

The full details of each of these concretes with regard to their compressive strengths, age of loading, elastic moduli, applied stress and stress levels may be found in Section 5.2.8.5. To enable comparison with conventional concretes, the 60-day "unbiased" and also "normalized" creep factors, as defined in Section 5.2.8.4, were calculated.

The unbiased 60-day creep factor for MIX 1 was found to be 2.09, whereas for MIX 2 it was found to be 1.77 - which would be expected as the concrete from MIX 2 was subject to a lower stress level of 25%, as opposed to the stress level of 40% for MIX 1. The higher cement content of MIX 2 would also aid in reducing its creep potential compared to MIX 1. On the other hand, MIX 2 was, however, loaded one day earlier than was MIX 1, which would increase its creep potential slightly.

The normalized 60-day creep factors for the two recycled concretes are: MIX 1, the weaker concrete, 2.09; and MIX 2, the stronger concrete, 2.01. As expected, the process of "normalizing" the results to a standard set of parameters, as discussed in Section 5.2.8.4, has brought the creep factors for the two recycled concretes quite close together. The mean 60-day normalized creep factor for the recycled aggregate concrete is then 2.05. It is assumed that the process of "normalizing" has taken account of the different cement/water ratios, ages of loading, and especially the different stress levels applied to the two concretes. The fact that the 60-day factor for MIX 2 is slightly lower than for MIX 1 is attributable to the lower stress level this concrete has received.

5.3.4.1: Comparison of Shrinkage Data Available.

(i) In his MSc thesis of 1981, Hoppe (*59) investigated the creep and shrinkage of concrete made with Windhoek quartzite aggregate. The concrete which he made had a cement content of 445 kg/m^3, 515 kg/m^3 of sand, and 1280 kg/m^3 of a two-sized coarse stone. When 200 litres of water per cubic metre was added, the cement/water ratio was 2.23 and the f_{cu} at 14 days was 43.1 MPa.

Hoppe's shrinkage specimens were stored in the same creep room as were the ones belonging to this author, and the 60-day shrinkage strain was found to be 40.5 x 10^{-5}.

(ii) Ballim and Alexander (*60) of the University of the Witwatersrand conducted shrinkage and creep tests on concretes made with andesite and quartzite aggregates found in the Transvaal. For each aggregate type, cement/water ratios of 1.20 to 2.40 were investigated - the cement contents were between 246 and 492 kg/m^3 for the andesite and between 258 and 516 kg/m^3 for the quartzite. The water and ~~sand~~ stone contents of the mixes were kept constant, that is, 205 l/m^3 of water and 1005 kg/m^3 of stone for the andesite concrete, and 215 l/m^3 of water and 1036 kg/m^3 of stone for the quartzite concrete. For the sand contents, the andesite mixes had between 844 and 1073 kg/m^3 and the quartzite concretes between 640 and 861 kg/m^3.

The shrinkage specimens were stored at a temperature of 21°C and on average relative humidity of 43%. This means that these concretes were likely to shrink slightly more than the ones in the UCT Creep Room. The 60-day shrinkage strains of the quartzite concrete were between 36 and 44 x 10^{-5}. For the andesite concretes the 60-day shrinkage strains were marginally lower at between 32 and 38 x 10^{-5}.

(iii) If the CEB-FIP method (*38) of estimating the shrinkage of a concrete is used, as is shown in Appendix A9, another value may also be obtained for comparison purposes. The formula for the shrinkage is:

$$\text{Shrinkage strain} = S \,.\, K_1 \,.\, K_2 \,.\, K_3 \,.\, K_4 \qquad \text{. . . equation 5.41}$$

where S = the basic ultimate shrinkage strain of an unreinforced concrete and its volume is found in the figure provided;

K_1 = a factor that depends on the thickness of the section;
K_2 = a factor dependent on the cement/water ratio and cement content;
K_3 = a factor accounting for the age of the concrete, and
K_4 = a factor that accounts for the amount of steel reinforcement.

For the two recycled concretes made, the values of these parameters were:

S = 37.0×10^{-5};
K_1 = 1.2;
K_2 = 1.04 (MIX 1) and 1.10 (MIX 2);
K_3 = 0.70 for the 60-day determinant, and
K_4 = 1.00, as there is no reinforcement.

The CEB-FIP estimate of the 60-day shrinkage strain is therefore 32×10^{-5} for MIX 1, and 34×10^{-5} for MIX 2.

Comments:

The CEB-FIP method produced a fairly accurate estimation of the 60-day shrinkage for the recycled concretes. It yielded a mean value of 33×10^{-5}, whereas the actual mean shrinkage was 29×10^{-5}

The shrinkage of the recycled concrete was less than the concretes made with the Windhoek quartzite (40×10^{-5}), the Witwatersrand quartzite (mean of 40×10^{-5}), and the Eikenhof andesite (mean of 35×10^{-5}).

The recycled concretes should, however, have experienced greater shrinkage strains than did the conventional concretes, as recycled concretes are considered to have a higher creep and shrinkage potential. This potential was discussed in Section 5.1.8, but no tests were performed.

5.3.4.2: Comparison of Creep Data Available.

(i) The Windhoek quartzite concrete made by Hoppe (*59) was loaded at 14 days when the f_{cu} (with OPC) was 43.1 MPa, the E-modulus was 28.50 GPa and the stress applied was 10.13 MPa. This meant that the stress level was 23.5%. At 28 days the elastic modulus was 31.35 GPa.

The 60-day creep strain was found to be 54×10^{-5}, the specific creep at this age therefore 53.3×10^{-6}/ MPa, and the 60-day unbiased creep factor therefore 1.67.

To convert this value to the "normalized" creep factor, the values of Kb and Kd are found from the appropriate CEB 1970 (*58) tables. The loading of an OPC concrete at 14 days means that Kd = 1.20, and the water/cement ratio of 0.45 with a cement content of 445 kg/m^3 yields a value of 1.04 for Kb. The 60-day normalized creep factor for Hoppe's concrete is therefore 1.34.

(ii) In his MSc thesis of 1985, Mallows (*49) investigated the creep characteristics of various South African aggregates. From his work, the figures for the unbiased and normalized creep factors of these aggregates at 60 days, shown in Table 5.6, were extracted.

Mallows also made the following interesting conclusions regarding the creep factors of a concrete:

(a) The creep factor increases by 25% if Eastern Province cements are used as opposed to Western Province cements;

(b) The creep factor increases by 25% if rapid-hardening cement is used as opposed to ordinary Portland cement;

(c) The use of an admixture, Pozzolith P4, increases the creep factor by 23% if the water content remains the same, and

(d) The creep factor will be reduced by 45% if heat curing is applied to the concrete.

From Table 5.6, the mean 60-day normalized creep factors for the various aggregates are thus:

1. Eastern Cape quartzite : 1.25
2. Garden Route quartzite : 1.16
3. Garden Route reef quartzite : 1.32
4. Plettenberg Bay reef quartzite : 1.17
5. Bloukrans quartzite sandstone : 1.78
6. Moregrove quartzite : 1.32
7. Coega pure quartzite : 1.71
8. Arnoldton micaceous quartzite : 1.70
9. Border pyritic quartzite : 1.09
10. Transkeian dolerite : 1.09
11. Cape Town hornfels : 1.62
12. Cape Town granite : 1.45
13. Windhoek quartzite : 1.34
14. Aggregate recycled from crushed concrete : 2.05

Comments:

As was expected from the discussion of the creep and shrinkage potential of recycled concretes in Section 5.1.8, the 60-day normalized creep factor for the recycled aggregate concrete is substantially more than those for the natural South African aggregates. It is, for example, 26% higher than for the hornfels commonly used in the Cape Town area, and 41% higher than for the other common Cape aggregate, namely granite.

In the determinations of these creep factors for the Cape granite, hornfels and recycled aggregate, rapid-hardening cement as well as Klipheuwel sand were used in all three instances, so direct comparison between these three aggregates is then fully valid.

From Mallows' second conclusion, the probable 60-day normalized creep factor for the crushed concrete aggregate could be as low as 1.64, had ordinary Portland cement been used. This certainly

Details of Aggregate Used	Age at loading (days)	Stress Level (%)	fcu at loading (MPa)	Unbiased Creep Factor at 60 days	Normalised Creep Factor at 60 days
1. Eastern Cape quartzites (with OPC)	32	26.7	50.0	1.26	1.20
	36	27.1	51.0	1.51	1.36
	43	25.6	54.0	1.22	1.22
	50	24.2	57.0	0.96	1.23
mean normalised ø					1.25
2. Garden Route quartzite (OPC)	10	25.2	47.6	1.62	1.16
3. Garden Route reef quartzite (using OPC)	14	26.7	45.0	1.70	1.32
	16	26.6	45.1	1.65	1.31
mean normalised ø					1.32
4. Plettenberg Bay "ralbob" (quartzitic river gravel) (using OPC)	3	29.2	34.3	1.60	1.00
	7	20.2	49.5	1.41	1.02
	28	17.5	57.1	1.50	1.50
mean normalised ø					1.17
5. Bloukrans River Bridge (quartzitic sandstone) (using OPC)	3	39.2	25.5	2.85	1.78
	14	24.1	41.5	2.14	1.78
	28	21.1	47.5	1.78	1.78
mean normalised ø					1.78
6. Moregrove quartzite (OPC)	14	24.0	46.7	1.70	1.32
7. Coega pure quartzite (OPC)	14	25.3	44.3	2.20	1.71
8. Arnoldton micaceous quartzite	14	25.7	43.6	2.18	1.70
9. Pyritic reef quartzite (OPC)	14	23.3	48.0	1.85	1.44
10. Tina / Umzimvubu Bridge (Transkeian dolerite) (using OPC)	7	20.0	50.0	1.35	1.00
	14	17.5	57.0	1.40	1.20
	28	15.2	66.0	1.05	1.08
mean normalised ø					1.09
11. Groote Schuur hospital (hornfels with RHC)	1	30.7	22.8	2.41	1.59
	2	21.7	32.2	2.33	1.65
mean normalised ø					1.62
12. Cape granite (with RHC)	taken from Mallows's summary of creep factors				1.45
13. Windhoek quartzite (OPC)	14	23.5	43.1	1.67	1.34
14. Recycled aggregate (RHC)	10	40.4	22.0	2.09	2.09
	9	25.3	33.0	1.77	2.01
mean normalised ø					2.05

TABLE 5.6 : Comparison of the 60-day Normalised Creep Factors for 13 diffirent natural aggregates and a recycled aggregate.

improves the creep outlook for recycled aggregate concrete, but its "higher than average" creep potential should not be overlooked.

Unfortunately, none of the international researchers into recycled concrete appear to have done any creep testing on these concretes, and so no other figures are available for comparison. Based on their experience with conventional and lightweight concretes, they have however, also recognized the higher creep potential that should exist for recycled aggregate concretes. This would be largely due to the lower stiffness of such recycled aggregates which therefore offer less resistance to volumetric change than would hard natural stone.

6: CONCLUSION.

The aim of this thesis was to introduce the concept of concrete recycling, i.e. crushing a demolished concrete to produce aggregate and using it in fresh concrete. The work was done in three phases, and it is hoped that it may serve as a guide to prospective users of concrete.

6.1: The Testing of Recycled Aggregates.

Various tests were performed on the samples of recycled aggregate collected. The tests were done according to the BS 812 and SABS 1083 specifications, and the results from these tests may thus serve as a database for work involving recycled aggregates.

(i) The recycled aggregates were found to have a fairly harsh surface texture, but were mostly of satisfactory shape as their flakiness and elongation indices compared favourably with those of natural stone.

(ii) The recycled fine aggregates (or "sand"), i.e. all particles below 4.75 mm in diameter, were found to have rather high fineness moduli - generally between 2.93 and 3.36. These fines were also prone to bulking when wetted.

(iii) The angularity of the coarse recycled aggregate, as measured by its angularity number, depends largely on the crushing process employed. For a particular process, the angularity numbers of the aggregate will fall into a fairly narrow range.

(iv) The absorption of water by porous recycled aggregates is an important parameter in the making of recycled concrete. For the commonly-used 13.2 - 19.0 mm size fraction, the absorption coefficients for these aggregates were between 5.0 and 7.9%.

(v) The absorption and porosity of a recycled aggregate increases as the particle size decreases - this is because the natural stone of the parent concrete is contained mainly in the larger size fractions - and it is the mortar of the parent concrete that provides the porosity and therefore the absorption potential.

(vi) The specific gravity of a recycled aggregate is less than those of its constituent sand and stone, due to the porosity of the aggregate. The "apparent" specific gravity as a porous material should be determined and this value used in batch calculations.

(vii) Since the 10% fines crushing test was found to produce rather variable results , a new test called the "Remoulded Peak Strength Test" was developed to gain a more accurate measure of the recycled aggregate strengths. The peak strength of a recycled concrete was then found to be between 56 and 71 MPa, although a "ceiling-strength" of 50 MPa for such concrete was then suggested.

(viii) Recycled aggregates are by their nature prone to contamination by deleterious substances such as chlorides and sulphates. Only slight traces of sulphate were found in two of the samples collected, otherwise no contaminants were encountered.

6.2: Mix Design with Recycled Aggregates.

The water demand of recycled fine aggregates was investigated and compared to a natural sand. A series of recycled mixes were made using a coarse recycled stone and a natural sand so that the concrete-making properties of such a process could be established. In this test series, the coarse recycled aggregate was WET-batched. Methods for the DRY-batching of recycled aggregate were then discussed and in the final test of this phase, a comparison was made between the WET- and DRY-batching methods of producing recycled concretes.

(i) The water demand of the recycled sand for a 75 mm slump using a 13.2 - 19.0 mm stone size with rapid-hardening cement was found to be 258 litres per cubic metre. For the Klipheuwel sand the corresponding figure was 171 litres, which indicates the high water requirement, and consequently, high cement contents that would result using fine recycled sand as the fine aggregate of a concrete.

(ii) In the process of pre-soaking and wet-batching the recycled coarse aggregate, the porosity and absorption characteristics of these aggregates are neutralized and good concreting properties are attained. Care should be taken to achieve a consistent water content in these recycled stones from batch to batch, or else strength fluctuations will occur. Strength charts for different stone:sand ratios are shown in Section 4.2 and the required cement:water ratios may be obtained from these.

(iii) The wet-batch method produces good workability in the fresh concrete, especially when the sand content is between 40 and 50% by mass of total aggregate. For this range of ~~of~~ sand content, the mortar excess of between 3 and 11% is within desired limits, and good finishing of the concrete would be possible.

(iv) Lean recycled concrete mixes (i.e. low cement:water ratio) are prone to segregation, which is especially evident when the sand content is also low.

(v) Compressive strengths of up to 62 MPa were attained with cement:water ratios ~~of between 1.0 and~~ near 3.0, indicating that fairly strong concrete is possible when recycled coarse aggregates are used. For the same cement:water ratio, an increase in the sand content is seen to produce an increase in strength.

(vi) In the mix calculations, i.e. batch and yield determinations, it is important to use the correct values of the specific gravity of the aggregates, else disparities will arise. These should be determined as shown and then applied in calculations - the porous or apparent specific gravity of the recycled stone is particularly important. The absorbed water inside the pores of the recycled stone should not be included in the volume-yield of the mix.

(vii) If dry batching of recycled aggregate is preferred, then the absorption potential of the aggregate must be accounted for. This can be done in three ways:

(a) By using the additional absorption coefficient to enable more accurate use of the *effective* cement:water ratio and thereby save an appreciable amount of cement. (Section 4.2.3.1)

(b) By using the absorption coefficient of the aggregate and then adding free water to the mix to again save cement and also improve workability. (Section 4.2.3.2)

(c) By using a strength chart of the *gross* cement:water ratio, thereby bypassing the question of water absorption and also being independent of control concretes. (Section 4.2.3.3)

6.3: The Mechanical Properties of Recycled Concrete.

Large batches of two recycled concretes (one weak and one strong) were made using a 9 - 13 mm stone, Klipheuwel sand and rapid-hardening cement. Specimens were made to test the compressive strength gain of the concrete with time, the tensile strengths, the modulus of elasticity, and the shrinkage and creep characteristics of the recycled concrete.

(i) A plot of compressive strength against time, as in Figure 5.5, shows that recycled concrete is no different from its conventional counterpart, other than that appears to reach maturity in terms of compressive strength at an earlier age.

(ii) The recycled concretes had satisfactory flexural strengths that were somewhat higher than what the predictive equations for normal concretes would produce. The following relation was found for the recycled concrete:

$$f_{tf} = 0.82 * SQRT\ (f_{cu})$$

(iii) The same satisfactory trend was found regarding the tensile splitting strength of recycled concrete and the following formulae were generated for the 28-day age with rapid-hardening cement:

$$f_{ts} = 0.36 * CUBERT\ (f_{cu})$$

$$f_{ts} = 0.64 * SQRT\ (f_{cu})$$

(iv) The elastic moduli of recycled concretes are lower than those of a conventional concrete of equal compressive strength. This is because of the lower elastic modulus of the recycled aggregate compared with natural stone. The modulus of elasticity of recycled concrete would generally be between 15 and 30% lower than a control concrete. The following relations were established:

$$E = Ke * SQRT\ (f_{cu})$$

with Ke = 4.97 at 7 days, and Ke = 4.61 at 28 days.

$$E = Ce * SQRT\ (\underline{m} . f_{cu})$$

with Ce = 0.043 at 7 days, and Ce = 0.040 at 28 days.

The mass density is denoted by a m and the second formula is preferred provided that the value of m is known.

(v) Researchers have predicted, and found, that recycled concretes experience greater shrinkage than normal dense concretes. But in this work the shrinkage values found were very much in the same range as those available for conventional concretes.

(vi) The 60-day creep factors of the recycled concrete were "normalized" by the method described by Mallows (* 49), which uses the CEB 1970 (* 58) creep prediction tables. In this way direct comparison of creep potential between different types of aggregates is possible. As expected (from theoretical considerations) the creep of the recycled concrete was higher than that of conventional concretes. For rapid-hardening cements the 60-day creep factor was normalized at 2.05, and if ordinary Portland cement was to be used it would be about 25% lower. Certain Eastern Cape aggregates renowned for their creep potential in concrete would have marginally higher creep factors (1.70 - 1.80) than the recycled aggregate. As a comparison, the hornfels and granite aggregates commonly used in the Cape Town area have 60-day creep factors of 1.62 and 1.45 respectively.

In general, recycled aggregate is found to be very similiar to conventional concrete in both the fresh and hardened states. The main factor for consideration is the absorption due to porosity of the recycled aggregates - once it is accounted for, the concrete is no different. The recycled fine aggregate has a high water demand, very coarse grading and may be contaminated by, for example, sulphates, and its use in good quality plain or reinforced concretes would not be recommended.

CONCLUSION

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APPENDICES

A1 : Particle Size Analysis.

A2 : Initial Moisture Contents.

A3 : BS812 specifications for Particle Shape Analysis.
Flakiness and Elongation Indices.
Angularity Numbers.

A4 : Determination of Specific Gravity, Absorption Coefficients, Density, Void Content and Bulking.

A5 : BS812 specification for the 10% Fines Crushing Test.
Determination of 10% FACT values.

A6 : Details of the Wet Batched Recycled Concrete Mixes.
Record of the Moisture Content of the Klipheuwel Sand.
Correlation of actual and theoretical mortar excess measurements.

A7 : BS1881 specification for the determination of Elastic Modulus.
Determination of the Modulus of Elasticity of the Recycled Concrete.

A8 : Calibration sheets for the Creep Rig.
Readings taken and Processing of data for Shrinkage and Creep.

A9 : CEB of 1970 methods of estimating Shrinkage and Creep in Concrete.

A10 : Copies of the 20 credit Course Work Completed.

APPENDIX A1

Particle Size Analyses of the Recycled Aggregates

(includes Grading Curves of each sample)

Sieve-Analysis of Crushed Rubble Samples.

Clayton Frick, U.C.T.

SAMPLE REF. NO.	# 1	Date of sieving :	Tue 20 · 08 · 85

Sieve Size mm	Gross Weight gr	Wt. of container on scale gr	Nett wt on sieve gr
26.5	311	212	99
19.0	2281	212	2069
13.2	5076	212	4864
9.5	1955	212	1743
6.70	1615	212	1403
4.75	1212	212	1000
Fines ≤ 4.75	5123	783	4340

Total mass : 15 518 gr

The fines below 4.75 mm will be sieved further down to 150 µm.

Grading particulars of the "coarse" aggregate i.e. ≥ 4.75 mm.

Sieve Size mm	Mass retained on sieve gr	% of total mass %	Total percentage retained on sieve %	Total percentage passing sieve %
26.5	99		0	100.0
19.0	2069	13.42	13.42	86.58
13.2	4864	31.55	44.97	55.03
9.5	1743	11.30	56.27	43.73
6.70	1403	9.10	65.37	34.63
4.75	1000	6.49	71.86	28.14
passing 4.75	4340	28.15	—	—
TOTALS	15 419	100.01	251.89	—

form # : CF85 : 001

Sieve Analysis of "Sand" derived from the Crushed Rubble.

Sample Ref. No.	Fines of # 1.	**Date** : 31. 08 85 Monday

SABS sieve µm	Gross Weight gr	Wt. of container gr	Nett wt. on sieve gr
4750	212	212	0
2360	1363	213	1150
1180	1077	211	866
600	822	211	611
300	844	211	633
150	604	212	392
dust ≤ 150	631	213	418

Grading particulars of the "fine aggregate", i.e. ≤ 4.75 mm:

SABS sieve µm	Mass retained on sieve gr	% of total mass %	Total percentage retained on sieve %	Total percentage passing sieve %
4750	0	0	0	100
2360	1150	28.3	28.3	71.7
1180	866	21.3	49.5	50.5
600	611	15.0	64.5	35.5
300	633	15.6	80.1	19.9
150	392	9.6	89.7	10.3
passing 150	418	10.3	——	——
TOTALS	4070	100.0	312.1	——

Fineness Modulus of aggregate = 312 / 100 = 3.12

form # : CF85 - 003

Particle Size Analysis of Crushed Rubble Samples.

SAMPLE REFERENCE # : 1	Demolition rubble collected from dump in Koeberg Rd, Milnerton.

Brief Description of sample :

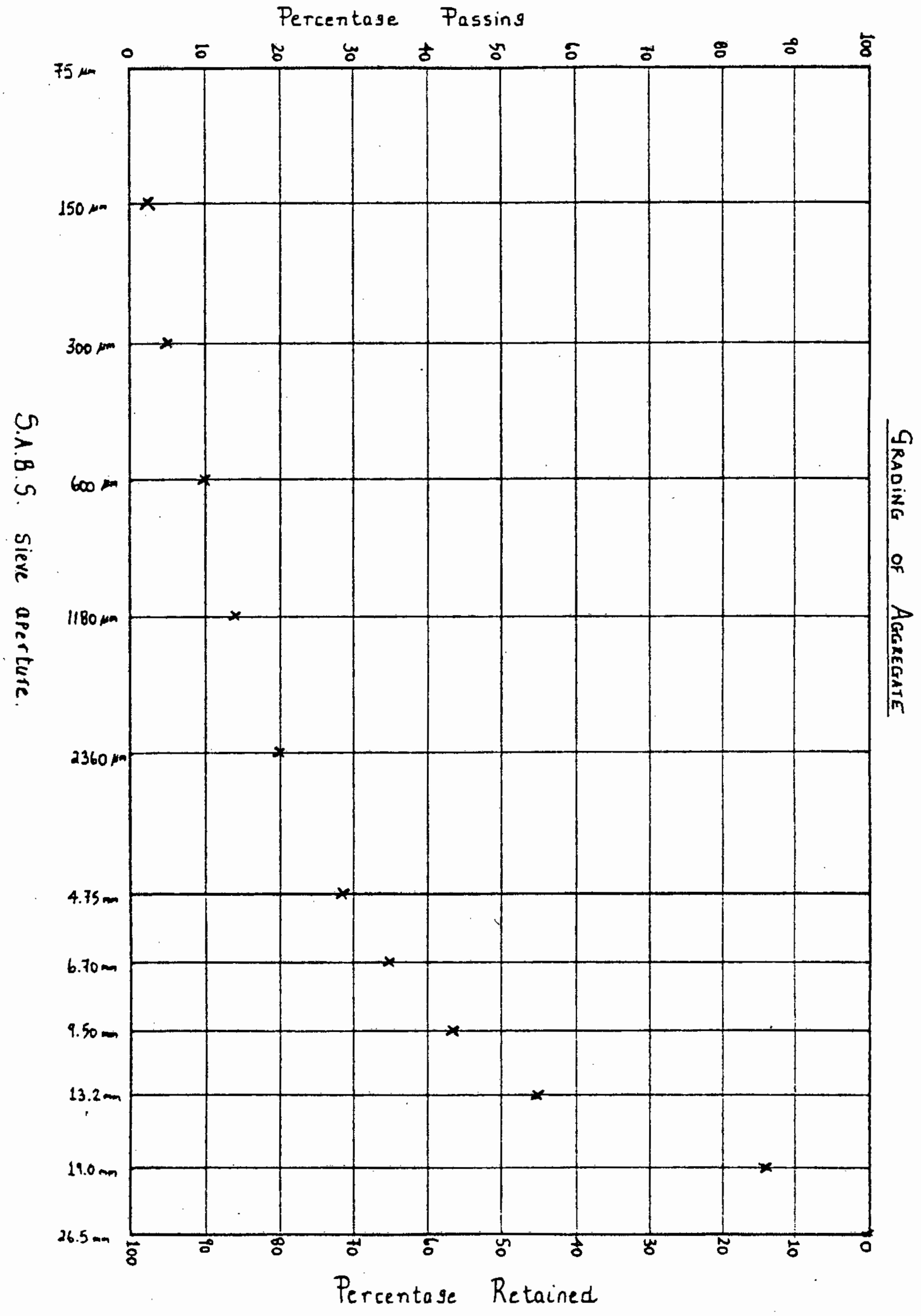
A rather old looking concrete although it is visibly quite strong. The original aggregate is brown-grey and the mortar a whitish grey and fairly porous.

S.A.B.S. Sieve Size	Percentage of total mass %	Total percentage retained on sieve %	Total percentage passing sieve %
26.5 mm	0.0	0.0	100.0
19.0 mm	13.4	13.4	86.6
13.2 mm	31.6	45.0	55.0
9.5 mm	11.3	56.3	43.7
6.70 mm	9.1	65.4	34.6
4750 µm	6.5	71.9	28.1
2360 µm	8.0	79.9	20.1
1180 µm	6.0	85.9	14.1
600 µm	4.2	90.1	9.9
300 µm	4.4	94.5	5.5
150 µm	2.7	97.2	2.8
passing 150 µm	2.9	—	—
TOTALS	100.1	699.6	—

The "relative" fineness modulus of material = 6.99

The fineness modulus of the fine aggregate ≤ 4750 µm was found to be : 3.12

The Grading of Sample # 1



Form # : CFBS - 007

Sieve-Analysis of Crushed Rubble Samples.

Clayton Frick, U.C.T.

SAMPLE REF. NO.	# 4	Date of sieving :	Tue · 20 · 08 · 85

Sieve Size mm	Gross weight gr	Wt. of container on scale gr	Nett wt on sieve gr
26.5	749	212	537
19.0	4182	212	3970
13.2	4679	212	4467
9.5	2262	212	2050
6.70	1917	212	1705
4.75	1404	212	1192
fines ≤ 4.75	6181	780	5401

Total mass : 19 322 gr

The fines below 4.75 mm will be sieved further down to 150 μm.

Grading particulars of the "coarse" aggregate i.e. ≥ 4.75 mm.

Sieve Size mm	Mass retained on sieve gr	% of total mass %	Total percentage retained on sieve %	Total percentage passing sieve %
26.5	537		0.0	100.0
19.0	3970	21.1	21.1	78.9
13.2	4467	23.8	44.9	55.1
9.5	2050	10.9	55.8	44.2
6.70	1705	9.1	64.9	35.1
4.75	1192	6.3	71.2	28.8
passing 4.75	5401	28.8	—	—
TOTALS	18 785	100.0	257.9	—

form # : CF85 : 001

Sieve Analysis of "Sand" derived from the Crushed Rubble.

Sample Ref. No.	The fines of Sample # 4.	**Date** : Thurs 29 [illegible]

SABS sieve µm	Gross Weight gr	Wt. of container gr	Nett wt. on sieve gr
4750	212	212	0
2360	1550	212	1338
1180	1112	212	900
600	936	210	726
300	1084	212	872
150	859	211	648
dust ≤ 150	79	21[illegible]	580

Grading particulars of the "fine aggregate", i.e. ≤ 4.75 mm:

SABS sieve µm	Mass retained on sieve gr	% of total mass %	Total percentage retained on sieve %	Total percentage passing sieve %
4750	0	0.0	0.0	100.0
2360	1338	26.4	26.4	73.6
1180	900	17.8	44.2	55.8
600	726	14.3	58.5	41.5
300	872	17.2	75.8	24.2
150	648	12.8	88.5	11.5
passing 150	580	11.5	—	—
TOTALS	5064	100.0	293.4	—

Fineness Modulus of aggregate = 293 / 100 = 2.93

form # : CF85-003

Particle Size Analysis of Crushed Rubble Samples.

SAMPLE REFERENCE # : 4.	Demolition rubble collected from dump in Milnerton.

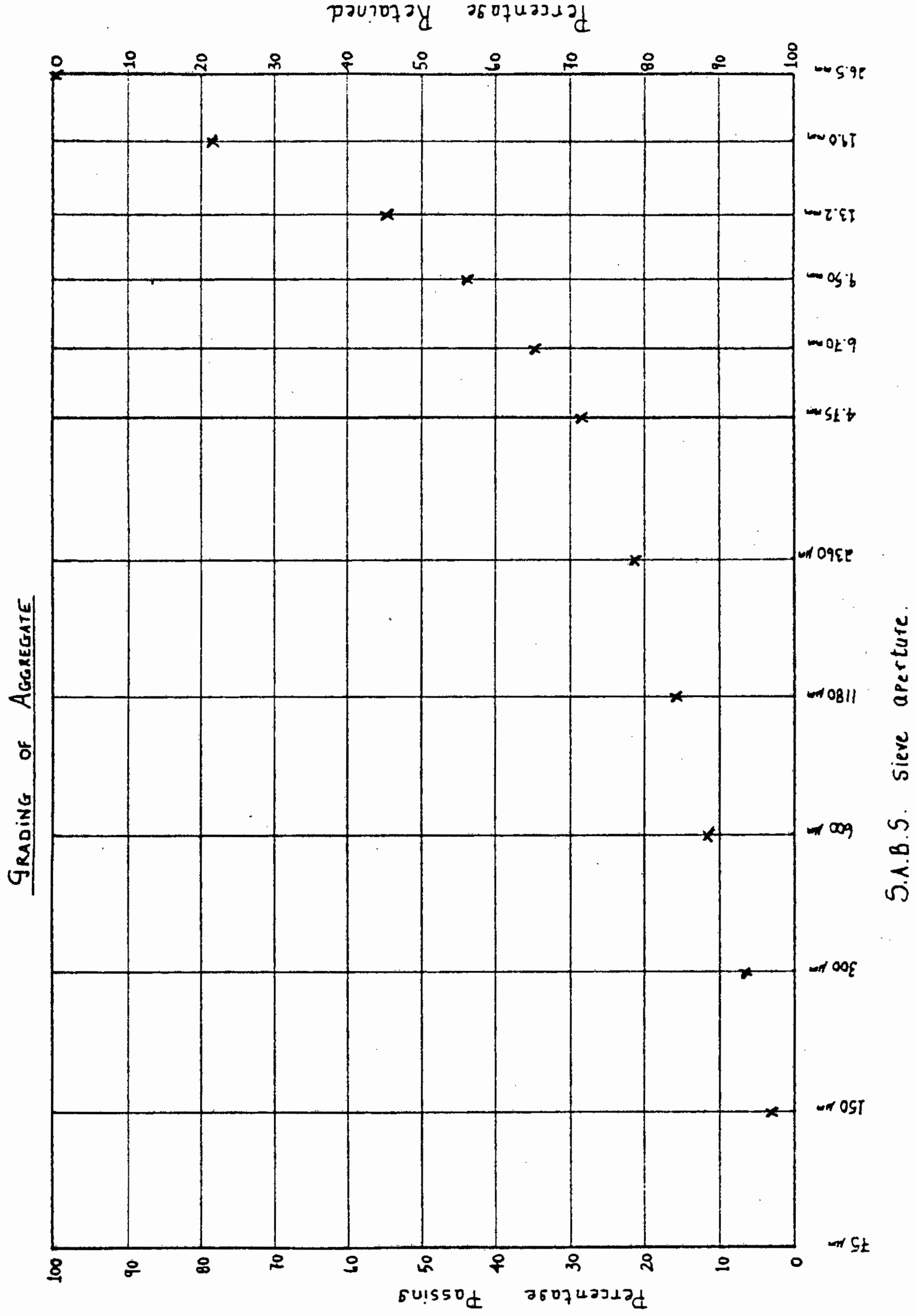
Brief Description of sample :

Very similar to sample # 1, but more dirty with dust and mud which was washed out afterwards before testing. Hornfelsic stone of approx. 1 inch max. size set in a whitish - grey mortar matrix.

S.A.B.S. Sieve Size	Percentage of total mass %	Total percentage retained on sieve %	Total percentage passing sieve %
26.5 mm	0.0	0.0	100.0
19.0 mm	21.1	21.1	78.9
13.2 mm	23.8	44.9	55.1
9.5 mm	10.9	55.8	44.2
6.70 mm	9.1	64.9	35.1
4750 µm	6.3	71.2	28.8
2360 µm	7.6	78.8	21.2
1180 µm	5.1	83.9	16.1
600 µm	4.1	88.0	12.0
300 µm	4.9	92.9	7.1
150 µm	3.7	96.6	3.4
passing 150 µm	3.3	—	—
TOTALS	99.9	698.1	—

The "relative" fineness modulus of material = 6.99

The fineness modulus of the fine aggregate ≤ 4750 µm was found to be : 2.93



Form # : CFBS - 007

The Grading of Sample # 4.

Sieve-Analysis of Crushed Rubble Samples.

Clayton Frick, U.C.T.

SAMPLE REF. NO.	#5	Date of sieving :	Thu 22-08-85

Sieve Size mm	Gross Weight gr	Wt. of container on scale gr	Nett wt on sieve gr
26.5	257	212	45
19.0	1622	212	1410
13.2	5326	180	5146
9.5	2635	180	2455
6.70	2059	180	1879
4.75	1361	180	1181
fines ≤4.75	4752	180	4572

Total mass : 16 688 gr

The fines below 4.75 mm will be sieved further down to 150 μm.

Grading particulars of the "coarse" aggregate i.e. ≥ 4.75 mm.

Sieve Size mm	Mass retained on sieve gr	% of total mass %	Total percentage retained on sieve %	Total percentage passing sieve %
26.5	45		0.0	100.0
19.0	1410	8.5	8.5	91.5
13.2	5146	30.9	39.4	60.6
9.5	2455	14.8	54.2	45.8
6.70	1879	11.3	65.5	34.5
4.75	1181	7.1	72.6	27.4
passing 4.75	4572	27.5	—	—
TOTALS	16 643	100.0	240.2	——

form # : CF85 : 001

Sieve Analysis of "Sand" derived from the Crushed Rubble.

Sample Ref. No.	The fines of #5	**Date** :	28-08-85

SABS sieve µm	Gross Weight gr	Wt. of container gr	Nett wt. on sieve gr
4750	212	212	0
2360	1504	212	1292
1180	1282	212	1070
600	920	210	710
300	802	212	590
150	595	211	384
dust ≤ 150	549	211	338

Grading particulars of the "fine aggregate", i.e. ≤ 4.75 mm:

SABS sieve µm	Mass retained on sieve gr	% of total mass %	Total percentage retained on sieve %	Total percentage passing sieve %
4750	0	0.0	0.0	100.0
2360	1292	29.5	29.5	70.5
1180	1070	24.4	53.9	46.1
600	710	16.2	70.1	29.9
300	590	13.5	83.5	16.5
150	384	8.8	92.3	7.7
passing 150	338	7.7	—	—
TOTALS	4384	100.0	329.3	———

Fineness Modulus of aggregate = 329 / 100 = 3.29

form # : CF85 - 003

Particle Size Analysis of Crushed Rubble Samples.

SAMPLE REFERENCE # : 5.

Demolition rubble collected from Milnerton dump.

Brief Description of sample :

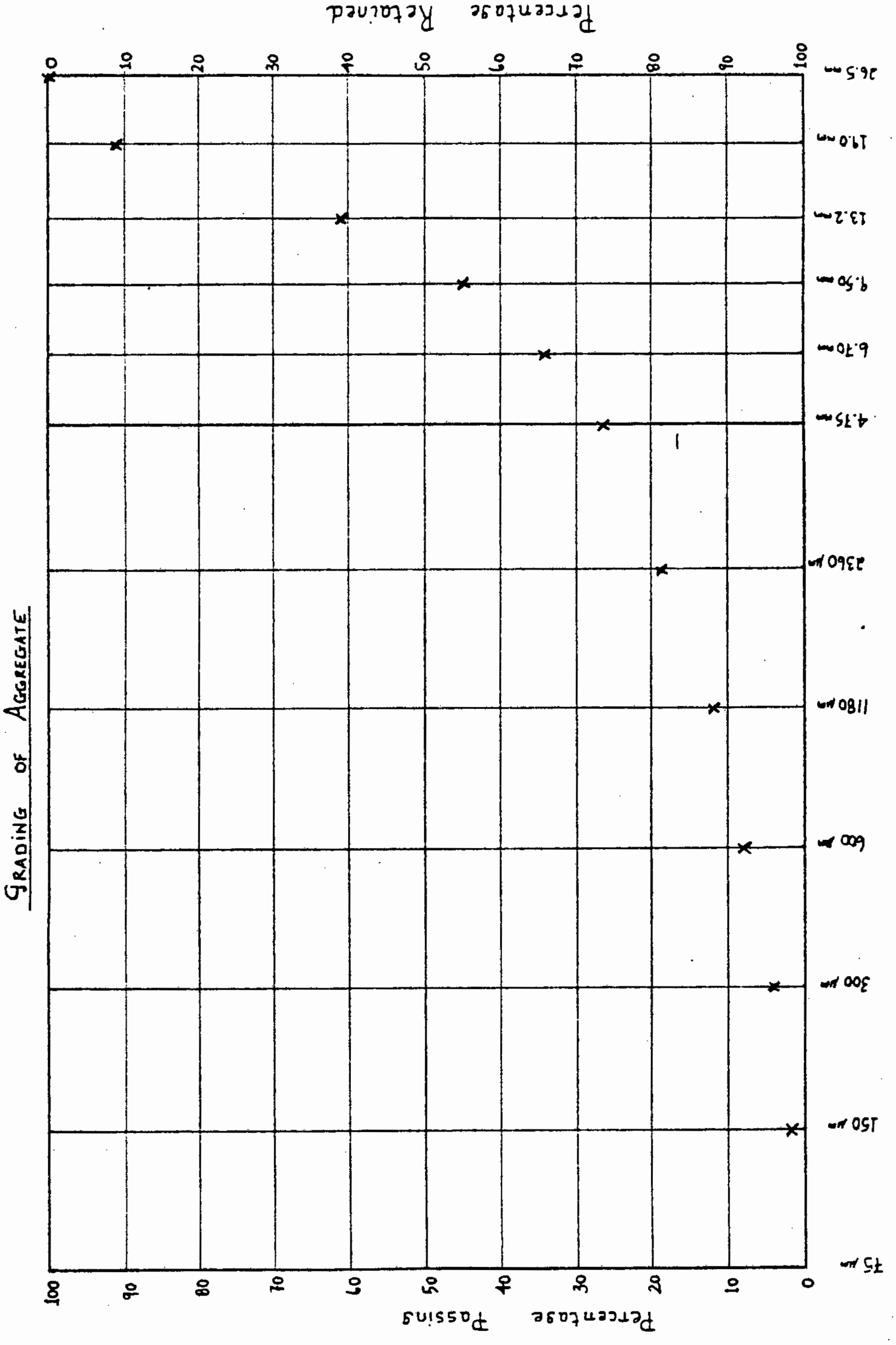
Flaky grey-black natural stone set in a brownish-grey mortar matrix which is visibly porous, but the concrete (or aggregate) seems to be fairly strong.

S.A.B.S. Sieve Size	Percentage of total mass %	Total percentage retained on sieve %	Total percentage passing sieve %
26.5 mm	0.0	0.0	100.0
19.0 mm	8.5	8.5	91.5
13.2 mm	30.9	39.4	60.6
9.5 mm	14.8	54.2	45.8
6.70 mm	11.3	65.5	34.5
4750 µm	7.1	72.6	27.4
2360 µm	8.1	80.7	19.3
1180 µm	6.7	87.4	12.6
600 µm	4.5	91.9	8.1
300 µm	3.7	95.6	4.4
150 µm	2.4	98.0	2.0
passing 150 µm	2.1	—	—
TOTALS	100.1	693.8	—

The "relative" fineness modulus of material = 6.93

The fineness modulus of the fine aggregate ≤ 4750 µm was found to be : 3.29

form # : CFBS - 007



Grading Curve of Sample # 5.

Sieve - Analysis of Crushed Rubble Samples.

Clayton Frick, U.C.T.

SAMPLE REF. NO.	# 6	Date of sieving :	Tue 20 Aug '85

Sieve Size mm	Gross Weight gr	Wt. of container on scale gr	Nett wt on sieve gr
26.5	550	221	329
19.0	2504	221	2283
13.2	3699	221	3478
9.5	1834	221	1613
6.70	1478	221	1257
4.75	1136	221	915
fines ≤ 4.75	3850	221	3629

Total mass : 13 504 gr

The fines below 4.75 mm will be sieved further down to 150 μm.

Grading particulars of the "coarse" aggregate i.e. ≥ 4.75 mm.

Sieve Size mm	Mass retained on sieve gr	% of total mass %	Total percentage retained on sieve %	Total percentage passing sieve %
26.5	329	—	0.0	100.0
19.0	2283	17.3	17.3	82.7
13.2	3478	26.4	43.7	56.3
9.5	1613	12.2	56.0	44.0
6.70	1257	9.5	65.5	34.5
4.75	915	6.9	72.5	27.~~8~~5
passing 4.75	3629	27.5	—	—
TOTALS	13 175	100.0	255.0	—

form # : CF85 : 001

Sieve Analysis of "Sand" derived from the Crushed Rubble.

Sample Ref. No. Fines of # 6

Date : Mon. 2 Sept 85

SABS sieve µm	Gross Weight gr	Wt. of container gr	Nett wt. on sieve gr
4750	212	212	0
2360	1379	212	1167
1180	1175	212	963
600	866	210	656
300	837	211	626
150	498	211	287
dust ≤ 150	527	211	316

Grading particulars of the "fine aggregate", i.e. ≤ 4.75 mm :

SABS sieve µm	Mass retained on sieve gr	% of total mass %	Total percentage retained on sieve %	Total percentage passing sieve %
4750	0	0.0	0.0	100.0
2360	1167	29.1	29.1	70.9
1180	963	24.0	53.1	46.9
600	656	16.3	69.4	30.6
300	626	15.6	85.0	15.0
150	287	7.1	92.1	7.9
passing 150	316	7.9	—	—
TOTALS	4015	100.0	328.7	—

Fineness Modulus of aggregate = 329 / 100 = 3.29

form # : CF85 - 003

Particle Size Analysis of Crushed Rubble Samples.

SAMPLE REFERENCE # : 6.

Demolished rubble aggregate collected from Milnerton dump.

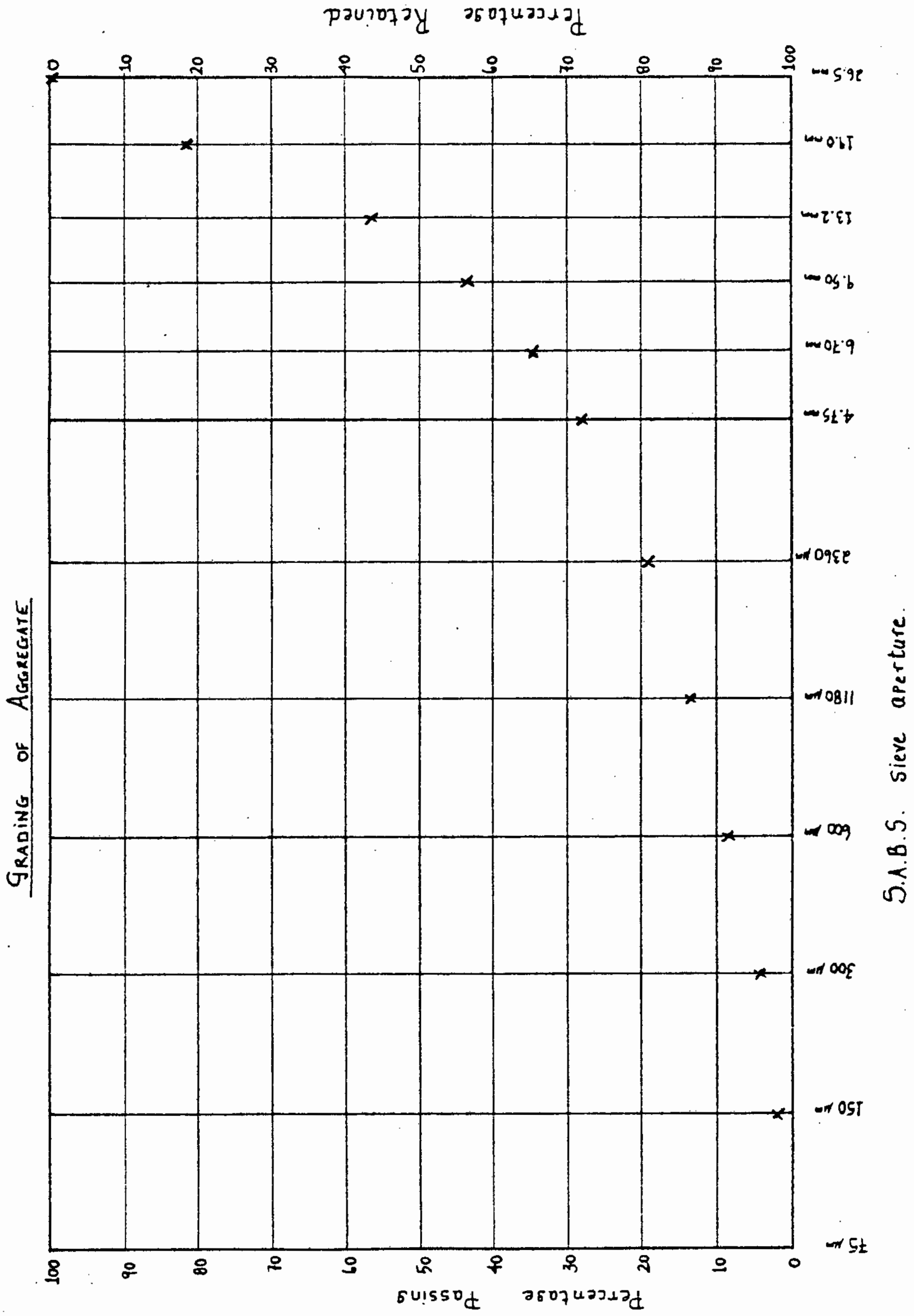
Brief Description of sample :

A weak looking sample : Mortar is porous and is a yellowish - white colour, the natural stone fractured in a brittle manner - it's colour is dark (blackish) and the maximum size previously must have been at least 2 inches (± 50 mm)

S.A.B.S. Sieve Size	Percentage of total mass %	Total percentage retained on sieve %	Total percentage passing sieve %
26.5 mm	0.0	0.0	100.0
19.0 mm	17.3	17.3	82.7
13.2 mm	26.4	43.7	56.3
9.5 mm	12.2	56.0	44.0
6.70 mm	9.5	65.5	34.5
4750 µm	6.9	72.4	27.6
2360 µm	8.0	80.4	19.6
1180 µm	6.6	87.0	13.0
600 µm	4.5	91.5	8.5
300 µm	4.3	95.8	4.2
150 µm	2.0	97.8	2.2
passing 150 µm	2.2	—	—
TOTALS	100.0	707.4	—

The "relative" fineness modulus of material = 7.07

The fineness modulus of the fine aggregate ≤ 4750 µm was found to be : 3.29



Form # : CFBS - 007

Grading curve of Sample # 6.

Sieve - Analysis of Crushed Rubble Samples.

Clayton Frick, U.C.T.

SAMPLE REF. NO.	# 8	Date of sieving :	Tue 20-08-85

Sieve Size mm	Gross weight gr	Wt. of container on scale gr	Nett wt on sieve gr
26.5	515	212	303
19.0	2487	212	2275
13.2	3879	212	3667
9.5	1948	212	1736
6.70	1645	212	1433
4.75	1241	212	1029
fines ≤ 4.75	4652	704	3948

Total mass : 14 391 gr

The fines below 4.75 mm will be sieved further down to 150 µm.

Grading particulars of the "coarse" aggregate i.e. ≥ 4.75 mm.

Sieve Size mm	Mass retained on sieve gr	% of total mass %	Total percentage retained on sieve %	Total percentage passing sieve %
26.5	303	——	0.0	100.0
19.0	2275	16.1	16.1	83.9
13.2	3667	26.0	42.1	57.9
9.5	1736	12.3	54.4	45.6
6.70	1433	10.2	64.6	35.4
4.75	1029	7.3	71.9	28.1
passing 4.75	3948	28.0	——	——
TOTALS	14088	100.0	249.1	——

form # : CF85 : 001

Sieve Analysis of "Sand" derived from the Crushed Rubble.

Sample Ref. No.	Fines of #8	**Date** : Tue 27 08 05

SABS sieve µm	Gross Weight gr	Wt. of container gr	Nett wt. on sieve gr
4750	212	212	0
2360	1314	212	1102
1180	950	212	738
600	717	211	506
300	851	210	641
150	541	211	330
dust ≤ 150	562	211	351

Grading particulars of the "fine aggregate", i.e. ≤ 4.75 mm:

SABS sieve µm	Mass retained on sieve gr	% of total mass %	Total percentage retained on sieve %	Total percentage passing sieve %
4750	0	0.0	0.0	100.0
2360	1102	30.0	30.0	70.0
1180	738	20.1	50.2	49.8
600	506	13.8	64.0	36.0
300	641	17.5	81.4	18.6
150	330	9.0	90.4	9.6
passing 150	351	9.6	—	—
TOTALS	3668	100.0	316.0	—

Fineness Modulus of aggregate = 316 / 100 = 3.16

Particle Size Analysis of Crushed Rubble Samples.

SAMPLE REFERENCE # : 8

Rubble collected from dump in Milnerton

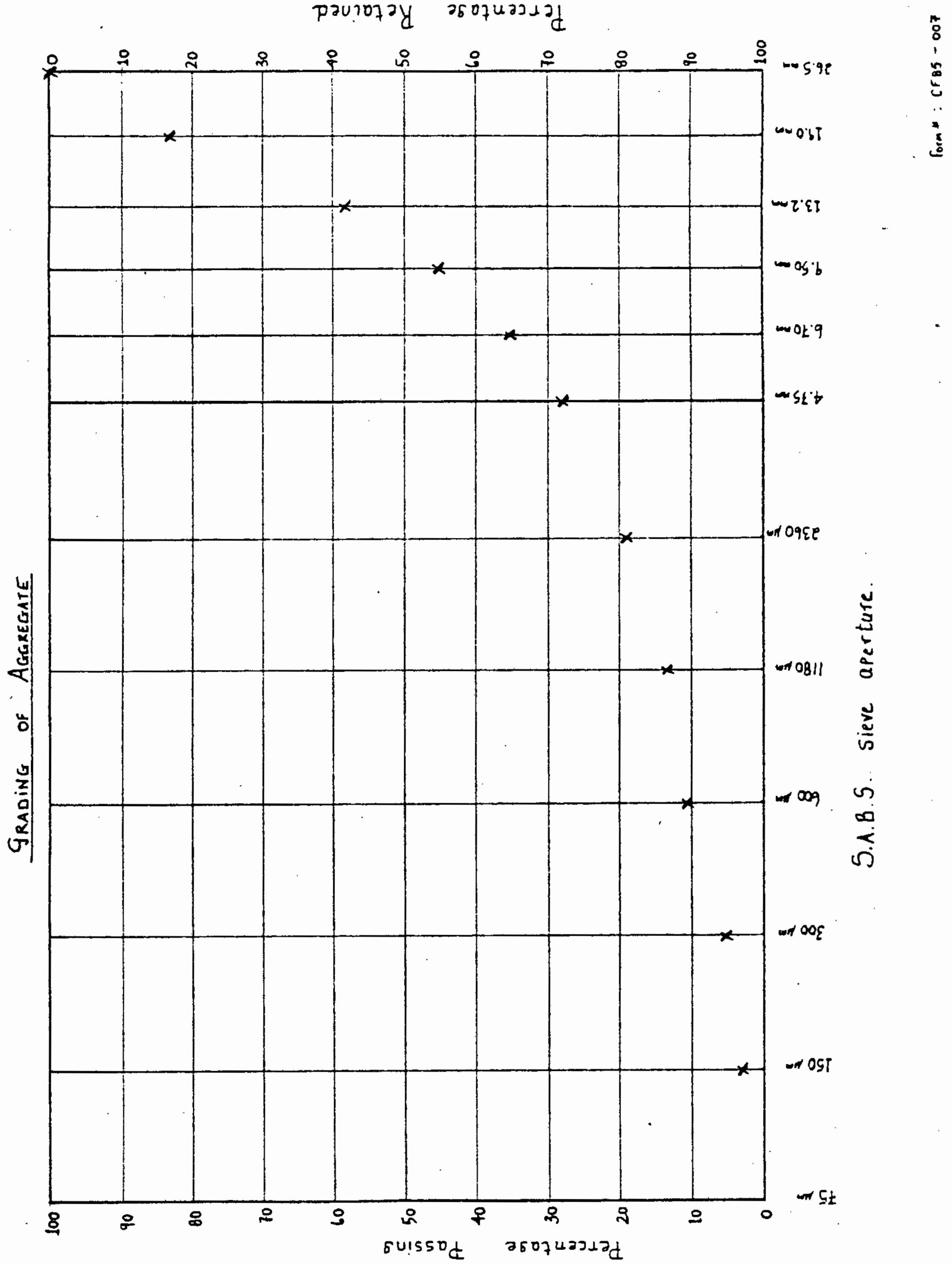
Brief Description of sample :

Angular coarse aggregate in a white, chalklike mortar matrix, not so porous. No contamination present. Max. previous aggregate size ≥ 26 mm.

S.A.B.S. Sieve Size	Percentage of total mass %	Total percentage retained on sieve %	Total percentage passing sieve %
26.5 mm	0.0	0.0	100.0
19.0 mm	16.1	16.1	83.9
13.2 mm	26.0	42.1	57.9
9.5 mm	12.3	54.4	45.6
6.70 mm	10.2	64.6	35.4
4750 µm	7.3	71.9	28.1
2360 µm	8.4	80.3	19.7
1180 µm	5.6	85.9	14.1
600 µm	3.9	89.8	10.2
300 µm	4.9	94.7	5.3
150 µm	2.5	97.2	2.8
passing 150 µm	2.7	—	—
TOTALS	99.4	697.0	—

The "relative" fineness modulus of material = 6.95

The fineness modulus of the fine aggregate ≤ 4750 µm was found to be : 3.16



Grading curve of Sample # 8.

Sieve - Analysis of Crushed Rubble Samples.

Clayton Frick , U.C.T.

SAMPLE REF. NO.	#9	Date of sieving :	Thu . 25 06 85

Sieve Size mm	Gross weight gr	Wt. of container on scale gr	Nett wt on sieve gr
26.5	211	211	0
19.0	945	211	734
13.2	4015	211	3804
9.5	3673	211	3462
6.70	2142	211	1931
4.75	1424	211	1213
fines ≤4.75	4169	121	4008

Total mass : 15 152 gr

The fines below 4.75mm will be sieved further down to 150 μm.

Grading particulars of the "coarse" aggregate i.e. ≥ 4.75 mm.

Sieve Size mm	Mass retained on sieve gr	% of total mass %	Total percentage retained on sieve %	Total percentage passing sieve %
26.5	0	0.0	0.0	100.0
19.0	734	4.8	4.8	95.2
13.2	3804	25.1	29.9	70.1
9.5	3462	22.8	52.8	47.2
6.70	1931	12.7	65.5	34.5
4.75	1213	8.0	73.5	26.5
passing 4.75	4008	26.5	—	—
TOTALS	15 152	100.0	226.5	—

form # : CF85 : 001

Sieve Analysis of "Sand" derived from the Crushed Rubble.

Sample Ref. No.	Fines of # 9.	**Date** : Mon 26 00 05

SABS sieve µm	Gross Weight gr	Wt. of container gr	Nett wt. on sieve gr
4750	211	211	0
2360	1520	212	1308
1180	997	212	785
600	675	210	465
300	776	211	565
150	499	213	286
dust ≤ 150	525	213	312

Grading particulars of the "fine aggregate", i.e. ≤ 4.75 mm:

SABS sieve µm	Mass retained on sieve gr	% of total mass %	Total percentage retained on sieve %	Total percentage passing sieve %
4750	0	0.0	0.0	100.0
2360	1308	35.2	35.2	64.8
1180	785	21.1	56.2	43.8
600	465	12.5	68.7	31.3
300	565	15.2	83.9	16.1
150	286	7.7	91.6	8.4
passing 150	312	8.4	—	—
TOTALS	3721	100.0	335.6	—

Fineness Modulus of aggregate = 336 / 100 = 3.36.

Particle Size Analysis of Crushed Rubble Samples.

SAMPLE REFERENCE # : 9

Demolished slabs made at U.C.T. labs in 1983.

Brief Description of sample :

Chunky aggregate pieces with near-equal amounts of rich grey mortar and the 13.2 mm maximum-size hornfels aggregate. Very little contamination although the thin wires of the reinforcement fixing still present.

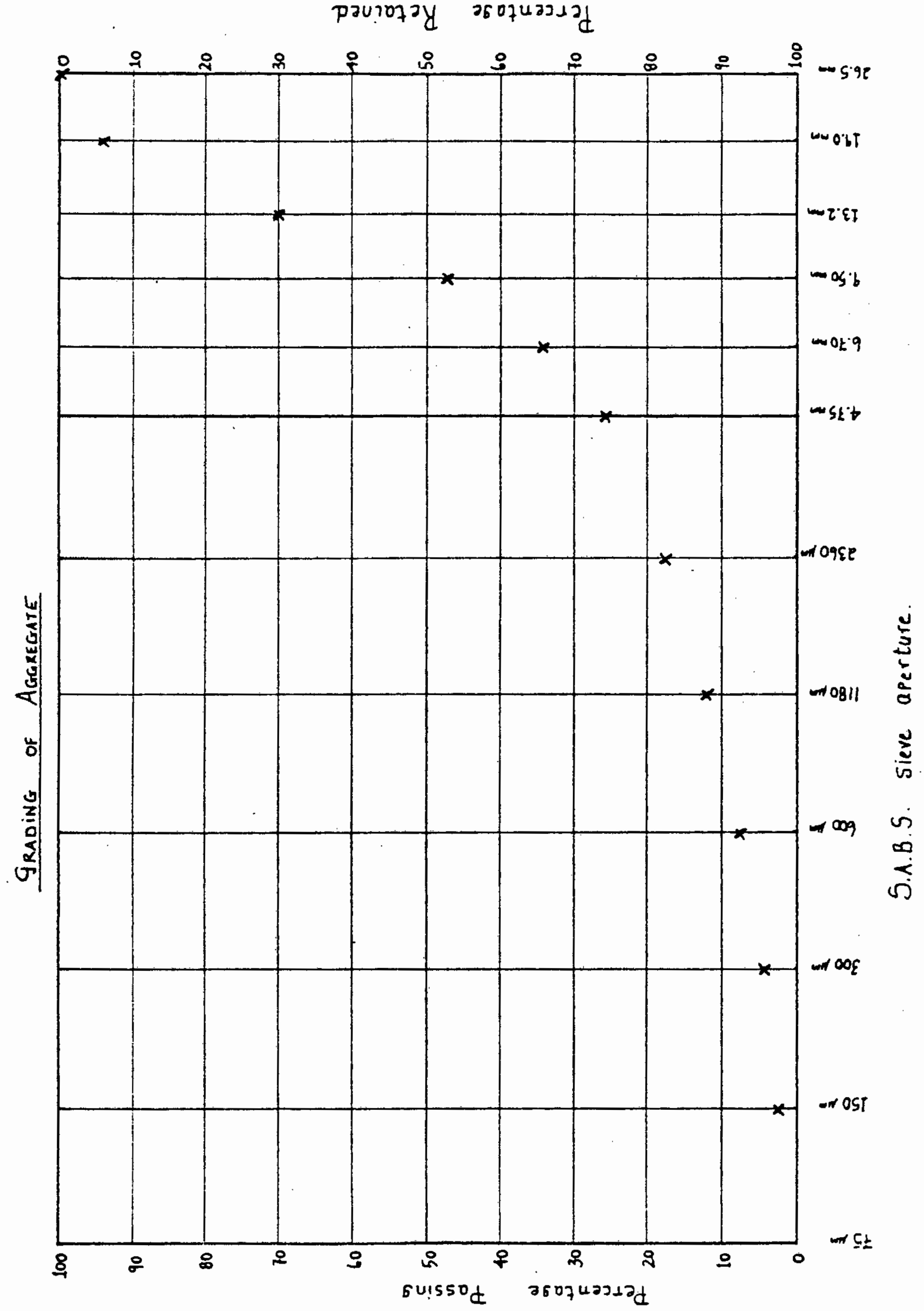
S.A.B.S. Sieve Size	Percentage of total mass %	Total percentage retained on sieve %	Total percentage passing sieve %
26.5 mm	0.0	0.0	100.0
19.0 mm	4.8	4.8	95.2
13.2 mm	25.1	29.9	70.1
9.5 mm	22.8	52.7	47.3
6.70 mm	12.7	65.4	34.6
4750 μm	8.0	73.4	26.6
2360 μm	9.3	82.7	17.3
1180 μm	5.6	88.3	11.7
600 μm	3.3	91.6	8.4
300 μm	4.0	95.6	4.4
150 μm	2.0	97.6	2.4
passing 150 μm	2.2	—	—
TOTALS	99.8	682.0	—

The "relative" fineness modulus of material = 6.83

The fineness modulus of the fine aggregate ≤ 4750 μm was found to be : 3.36

form # : CFB5 – 004

Form # : CFBS - 007



Grading curve of Sample # 9.

Sieve - Analysis of Crushed Rubble Samples.

Clayton Frick, U.C.T.

SAMPLE REF. NO.	# 10	Date of sieving :	Thurs 22-8-85

Sieve Size mm	Gross Weight gr	Wt. of container on scale gr	Nett wt on sieve gr
26.5	254	212	42
19.0	2364	212	2152
13.2	4842	212	4630
9.5	2287	212	2075
6.70	1830	212	1618
4.75	1430	212	1218
fines ≤ 4.75	4473	181	4292

Total mass : 16 027 gr

The fines below 4.75 mm will be sieved further down to 150 μm.

Grading particulars of the "coarse" aggregate i.e. ≥ 4.75 mm.

Sieve Size mm	Mass retained on sieve gr	% of total mass %	Total percentage retained on sieve %	Total percentage passing sieve %
26.5	~~42~~	—	0.0	100.0
19.0	2152	13.5	13.5	86.5
13.2	4630	29.0	42.4	57.6
9.5	2075	13.0	55.4	44.6
6.70	1618	10.1	65.5	34.5
4.75	1218	7.6	73.1	26.9
passing 4.75	4292	26.9	—	—
TOTALS	15 985	100.0	249.9	—

Sieve Analysis of "Sand" derived from the Crushed Rubble.

Sample Ref. No.	Fines of # 10.	**Date** : Mon. 26-08-85

SABS sieve µm	Gross Weight gr	Wt. of container gr	Nett wt. on sieve gr
4750	212	212	0
2360	1525	212	1313
1180	981	212	769
600	801	211	590
300	988	212	776
150	612	212	400
dust ≤ 150	582	213	369

Grading particulars of the "fine aggregate", i.e. ≤ 4.75 mm:

SABS sieve µm	Mass retained on sieve gr	% of total mass %	Total percentage retained on sieve %	Total percentage passing sieve %
4750	0	0	0	100
2360	1313	31.1	31.1	68.9
1180	769	18.2	49.3	50.7
600	590	14.0	63.4	36.6
300	776	18.4	81.8	18.2
150	400	9.5	91.2	8.8
passing 150	369	8.8	——	——
TOTALS	4217	100.0	316.8	——

Fineness Modulus of aggregate = 317 / 100 = 3.17

form # : CF85-003

Particle Size Analysis of Crushed Rubble Samples.

SAMPLE REFERENCE # : 10	Demolition rubble collected from Milnerton dump in 1984.

Brief Description of sample :

Flaky coarse aggregate pieces set in a light-coloured, very porous mortar matrix. Slightly contaminated with bitumen and brick. Orange oxide stains on the aggregate particles also visible. Max. previous stone size ≥ 26 mm.

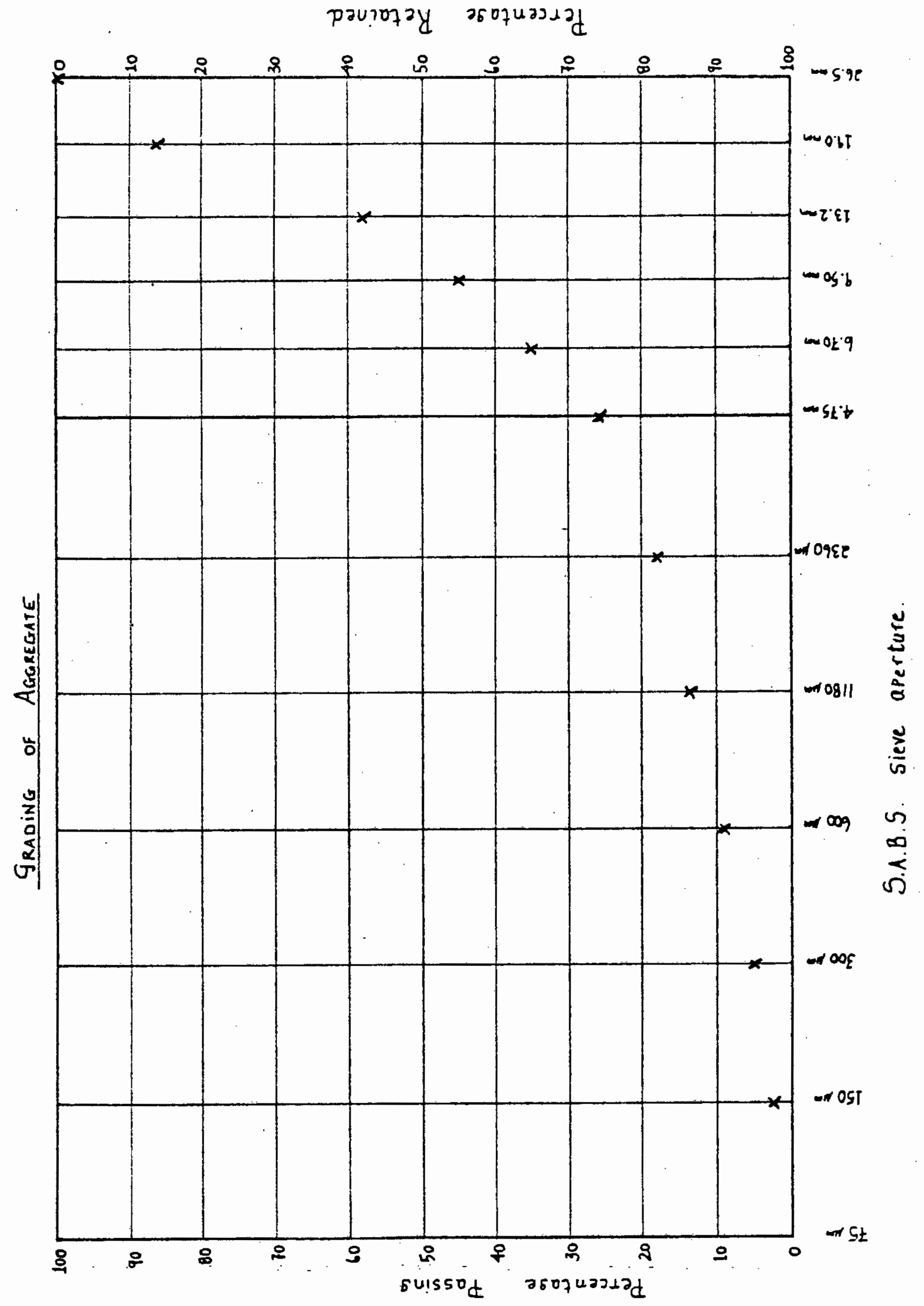
S.A.B.S. Sieve Size	Percentage of total mass %	Total percentage retained on sieve %	Total percentage passing sieve %
26.5 mm	0.0	0.0	0.0
19.0 mm	13.5	13.5	86.5
13.2 mm	29.0	42.5	57.5
9.5 mm	13.0	55.5	44.5
6.70 mm	10.1	65.6	34.4
4750 µm	7.6	73.2	26.8
2360 µm	8.4	81.6	18.4
1180 µm	4.9	86.5	13.5
600 µm	3.8	90.3	9.7
300 µm	4.9	95.2	4.8
150 µm	2.6	97.8	2.2
passing 150 µm	2.4	—	—
TOTALS	100.2	701.7	—

The "relative" fineness modulus of material = 7.00

The fineness modulus of the fine aggregate ≤ 4750 µm was found to be : 3.17

form # : CFBS - 004

Form # : CFBS - 007



Grading curve of Sample # 10.

Sieve - Analysis of Crushed Rubble Samples.

Clayton Frick, U.C.T.

SAMPLE REF. NO.	MIX DESIGN STOCKPILE.	Date of sieving :	05 - 12 - 85

Sieve Size mm	Gross weight gr	Wt. of container on scale gr	Nett wt on sieve gr
26.5			
19.0			
13.2			
9.5			
6.70			
4.75			
fines ≤ 4.75			

Sieved 4 samples and combined the overall results in this table.

Total mass :

The fines below 4.75 mm will be sieved further down to 150 μm.

Grading particulars of the "coarse" aggregate i.e. ≥ 4.75 mm.

Sieve Size mm	Mass retained on sieve gr	% of total mass %	Total percentage retained on sieve %	Total percentage passing sieve %
26.5	0	0.0	0.0	100.0
19.0	28 673	25.5	25.5	74.5
13.2	27 804	24.8	50.3	49.7
9.5	13 017	11.6	61.9	38.1
6.70	10 276	9.1	71.0	29.0
4.75	6 534	5.8	76.8	23.2
passing 4.75	26 015	23.2	—	—
TOTALS	112 319 gr	100.0	285.5	—

form # : CF85 : 001

Sieve Analysis of "Sand" derived from the Crushed Rubble.

Sample Ref. No. Mix Design sample

Date : 26-02-96

SABS sieve µm	Gross Weight gr	Wt. of container gr	Nett wt. on sieve gr
4750			
2360			
1180			
600			
300			
150			
dust ≤ 150			

Sieved 2 samples & combined results in this table.

Grading particulars of the "fine aggregate", i.e. ≤ 4.75 mm:

SABS sieve µm	Mass retained on sieve gr	% of total mass %	Total percentage retained on sieve %	Total percentage passing sieve %
4750	0	0.0	0.0	100.0
2360	3502	29.3	29.3	70.7
1180	2222	18.6	47.9	52.1
600	1801	15.1	63.0	37.0
300	2699	22.6	85.6	14.4
150	854	7.1	92.7	7.3
passing 150	883	7.4	—	—
TOTALS	11 961	100.1	318.5	—

Fineness Modulus of aggregate = 3.18

form # : CF85-003

Particle Size Analysis of Crushed Rubble Samples.

SAMPLE REFERENCE # : 11.

Mix Design Stockpile : collected from Milnerton - dump.

Brief Description of sample :

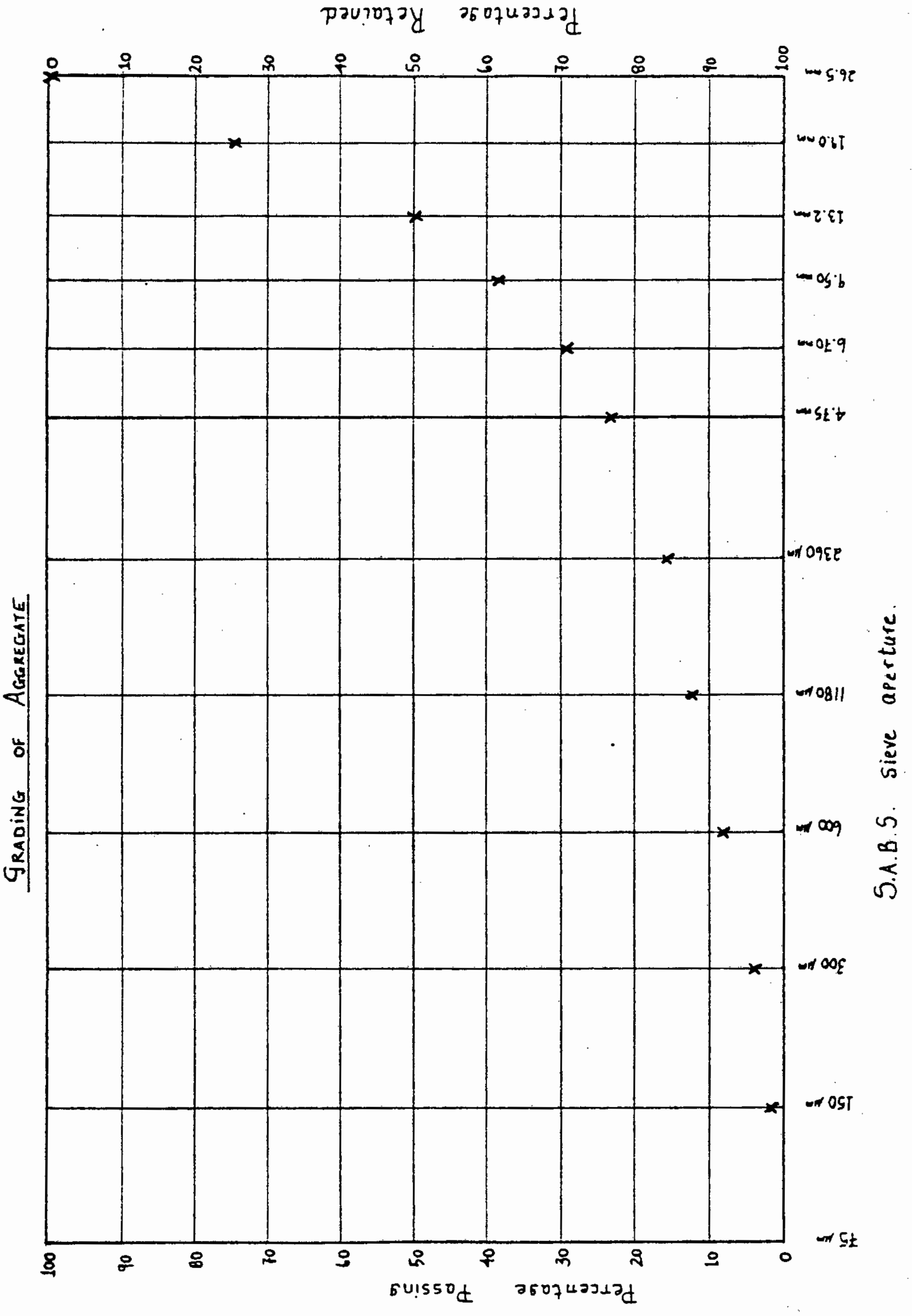
Rather similar to samples # 1 & 4 : a two inch hornfelsic aggregate set in a chalky looking whitish mortar matrix which is visibly quite porous. (Seems quite strong though.) The parent concrete was again quite old - at least 15-20 yrs.

S.A.B.S. Sieve Size	Percentage of total mass %	Total percentage retained on sieve %	Total percentage passing sieve %
26.5 mm	0.0	0.0	100.0
19.0 mm	25.5	25.5	74.5
13.2 mm	24.8	50.3	49.7
9.5 mm	11.6	61.9	38.1
6.70 mm	9.1	71.0	29.0
4750 µm	5.8	76.8	23.2
2360 µm	6.8	83.6	16.4
1180 µm	4.3	87.9	12.1
600 µm	3.5	91.4	8.6
300 µm	5.2	96.6	3.4
150 µm	1.6	98.2	1.8
passing 150 µm	1.7	—	—
TOTALS	100.0	743.2	—

The "relative" fineness modulus of material = 7.47

The fineness modulus of the fine aggregate ≤ 4750 µm was found to be : 3.18

Form # : CF85 - 007



Grading curve of the Mix-design-stockpile.

Sieve Analysis of "Sand" derived from the Crushed Rubble.

Sample Ref. No.	Laboratory Sand : "Pit sand" PS#1 Klipheuwel sand	**Date** : Thurs 29-08-85

SABS sieve µm	Gross Weight gr	Wt. of container gr	Nett wt. on sieve gr
4750	212	212	0
2360	222	212	10
1180	595	212	383
600	655	210	445
300	897	212	685
150	526	211	315
dust ≤ 150	531	211	320

Grading particulars of the "fine aggregate", i.e. ≤ 4.75 mm:

SABS sieve µm	Mass retained on sieve gr	% of total mass %	Total percentage retained on sieve %	Total percentage passing sieve %
4750	0	0.0	0.0	100.0
2360	10	0.5	0.5	99.5
1180	383	17.7	18.2	81.8
600	445	20.6	38.8	61.2
300	685	31.7	70.6	29.4
150	315	14.6	85.2	14.8
passing 150	320	14.8	—	—
TOTALS	2158	100.0	213.3	—

Fineness Modulus of aggregate = 213/100 = 2.13

form # : CF85-003

Sieve Analysis of "Sand" derived from the Crushed Rubble.

Sample Ref. No. Laboratory sand : "Pit sand" PS#2
Cape Flats Sand

Date : Fri 30 - 08 - 85

SABS sieve µm	Gross Weight gr	Wt. of container gr	Nett wt. on sieve gr
4750	212	212	0
2360	217	212	5
1180	232	212	20
600	674	210	464
300	1185	211	974
150	571	211	360
dust ≤ 150	275	211	64

This sand is used in the concrete laboratory at U.C.T.

Grading particulars of the "fine aggregate", i.e. ≤ 4.75 mm:

SABS sieve µm	Mass retained on sieve gr	% of total mass %	Total percentage retained on sieve %	Total percentage passing sieve %
4750	0	0.0	0.0	100.0
2360	5	0.3	0.3	99.7
1180	20	1.1	1.3	98.7
600	464	24.6	25.9	74.1
300	974	51.6	77.5	22.5
150	360	19.1	96.6	3.4
passing 150	64	3.4	—	—
TOTALS	1887	100.0	201.6	—

Fineness Modulus of aggregate = 202 / 100 = 2.02

form # : CF85 - 003

Sieve Analysis of "Sand" derived from the Crushed Rubble.

Sample Ref. No.	Laboratory sand : "Pit sand" PS#3 Cape Flats Sand.	Date : Mon 02-04 85

SABS sieve µm	Gross Weight gr	Wt. of container gr	Nett wt. on sieve gr
4750	212	212	0
2360	212	212	0
1180	232	212	20
600	683	210	473
300	1143	211	932
150	562	211	351
dust ≤ 150	269	211	58

Grading particulars of the "fine aggregate", i.e. ≤ 4.75 mm:

SABS sieve µm	Mass retained on sieve gr	% of total mass %	Total percentage retained on sieve %	Total percentage passing sieve %
4750	0	0.0	0.0	100.0
2360	0	0.0	0.0	100.0
1180	20	1.1	1.1	98.9
600	473	25.8	26.9	73.1
300	932	50.8	77.7	22.3
150	351	19.1	96.8	3.2
passing 150	58	3.2	—	—
TOTALS	1834	100.0	202.5	—

Fineness Modulus of aggregate = 203 / 100 = 2.02

APPENDIX A2

Initial Moisture Contents of the Recycled Aggregates

Determination of Moisture Content by oven-drying at 105°C.

SAMPLE REF. NO.	The fines of sample # 1		**Date** : Fri 25-02-05
	Container # 1	Container # 2.	
A. Mass of empty container initially container # 145	940 gr		
B. Mass of container and moist sample	5280 gr		
C. Mass of container and oven-dried sample.	4997 .gr		
* Check mass of empty container afterwards	940 gr		
* Approximate oven-drying period	66 hrs		
D. Mass of moist sample : B − A	4340 gr		
E. Mass of oven-dry sample : C − A	4057 gr		
F. Mass of moisture lost : D − E	283 gr		
Moisture Content expressed as a percentage of the oven-dry mass of sample $^{F}/_{E}$ * 100 % or $^{B-C}/_{C-A}$ * 100%	$^{283}/_{4057}$ × 100		6.98 % ± 0.02 %

Any further comments or information:

Brown grey powder, less brown than # 8, with grey mortar chips and grey aggregate chips

Also chips of brick seen.

Very dusty material too.

readings taken to 1 gram :: i.e. $^{1}/$ mass of sample * 100 = error % ± 0.02 %

form # : CF85-002.

Determination of Moisture Content by oven-drying at 105°C.

SAMPLE REF. NO. Fines of sample # 4

Date : Mon 21 02 05

	Container # 1	Container # 2.	
A. Mass of empty container initially Container # 141	910 gr		
B. Mass of container and moist sample	6307 gr		
C. Mass of container and oven-dried sample.	5966 gr		
* Check mass of empty container afterwords	910 gr		
* Approximate oven-drying period	48 hrs		
D. Mass of moist sample : B − A	5397 gr		
E. Mass of oven-dry sample : C − A	5056 gr		
F. Mass of moisture lost : D − E	341 gr		
Moisture content expressed as a percentage of the oven-dry mass of sample. $F/E * 100\ \%$ or $B-C / C-A * 100\%$	$341/5056$ $\times 100$		6.74 % ± 0.02 %

Any further comments or information:

form # : CF85-002.

Determination of Moisture Content by oven-drying at 105°C.

SAMPLE REF. NO.	Fines of sample # 5		Date : [illegible]
	Container # 1	**Container # 2.**	
A. Mass of empty container initially container # 134	849 gr		
B. Mass of container and moist sample	5419 gr		
C. Mass of container and oven-dried sample.	5203 gr		
* Check mass of empty container afterwards	849 gr		
* Approximate oven-drying period	48 hrs		
D. Mass of moist sample : B − A	4570 gr		
E. Mass of oven-dry sample : C − A	4354 gr		
F. Mass of moisture lost : D − E	216 gr		
Moisture content expressed as a percentage of the oven-dry mass of sample. $F/E * 100\%$ or $\frac{B-C}{C-A} * 100\%$	$216/4354$ $* 100$		4.96 % ± 0.02 %

Any further comments or information:

Readings taken to 1 gram => error % = $1/\text{mass} \times 100\ \%$ = $1/4354 \times 100$ = 0.02 %

form # : CFB5-002.

Determination of Moisture Content by Oven-drying at 105°C.

SAMPLE REF. NO.	Fines of Sample #6	**Date** : Wed 28 [illegible] 05

	Container # 1	Container # 2.	
A. Mass of empty container initially #141	905 gr		
B. Mass of container and moist sample	5139 gr		
C. Mass of container and oven-dried sample.	4910 gr		
* Check mass of empty container afterwards	903 gr		
* Approximate oven-drying period	44 hrs		
D. Mass of moist sample : B − A	4234 gr		
E. Mass of oven-dry sample : C − A	4007 gr		
F. Mass of moisture lost : D − E	227 gr		
Moisture Content expressed as a percentage of the oven-dry mass of sample. $F/E * 100\%$ or $\frac{B-C}{C-A} * 100\%$	$227/4007$ * 100%		5.67% ± 0 02%

Any further comments or information:

form # : CF85-002.

Determination of Moisture Content by Oven-drying at 105°C.

SAMPLE REF. NO.	The fines of sample # 8 (≤ 4.75 mm)		Date : Fri 23 oc 85
	Container # 1	Container # 2	
A. Mass of empty container initially container # 134	849 gr		
B. Mass of container and moist sample	4794 gr		
C. Mass of container and oven-dried sample.	4500 gr		
* Check mass of empty container afterwards	849 gr		
* Approximate oven-drying period	66 hrs		
D. Mass of moist sample : B − A	3945 gr		
E. Mass of oven-dry sample : C − A	3651 gr		
F. Mass of moisture lost : D − E	294 gr		
Moisture content expressed as a percentage of the oven-dry mass of sample. $F/E * 100\,\%$ or $B-C / C-A * 100\,\%$	$294 / 3651$ $* 100$		This sample was collected from the rubble dump in Milnerton in a fairly moist condition. It had been crushed and kept in airtight container for 3 weeks. So some moisture was lost. 8.05 % ± 0.03 %

Any further comments or information:

Brownish grey powder with equal amounts of mortar chips and original stone chips.

Very dusty material, more so than # 10 or # 9 was.

Readings taken to 1 gram => error % = 1 / mass × 100 = 0.03 %

form # : CF85-002.

Determination of Moisture Content by oven-drying at 105°C.

SAMPLE REF. NO.	The fines of sample # 9 (≤ 4.75 mm	Date : 5. II. 2005

	Container # 1	Container # 2	
A. Mass of empty container initially container = 141	910 gr		
B. Mass of container and moist sample	4916 gr		
C. Mass of container and oven- dried sample.	4764 gr		
* Check mass of empty container afterwards	910 gr		
* Approximate oven-drying period	66 hrs		
D. Mass of moist sample : B − A	4006 gr		
E. Mass of oven-dry sample : C − A	3854 gr		
F. Mass of moisture lost : D − E	152 gr		
Moisture Content expressed as a percentage of the oven-dry mass of sample. $F/E * 100\%$ or $B-C / C-A * 100\%$	$152 / 3854$ $* 100$		This sample was taken from the old laboratory slabs with painted surfaces and has been stockpiled in air for about 10 months. 3.94% ± 0.03%

Any further comments or information:

Material has rich grey colour. Powder + chips (mostly mortar chips) similar colour. No contaminated matter seen. White painted surfaces still seen.

The original mix design of this sample of crushed concrete is known - see undergraduate thesis.

Readings taken to 1 gram ⇒ error % = $1/\text{mass} * 100$ = 0.03 %

Form # : CF85-002.

Determination of Moisture Content by Oven-drying at 105°C.

SAMPLE REF. NO. The fines (≤ 4.75mm) of sample # 10

Date : Fr 13 Dec '85

	Container # 1	Container # 2.	
A. Mass of empty container initially container # 132	906 gr		
B. Mass of container and moist sample	5193 gr		
C. Mass of container and oven-dried sample.	5115. gr		
* Check mass of empty container afterwards	904 gr		
* Approximate oven-drying period	66 hrs		
D. Mass of moist sample : B − A	4288 gr		
E. Mass of oven-dry sample : C − A	4210 gr		
F. Mass of moisture lost : D − E	78 gr		
Moisture content expressed as a percentage of the oven-dry mass of sample. $\frac{F}{E}$ * 100 % or $\frac{B-C}{C-A}$ * 100 %	$\frac{78}{4210}$ * 100		This sample was taken from the lab of previously used rubble i.e. it has been air drying for about 4 months, hence the low initial moisture content. 1.85 % ± 0.02 %

Any further comments or information:

The colour of the material is whitish grey powder with (dark grey) black original coarse aggr. particles and grey mortar chips. More chips of mortar than original stone.

Some black carbon particles evident i.e. some combustible matter was burnt in oven.

Readings taken to 1 gram => error = 1/mass * 100 % = 1/4210 * 100 = 0.02 %

form # : CF85-002.

Determination of Moisture Content by Oven-drying at 105°C.

SAMPLE REF. NO.	Stockpile of aggregate for the Mix Design	Date : 04-12-85

	Container # 1	Container # 2	Container # 3	
A. Mass of empty container initially	210 gr	212 gr	212 gr	
B. Mass of container and moist sample	2254	2549	2557	
C. Mass of container and oven-dried sample.	2172	2457	2460	
* Check mass of empty container afterwards	✓	✓	✓	
* Approximate oven-drying period	24hrs	24hrs	24hrs	
D. Mass of moist sample : B − A	2044 gr	2337 gr	2345 gr	
E. Mass of oven-dry sample : C − A	1962	2245	2248	
F. Mass of moisture lost : D − E	82	92	97	
Moisture content expressed as a percentage of the oven-dry mass of sample.	4.18 %	4.10 %	4.31 %	The initial moisture content is therefore $\bar{x}$ = 4.20 %
$F/E * 100\%$ or $B-C / C-A * 100\%$	$82/1962$ * 100	$92/2245$ * 100	$97/2248$ * 100	± 0.05 %

Any further comments or information:

The material dried here was the "sand" or "fines" which was then used in a particle size analysis.

Readings taken to 1 gram ⇒ error = $1/\text{mass} * 100\ \%$ ÷ 0.05 %

Form # : CF85-002.

APPENDIX A3

1. BS812 specifications for Particle Shape Analysis

2. Flakiness and Elongation Indices; Angularity Numbers

DETERMINATION OF FLAKINESS INDEX

15. *a.* **General.** The flakiness index of an aggregate is the percentage by weight of particles in it whose least dimension (thickness) is less than three fifths of their mean dimension. The test is not applicable to material passing a ¼ in (6·35 mm) BS sieve.

b. **Apparatus.** (i) A metal thickness gauge of the pattern shown in Fig. 5 or special sieves having elongated slots. The width of the slot used in the gauge or sieve shall be the dimension specified in the 'thickness gauge' column of Table 9 for the appropriate fractions.

(ii) A balance accurate to 0·5 per cent of the weight of the test sample.

c. **Sample quantity.** A quantity of aggregate shall be taken sufficient to provide at least 200 pieces for each size fraction which constitutes more than 15 per cent of the sample, and at least 100 pieces for each size fraction which constitutes between 5 per cent and 15 per cent of the sample. Size fractions which constitute less than 5 per cent of the sample shall not be tested.

d. **Sieving.** The sample shall be separated into the appropriate size fractions from Table 9, Columns 1 and 2 by sieving in accordance with the method described in Clause 11.

e. **Separation of flaky material.** Each appropriate fraction shall be gauged in turn for thickness on the thickness gauge or in bulk on the special sieves.

f. **Weighing of flaky material.** The total amount passing the thickness gauge or special sieves shall be weighed to an accuracy of at least 0·5 per cent of the weight of the test sample.

g. **Reporting of results.** The flakiness index is the total weight of the material passing the various thickness gauges or special sieves, expressed as a percentage of the total weight of the sample gauged to the nearest whole number and shall be reported together with the sieve analysis. If required the weight of each fraction passing the thickness gauge or special sieve shall be reported as a percentage of the weight of the fraction.

DETERMINATION OF ELONGATION INDEX

16. *a.* **General.** The elongation index of an aggregate is the percentage by weight of particles whose greatest dimension (length) is greater than 1⅘ times their mean dimension. Normally, the properties of interest to the engineer are sufficiently covered by the flakiness or angularity tests. The elongation test is not applicable to material passing a ¼ in (6·35 mm) BS sieve.

b. **Apparatus.** (i) A metal length gauge of the pattern shown in Fig. 6. The gauge lengths shall be those specified in the 'length gauge' column of Table 9 for the appropriate fraction.

(ii) A balance accurate to 0·5 per cent of the weight of the test sample.

c. **Sample quantity.** A quantity of aggregate shall be taken sufficient to provide at least 200 pieces for each size fraction which constitutes more than 15 per cent of the sample, and at least 100 pieces for each size fraction which constitutes between 5 per cent and 15 per cent of the sample. Size fractions which constitute less than 5 per cent of the sample shall not be tested.

d. **Sieving.** The sample shall be separated into the appropriate size fractions from Table 9, Columns 1 and 2 by sieving in accordance with the method described in Clause 11.

e. **Separation of elongated material.** Each appropriate fraction shall be gauged in turn for length on the length gauge.

f. **Weighing of elongated material.** The total amount retained by the length gauge shall be weighed to an accuracy of at least 0·5 per cent of the weight of the test sample.

g. **Reporting of results.** The elongation index is the total weight of the material retained on the various length gauges, expressed as a percentage of the total weight of the sample gauged to the nearest whole number and shall be reported together with the sieve analysis. If required the weight of each fraction retained on the length gauge shall be reported as a percentage of the weight of the fraction.

TABLE 9. DIMENSIONS OF THICKNESS AND LENGTH GAUGES

Size of aggregate				Thickness gauge*		Length gauge†	
Passing BS sieve		Retained BS sieve					
in	mm	in	mm	in	mm	in	mm
2½	63·50	2	50·80	1·35 ± 0·01	34·3 ± 0·25	—	—
2	50·80	1½	38·10	1·05 ± 0·01	26·7 ± 0·25	3·15 ± 0·01	80·0
1½	38·10	1¼	31·75	0·825 ± 0·01	20·95 ± 0·25	2·475 ± 0·01	62·86
1¼	31·75	1	25·40	0·675 ± 0·005	17·15 ± 0·13	—	—
1	25·40	¾	19·05	0·525 ± 0·005	13·34 ± 0·13	1·57 ± 0·01	39·9
¾	19·05	½	12·70	0·375 ± 0·005	9·53 ± 0·13	1·12 ± 0·01	28·5
½	12·70	⅜	9·52	0·263 ± 0·001	6·68 ± 0·03	0·79 ± 0·01	20·1
⅜	9·52	¼	6·35	0·188 ± 0·001	4·78 ± 0·03	0·56 ± 0·01	14·2

* This dimension is equal to 0·6 times the mean sieve size.

† This dimension is equal to 1·8 times the mean sieve size.

DETERMINATION OF ANGULARITY NUMBER

17. *a.* **General.** Angularity, or absence of rounding of the particles of an aggregate is a property which is of importance because it affects the ease of handling of a mixture of aggregate and binder (e.g. the workability of concrete) or the stability of mixtures that rely on the interlocking of the particles. It is emphasized that this is a method intended for determining this property of an aggregate for mix design and research purposes.

The angularity number is a measure of relative angularity based on the percentage of voids in the aggregate after compaction in the prescribed manner. The least angular (most rounded) aggregates are found to have about 33 per cent voids and the angularity number is defined as the amount by which the percentage of voids exceeds 33. The angularity number ranges from 0 to about 12.

Since considerably more compactive effort is used than in the test for bulk density and voids (Clause 24), the results of the two tests are different. Also, weaker aggregates may be crushed during compaction, and the angularity number test does not apply to any aggregate which breaks down during the test.

b. **Apparatus.** (i) A metal cylinder closed at one end of about 1/10 ft^3 (3 litres) capacity, the diameter and height of which should be approximately equal (e.g. 6 in (15 cm) and 6 in (15 cm)).

The cylinder shall be made from metal of a thickness not less than 0·116 in (11 SWG; 3 mm) and shall be of sufficient rigidity to retain its shape under rough usage.

(ii) A straight metal tamping rod of circular cross-section ⅝ in (16 mm) in diameter and 24 in (60 cm) long rounded at one end.

(iii) A balance or scale of capacity 10 kg accurate to 1 g.

(iv) A metal scoop approximately 8 × 4½ × 2 in (20 × 12 × 5 cm) (i.e. about 1000 cm^3 heaped capacity).

c. **Calibration of the cylinder.** The cylinder shall be calibrated by determining to the nearest gramme the weight of water at 20°C required to fill it so that no meniscus is present above the rim of the container (weight *C*).

d. **Preparation of the test sample.** (i) The amount of aggregate available shall be sufficient to provide, after separation on the appropriate pair of sieves, at least 10 kg of the predominant size as determined by sieve analysis on the ¾ (19·05 mm), ½ (12·70 mm), ⅜ (9·52 mm), ¼ (6·35 mm) and 3/16 in (4·76 mm) BS test sieves. (The testing of sizes of aggregate outside this range is covered by the Note below.)

The test sample shall consist of aggregate retained between the appropriate pair of BS perforated-plate test sieves from the following list:

¾ in (19·05 mm) and ½ in (12·70 mm)
½ in (12·70 mm) and ⅜ in (9·52 mm)
⅜ in (9·52 mm) and ¼ in (6·35 mm)
¼ in (6·35 mm) and 3/16 in (4·76 mm)

NOTE. In testing aggregates larger than ¾ in (19·05 mm) the volume of the cylinder must be greater than 1/10 ft^3 (3 litres), but for aggregates smaller than 3/16 in (4·76 mm) a smaller cylinder may be used. The procedure shall be the same as with the 1/10 ft^3 (3 litres) cylinder, except that the amount of compactive effort (weight of tamping rod × height of fall × number of blows) shall be proportioned to the volume of the cylinder used.

(ii) The aggregate to be tested shall be dried for at least 24 hours in shallow trays in a well-ventilated oven at a temperature of 105 ± 5°C, cooled in an airtight container and tested.

e. **Test procedure.** The scoop shall be filled and heaped to overflowing with the aggregate, which shall be placed in the cylinder by allowing it to slide gently off the scoop from the least height possible.

The aggregate in the cylinder shall be subjected to 100 blows of the tamping rod at a rate of about two blows per second. Each blow shall be applied by holding the rod vertical with its rounded end 2 in above the surface of the aggregate and releasing it so that it falls freely. No force shall be applied to the rod. The 100 blows shall be evenly distributed over the surface of the aggregate.

The process of filling and tamping shall be repeated exactly as described above with a second and third layer of aggregate; the third layer shall contain just sufficient aggregate to fill the cylinder level with the top edge before tamping.

After the third layer of aggregate has been tamped the cylinder shall be filled to overflowing, and the aggregate struck off level with the top, using the tamping rod as a straight-edge.

Individual pieces of aggregate shall then be added and 'rolled in' to the surface by rolling the tamping rod across the upper edge of the cylinder, and this finishing process shall be continued as long as the aggregate does not lift the rod off the edge of the cylinder on either side. The aggregate shall not be pushed in or otherwise forced down, and no downward pressure shall be applied to the tamping rod, which shall roll in contact with the metal on both sides of the cylinder.

The aggregate in the cylinder shall then be weighed to the nearest 5 g.

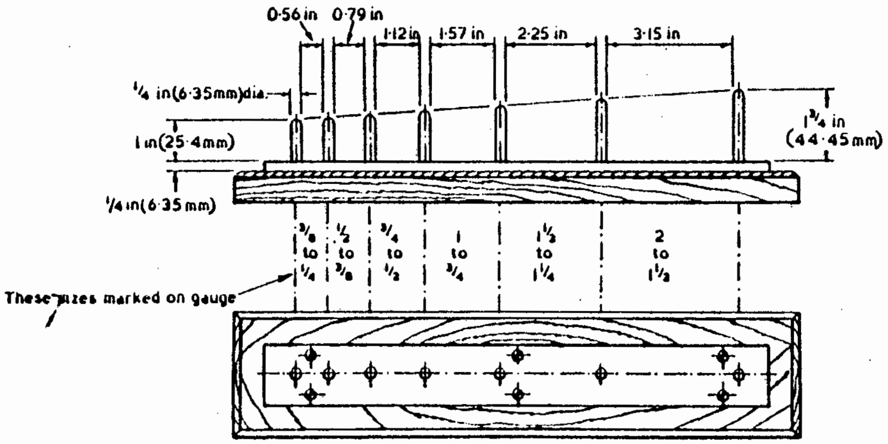
Three separate determinations shall be made, and the mean weight of aggregate in the cylinder calculated (weight *W*). If the result of any one determination differs from the mean by more than 25 g, three additional determinations shall immediately be made on the same material, and the mean of all six determinations calculated.

f. **Calculations.** The angularity number of the aggregate shall be calculated from the formula:

$$\text{Angularity number} = 67 - \frac{100W}{CG_A}$$

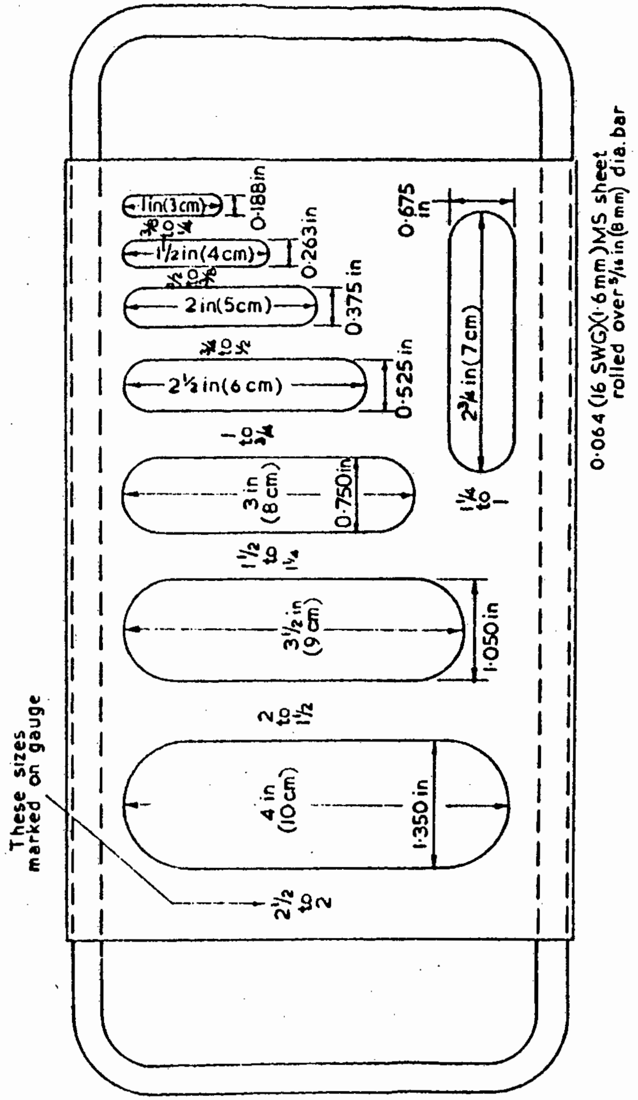
where W = mean weight (in grammes) of aggregate in the cylinder.
C = weight (in grammes) of water required to fill the cylinder.
G_A = specific gravity on an oven-dried basis of the aggregate determined in accordance with Section Four of this standard.

g. **Reporting of results.** The angularity number shall be reported to the nearest whole number.



NOTE. Metric equivalents of gauge lengths may be found in Table 9.

Fig. 6. Length gauge



NOTE. Metric equivalents of slot widths may be found in Table 9.

Fig. 5. Thickness gauge

PARTICLE SHAPE INDICATING TESTS : SAMPLE # : 1

1. Flakiness Index.

Size fraction		Mass retained	Mass passing	Total mass	Index
I	19.0 - 26.5 mm	1786 gr	204 gr	1990 gr	10
II	13.2 - 19.0 mm	1875	152	2027	7
III	9.5 - 13.2 mm	809	113	922	12
IV	6.7 - 9.5 mm	357	46	403	11
Sample total :		Σ :	515 gr	5342 gr	10

2. Elongation Index.

Size fraction		Mass Passing	Adjustment Factor †	Effective mass Passing	Total Mass	Index
I	19.0 - 26.5 mm	224 gr	1.004	225 gr	2000 gr	11
II	13.2 - 19.0 mm	163	0.903	147	956	15
III	9.5 - 13.2 mm	25	1.057	26	402	6
IV	6.7 - 9.5 mm	58	0.976	57	312	18
Sample total :			Σ :	455 gr	3670 gr	12

3. Angularity Number. *

Size fraction		Container Volume	Specific Gravity	Mass of Sample	Angularity Number
I	19.0 - 26.5 mm	1487 ml	2.30	1926 gr	10.7
II	13.2 - 19.0 mm	1487 ml	2.27	1977 gr	8.4
III	9.5 - 13.2 mm	1487 ml	2.00	1881 gr	3.8
IV	6.7 - 9.5 mm	1487 ml	1.96	not enough sample	—

* Angularity Number $= 67 - \dfrac{100 \cdot W}{C \cdot G_A}$

† Adjustment factor used to correct for small spacing errors in apparatus used.

PARTICLE SHAPE INDICATING TESTS : SAMPLE # : 4

1. Flakiness Index.

Size fraction		Mass retained	Mass passing	Total mass	Index
I	19.0 - 26.5 mm	3338 gr	372 gr	3710 gr	10
II	13.2 - 19.0 mm	1745	228	1973	12
III	9.5 - 13.2 mm	795	134	929	14
IV	6.7 - 9.5 mm	227	46	273	17
Sample total :		Σ :	780 gr	6885 gr	11

2. Elongation Index.

Size fraction		Mass Passing	Adjustment Factor †	Effective mass Passing	Total Mass	Index
I	19.0 - 26.5 mm	438 gr	0.993	435 gr	3698 gr	12
II	13.2 - 19.0 mm	269	0.947	255	1415	18
III	9.5 - 13.2 mm	93	1.049	98	611	16
IV	6.7 - 9.5 mm	72	0.986	71	349	20
Sample total :			Σ :	859 gr	6073 gr	14

3. Angularity Number. *

Size fraction		Container Volume	Specific Gravity	Mass of Sample	Angularity Number
I	19.0 - 26.5 mm	1487 ml	2.45	2107 gr	9.2
II	13.2 - 19.0 mm	1487 ml	2.27	2035	6.7
III	9.5 - 13.2 mm	1487 ml	1.95	1871	2.5
IV	6.7 - 9.5 mm	1487 ml	1.85	1781	2.3

* Angularity Number $= 67 - \frac{100 \cdot W}{C \cdot G_A}$

† Adjustment factor used to correct for small spacing errors in apparatus used.

PARTICLE SHAPE INDICATING TESTS : SAMPLE # : 5

1. Flakiness Index.

Size fraction		Mass retained	Mass passing	Total mass	Index
I	19.0 - 26.5 mm	1038 gr	85 gr	1123 gr	8
II	13.2 - 19.0 mm	1345	67	1412	5
III	9.5 - 13.2 mm	662	46	708	6
IV	6.7 - 9.5 mm	264	25	289	9
Sample total :		Σ:	223 gr	3532 gr	6

2. Elongation Index.

Size fraction		Mass Passing	Adjustment Factor †	Effective mass Passing	Total Mass	Index
I	19.0 - 26.5 mm	117 gr	0.993	116 gr	1122 gr	10
II	13.2 - 19.0 mm	124	0.947	117	1405	8
III	9.5 - 13.2 mm	42	1.049	44	710	6
IV	6.7 - 9.5 mm	44	0.986	43	289	15
Sample total :			Σ:	320 gr	3526 gr	9

3. Angularity Number. *

Size fraction		Container Volume	Specific Gravity	Mass of Sample	Angularity Number
I	19.0 - 26.5 mm	1487 ml	—	not enough sample	—
II	13.2 - 19.0 mm	1487 ml	2.27	2019 gr	7.2
III	9.5 - 13.2 mm	1487 ml	2.05	1934 gr	3.6
IV	6.7 - 9.5 mm	1487 ml	1.98	1900 gr	2.5

$$* \text{ Angularity Number} = 67 - \frac{100 \cdot W}{C \cdot G_A}$$

† Adjustment factor used to correct for small spacing errors in apparatus used.

PARTICLE SHAPE INDICATING TESTS : SAMPLE # : 6

1. Flakiness Index.

Size fraction		Mass retained	Mass passing	Total mass	Index
I	19.0 - 26.5 mm	1887 gr	297 gr	2184 gr	14
II	13.2 - 19.0 mm	818	108	926	12
III	9.5 - 13.2 mm	386	53	439	12
IV	6.7 - 9.5 mm	248	37	285	13
Sample total :		Σ:	495 gr	3834 gr	**13**

2. Elongation Index.

Size fraction		Mass Passing	Adjustment Factor †	Effective mass Passing	Total Mass	Index
I	19.0 - 26.5 mm	342 gr	0.993	340 gr	2184 gr	16
II	13.2 - 19.0 mm	158	0.947	150	926	16
III	9.5 - 13.2 mm	51	1.049	54	439	12
IV	6.7 - 9.5 mm	65	0.986	64	285	22
Sample total :			Σ:	608 gr	3834 gr	**16**

3. Angularity Number. *

Size fraction		Container Volume	Specific Gravity	Mass of Sample	Angularity Number
I	19.0 - 26.5 mm	1487 ml	2.46	2038 gr	11.3
II	13.2 - 19.0 mm	1487	2.24	1941	8.7
III	9.5 - 13.2 mm	1487	1.95	1859	2.9
IV	6.7 - 9.5 mm	1487	1.88	1803	2.5

$$* \text{ Angularity Number } = 67 - \frac{100 \cdot W}{C \cdot G_A}$$

† Adjustment factor used to correct for small spacing errors in apparatus used.

PARTICLE SHAPE INDICATING TESTS : SAMPLE # : 8

1. Flakiness Index.

Size fraction		Mass retained	Mass passing	Total mass	Index
I	19.0 - 26.5 mm	1815 gr	370 gr	2185 gr	17
II	13.2 - 19.0 mm	1000	101	1101	9
III	9.5 - 13.2 mm	307	75	382	20
IV	6.7 - 9.5 mm	218	47	265	18
Sample total :		Σ :	593 gr	3933 gr	**15**

2. Elongation Index.

Size fraction		Mass Passing	Adjustment Factor †	Effective mass Passing	Total Mass	Index
I	19.0 - 26.5 mm	455 gr	0.993	452 gr	2185 gr	21
II	13.2 - 19.0 mm	198	0.947	188	1101	17
III	9.5 - 13.2 mm	75	1.049	79	382	21
IV	6.7 - 9.5 mm	75	0.986	74	265	18
Sample total :			Σ :	793 gr	3933 gr	**20**

3. Angularity Number. *

Size fraction		Container Volume	Specific Gravity	Mass of Sample	Angularity Number
I	19.0 - 26.5 mm	1487 ml	2.47	2268 gr	5.3
II	13.2 - 19.0 mm	1487 ml	2.33	1991	9.5
III	9.5 - 13.2 mm	1487 ml	2.00	1937	1.9
IV	6.7 - 9.5 mm	1487 ml	1.92	1843	2.4

* Angularity Number $= 67 - \frac{100 \cdot W}{C \cdot G_A}$

† Adjustment factor used to correct for small spacing errors in apparatus used.

PARTICLE SHAPE INDICATING TESTS : SAMPLE # : 9

1. Flakiness Index.

Size fraction		Mass retained	Mass passing	Total mass	Index
I	19.0 - 26.5 mm	551 gr	29 gr	580 gr	5
II	13.2 - 19.0 mm	874 gr	60	934 gr	6
III	9.5 - 13.2 mm	640 gr	20	660	3
IV	6.7 - 9.5 mm	378 gr	18	396	5
Sample total :		Σ:	127 gr	2570 gr	5

2. Elongation Index.

Size fraction		Mass Passing	Adjustment Factor †	Effective mass Passing	Total Mass	Index
I	19.0 - 26.5 mm	39 gr	0.993	39 gr	580 gr	7
II	13.2 - 19.0 mm	102	0.947	97 gr	934	10
III	9.5 - 13.2 mm	20	1.049	21 gr	660	3
IV	6.7 - 9.5 mm	43	0.986	42 gr	396	11
Sample total :			Σ:	199 gr	2570 gr	8

3. Angularity Number. *

Size fraction		Container Volume	Specific Gravity	Mass of Sample	Angularity Number
I	19.0 - 26.5 mm	1487 ml	—	not enough sample	—
II	13.2 - 19.0 mm	1487	2.16	1882 gr	8.4
III	9.5 - 13.2 mm	1487	2.13	2014 gr	3.4
IV	6.7 - 9.5 mm	1487	2.09	1939 gr	4.6

$$* \text{ Angularity Number } = 67 - \frac{100 \cdot W}{C \cdot G_A}$$

† Adjustment factor used to correct for small spacing errors in apparatus used.

PARTICLE SHAPE INDICATING TESTS : SAMPLE # : 10

1. Flakiness Index.

Size fraction		Mass retained	Mass passing	Total mass	Index
I	19.0 - 26.5 mm	1766 gr	193 gr	1959 gr	10
II	13.2 - 19.0 mm	1114	94	1208	8
III	9.5 - 13.2 mm	666	52	718	7
IV	6.7 - 9.5 mm	282	17	299	6
Sample total :		Σ :	356 gr	4184	**9**

2. Elongation Index.

Size fraction		Mass Passing	Adjustment Factor †	Effective mass Passing	Total Mass	Index
I	19.0 - 26.5 mm	315 gr	0.993	313 gr	1959 gr	16
II	13.2 - 19.0 mm	191	0.947	181	1208	15
III	9.5 - 13.2 mm	52	1.049	55	718	8
IV	6.7 - 9.5 mm	44	0.986	43	299	14
Sample total :			Σ :	592 gr	4184	**14**

3. Angularity Number. *

Size fraction		Container Volume	Specific Gravity	Mass of Sample	Angularity Number
I	19.0 - 26.5 mm	1487 ml	2.40	2025 gr	10.3
II	13.2 - 19.0 mm	1487	2.34	2058	7.9
III	9.5 - 13.2 mm	1487	2.05	1954	2.9
IV	6.7 - 9.5 mm	1487	1.97	1828	4.5

* Angularity Number $= 67 - \frac{100 \cdot W}{C \cdot G_A}$

† Adjustment factor used to correct for small spacing errors in apparatus used.

PARTICLE SHAPE INDICATING TESTS : SAMPLE # : MIX DESIGN STOCKPILE

1. Flakiness Index.

Size fraction		Mass retained	Mass passing	Total mass	Index
I	19.0 - 26.5 mm	2023 gr	302 gr	2325 gr	13
II	13.2 - 19.0 mm	1238 gr	143 gr	1381 gr	10
III	9.5 - 13.2 mm	416 gr	86 gr	502 gr	17
IV	6.7 - 9.5 mm	256 gr	56 gr	312 gr	18
Sample total :		Σ:	587 gr	4520 gr	**13**

2. Elongation Index.

Size fraction		Mass Passing	Adjustment Factor †	Effective mass Passing	Total Mass	Index
I	19.0 - 26.5 mm	398 gr	0.993	395 gr	2325 gr	17
II	13.2 - 19.0 mm	234	0.947	222	1381	16
III	9.5 - 13.2 mm	91	1.049	95	502	19
IV	6.7 - 9.5 mm	73	0.986	72	312	23
Sample total :			Σ:	784 gr	4520 gr	**17**

3. Angularity Number. *

Size fraction		Container Volume	Specific Gravity	Mass of Sample	Angularity Number
I	19.0 - 26.5 mm	1487 ml	2.33	2061 gr	7.5
II	13.2 - 19.0 mm	1497 ml	2.21	2009	6.3
III	9.5 - 13.2 mm	1497 ml	2.04	2009	1.2
IV	6.7 - 9.5 mm	1487 ml	1.95	1935	0.3

$$* \text{ Angularity Number} = 67 - \frac{100 \cdot W}{C \cdot G_A}$$

† Adjustment factor used to correct for small spacing errors in apparatus used.

APPENDIX A4

Determination of the Specific Gravity, Absorption Coefficients, Densities, Void Content and Bulking of the recycled aggregates

TESTING FOR PHYSICAL PROPERTIES OF AGGREGATES.

Sample Ref. No. 1 : 19.0mm ≤ ∅ ≤ 26.0mm | Cylinder # 2 Volume V = 1487ml | Date : Mon 16-09-85

Readings taken :

A.	Mass of empty steel cylinder	gr	2638
B.	Mass of cylinder + oven dry stone	gr	4570
	POUR IN WATER AND LET SOAK FOR AT LEAST 24 HOURS.		
C.	Mass of cylinder + saturated stone + water	gr	5335
	EMPTY OUT WATER BY TURNING UPSIDE DOWN ON WIRE MESH.		
D.	Mass of cylinder + saturated stone (I)	gr	4699
	EMPTY OUT STONE, SURFACE DRY BRIEFLY + REFILL CYLINDER TO CHECK * BULKING.		
E.	Mass of cylinder + saturated stone (II)	gr	4681
	REFILL WITH WATER TO CHECK READING C.	gr	OK

Information gained : $\hat{D} = (D+E)/2 = 4690$ gr

F.	Mass of oven-dry aggregate in cylinder	: $B - A$	gr	1932
G.	Mass of water in the cylinder	: $C - B$	gr	765
H.	Mass of the saturated aggregate	: $\hat{D} - A$	gr	2052
I.	Mass of water absorbed by the aggregate	: $\hat{D} - B$.	gr	120
J.	Mass of the water emptied out	: $C - \hat{D}$	gr	645
K.	Absolute volume of saturated aggregate	: $(V - J) / 1\,gr/ml$	ml	842
L.	Absolute volume of oven-dry aggregate	: $(V - G) / 1\,gr/ml$	ml	722
M.	Total volume of voids : i.e. packing voids + pores	: $G / 1\,gr/ml$	ml	765

* Report on Bulking of Aggregate : None. 0%

Other Comments :

Calculation of Physical Properties using the info gained in the experiment.

SAMPLE REFERENCE : Sample # 1 : Coarse Aggregate : 19.0 m ≤ ∅ ≤ 26.0 mm

Calculations :

1. Dry bulk density (compacted) : $\frac{\text{mass of oven dry stone}}{\text{volume of cylinder}} = \frac{1932}{1487} = 1.299\ gr/ml$

2. Saturated bulk density (compacted) : $\frac{\text{mass of saturated stone}}{\text{volume of cylinder}} = \frac{2052}{1487} = 1.380\ gr/ml$

3. Absorption coefficient : $\frac{\text{mass of absorbed water}}{\text{oven dry mass of aggr.}} \times 100\% = \frac{120 \times 100}{1932} = 51.45\%$

4. Total voids percentage : $\frac{\text{total voids volume}}{\text{bulk volume}} \times 100\% = \frac{765 \times 100}{1487} = 6.21\%$

5. Porosity % of aggregate : $\frac{\text{vol of water poured in originally} - \text{vol. of water poured out}}{\text{absolute vol. of saturated aggregate}}$

$$= \frac{765 - 645}{842} \times 100\% = 14.25\%$$

6. Packing void percentage : $\frac{\text{volume of packing voids}}{\text{bulk volume of aggregate}} \times 100\%$

$$= \frac{645}{1487} \times 100\% = 43.38\%$$

7. (a) Absolute density with pores : $\frac{\text{mass of oven dry stone}}{\text{abs vol. of saturated stone}} = \frac{1932}{842} = 2.295\ gr/ml$

(b) Absolute density with no pores : $\frac{\text{mass of oven dry aggregate}}{\text{abs. vol. of dry aggregate}} = \frac{1932}{722} = 2.676\ gr/ml$

8. Specific gravity of material : 2.30 as porous material
2.68 as solid material

Comments : Compacted dry bulk mass ρ = 1299 kg/m³ ; dry bulk ρ = 12.75 kN/m³
" saturated " " ρ = 1380 kg/m³ ; sat. " ρ = 13.54 kN/m³
Absolute dry density ρ = 2295 kg/m³ ; absolute ρ = 22.51 kN/m³

TESTING FOR PHYSICAL PROPERTIES OF AGGREGATES.

Sample Ref. No. 1 : 13.2mm ≤ Ø ≤ 19.0mm	Cylinder # 1 Volume V = 1497 ml	Date : Tue 17-9-85

Readings taken :

A.	Mass of empty steel cylinder	gr	2677
B.	Mass of cylinder + oven dry stone	gr	4659
	POUR IN WATER AND LET SOAK FOR AT LEAST 24 HOURS.		
C.	Mass of cylinder + saturated stone + water	gr	5414
	EMPTY OUT WATER BY TURNING UPSIDE DOWN ON WIRE MESH.		
D.	Mass of cylinder + saturated stone (I)	gr	4804
	EMPTY OUT STONE, SURFACE DRY BRIEFLY + REFILL CYLINDER TO CHECK *BULKING.		
E.	Mass of cylinder + saturated stone (II)	gr	4780
	REFILL WITH WATER TO CHECK READING C.	gr	OK

Information gained : $\hat{D} = (D+E)/2 = 4792$ gr

F.	Mass of oven-dry aggregate in cylinder	: B − A	gr	1982
G.	Mass of water in the cylinder	: C − B	gr	755
H.	Mass of the saturated aggregate	: $\hat{D}$ − A	gr	2115
I.	Mass of water absorbed by the aggregate	: $\hat{D}$ − B.	gr	133
J.	Mass of the water emptied out	: C − D	gr	622
K.	Absolute volume of saturated aggregate	: (V − J) / 1 gr/ml	ml	875
L.	Absolute volume of oven-dry aggregate	: (V − G) / 1 gr/ml	ml	742
M.	Total volume of voids i.e. packing voids + pores	: G / 1 gr/ml	ml	755
*K	Report on Bulking of Aggregate	: None		0%

Other Comments :

Calculation of Physical Properties using the info gained in the experiment.

SAMPLE REFERENCE : Sample # 1 : Coarse Aggregate : 13.2mm ≤ Ø ≤ 19.0 mm

Calculations :

1. Dry bulk density (compacted) : $\frac{\text{mass of oven dry stone}}{\text{volume of cylinder}} = \frac{1982}{1497} = 1.324 \text{ gr/ml}$

2. Saturated bulk density (compacted) : $\frac{\text{mass of saturated stone}}{\text{volume of cylinder}} = \frac{2115}{1497} = 1.413 \text{ gr/ml}$

3. Absorption coefficient : $\frac{\text{mass of absorbed water}}{\text{oven dry mass of agr.}} \times 100\% = \frac{133 \times 100}{1982} = 6.71\%$

4. Total voids percentage : $\frac{\text{total voids volume}}{\text{bulk volume}} \times 100\% = \frac{755 \times 100}{1497} = 50.43\%$

5. Porosity % of aggregate : $\frac{\text{vol of water poured in originally} - \text{vol. of water poured out}}{\text{absolute vol. of saturated aggregate}}$

$$= \frac{755 - 622}{875} \times 100\% = 15.20\%$$

6. Packing void percentage : $\frac{\text{volume of packing voids}}{\text{bulk volume of aggregate}} \times 100\%$

$$= \frac{622}{1497} \times 100\% = 41.55\%$$

7. (a) Absolute density with pores : $\frac{\text{mass of oven dry stone}}{\text{abs vol. of saturated stone}} = \frac{1982}{875} = 2.265 \text{ gr/ml}$

   (b) Absolute density with no pores : $\frac{\text{mass of oven dry aggregate}}{\text{abs. vol. of dry aggregate}} = \frac{1982}{742} = 2.671 \text{ gr/ml}$

8. Specific gravity of material : 2.27 as porous matter
   2.67 as solid matter.

Comments :

compacted dry bulk densities = 1324 kg/m³ → 12.99 kN/m³

compacted saturated " " = 1413 kg/m³ → 13.86 kN/m³

absolute dry densities = 2265 kg/m³ → 22.22 kN/m³

TESTING FOR PHYSICAL PROPERTIES OF AGGREGATES.

Sample Ref. No. 1 : 4.75mm < 0 < 13.2mm	Cylinder # 1 Volume V : 1497	Date : Mon 11-9-85

Readings taken :

A.	Mass of empty steel cylinder	gr	2680
B.	Mass of cylinder + oven dry stone	gr	4599
	POUR IN WATER AND LET SOAK FOR AT LEAST 24 HOURS.		
C.	Mass of cylinder + saturated stone + water	gr	5326
	EMPTY OUT WATER BY TURNING UPSIDE DOWN ON WIRE MESH.		
D.	Mass of cylinder + saturated stone (I)	gr	4812
	EMPTY OUT STONE, SURFACE DRY BRIEFLY + REFILL CYLINDER TO CHECK *BULKING.		
E.	Mass of cylinder + saturated stone (II)	gr	4780
	REFILL WITH WATER TO CHECK READING C.	gr	OK

Information gained : $\hat{D} = (D+E)/2 = 4796$ gr

F.	Mass of oven-dry aggregate in cylinder	: B - A	gr	1919
G.	Mass of water in the cylinder	: C - B	gr	727
H.	Mass of the saturated aggregate	: $\hat{D}$ - A	gr	2116
I.	Mass of water absorbed by the aggregate	: $\hat{D}$ - B.	gr	197
J.	Mass of the water emptied out	: C - $\hat{D}$	gr	530
K.	Absolute volume of saturated aggregate	: (V - J) / 1 gr/ml	ml	967
L.	Absolute volume of oven-dry aggregate	: (V - G) / 1 gr/ml	ml	770
M.	Total volume of voids : ie packing voids + pores	: G / 1 gr/ml	ml	727

* Report on Bulking of Aggregate : Bulked slightly ~ 5mm ~ 1.5%

Other Comments :

Calculation of Physical Properties using the info gained in the experiment.

SAMPLE REFERENCE : Sample # 1 : Coarse Aggregate : 4.75mm < 0 < 13.2mm

Calculations :

1. Dry bulk density (compacted) : $\frac{\text{mass of oven dry stone}}{\text{volume of cylinder}} = \frac{1919 \text{ gr}}{1497 \text{ ml}} = 1.282 \text{ gr/ml}$

2. Saturated bulk density (compacted) : $\frac{\text{mass of saturated stone}}{\text{volume of cylinder}} = \frac{2116 \text{ gr}}{1497 \text{ ml}} = 1.413 \text{ gr/ml}$

3. Absorption coefficient : $\frac{\text{mass of absorbed water}}{\text{oven dry mass of agg.}} \times 100\% = \frac{197 \times 100}{1919} = 10.27\%$

4. Total voids percentage : $\frac{\text{total voids volume}}{\text{bulk volume}} \times 100\% = \frac{727 \times 100}{1497} = 48.56\%$

5. Porosity % of aggregate : $\frac{\text{vol of water poured in originally} - \text{vol. of water poured out}}{\text{absolute vol. of saturated aggregate}}$

$$= \frac{727 - 530}{967} \times 100\% = 20.37\%$$

6. Packing void percentage : $\frac{\text{volume of packing voids}}{\text{bulk volume of aggregate}} \times 100\%$

$$= \frac{530}{1497} \times 100\% = 35.40\%$$

7. (a) Absolute density with pores (i.e = original concrete density.) : $\frac{\text{mass of oven dry stone}}{\text{abs vol. of saturated stone}} = \frac{1919}{967} = 1.984 \text{ gr/ml}$

   (b) Absolute density with no pores : $\frac{\text{mass of oven dry aggregate}}{\text{abs. vol. of dry aggregate}} = \frac{1919}{770} = 2.492 \text{ gr/ml}$

8. Specific gravity of material : 1.98 as porous material
   2.49 as solid material.

Comments :

Compacted dry bulk mass ρ	=	1282 kg/m³	;	dry bulk ρ	=	12.58 kN/m³
Compacted saturated " " ρ	=	1413 kg/m³	;	saturated bulk ρ	=	13.87 kN/m³
Absolute mass density	=	1984 kg/m³	;	absolute ρ	=	19.47 kN/m³

TESTING FOR PHYSICAL PROPERTIES OF AGGREGATES.

Sample Ref. No. 4. 19 → 26 mm	Cylinder # 1 Volume V = 1497 ml	Date : 19/9/85

Readings taken :

A.	Mass of empty steel cylinder	gr	2678
B.	Mass of cylinder + oven dry stone	gr	4770
	POUR IN WATER AND LET SOAK FOR AT LEAST 24 HOURS.		
C.	Mass of cylinder + saturated stone + water	gr	5486
	EMPTY OUT WATER BY TURNING UPSIDE DOWN ON WIRE MESH.		
D.	Mass of cylinder + saturated stone (I)	gr	4851
	EMPTY OUT STONE, SURFACE DRY BRIEFLY + REFILL CYLINDER TO CHECK BULKING.		/
E.	Mass of cylinder + saturated stone (II)	gr	4833
	REFILL WITH WATER TO CHECK READING C.	gr	OK

Information gained : $\bar{D} = (D + E)/2 = 4842$ gr

F.	Mass of oven-dry aggregate in cylinder	: B − A	gr	2092
G.	Mass of water in the cylinder	: C − B	gr	716
H.	Mass of the saturated aggregate	: $\bar{D}$ − A	gr	2164
I.	Mass of water absorbed by the aggregate	: $\bar{D}$ − B	gr	72
J.	Mass of the water emptied out	: C − $\bar{D}$	gr	644
K.	Absolute volume of saturated aggregate	: (V − J) / 1 gr/ml	ml	853
L.	Absolute volume of oven-dry aggregate	: (V − G) / 1 gr/ml	ml	781
M.	Total volume of voids : i.e. packing voids + pores	: G / 1 gr/ml	ml	716

* Report on Bulking of Aggregate : None ~ 0%

Other Comments :

Calculation of Physical Properties using the info gained in the experiment.

SAMPLE REFERENCE : Sample # 4 : Coarse Aggregate : 19.0 ≤ D ≤ 26.5 mm

Calculations :

1. Dry bulk density (compacted) : $\dfrac{\text{mass of oven dry stone}}{\text{volume of cylinder}} = \dfrac{2092}{1497} = 1.397$ gr/ml

2. Saturated bulk density (compacted) : $\dfrac{\text{mass of saturated stone}}{\text{volume of cylinder}} = \dfrac{2164}{1497} = 1.446$ gr/ml

3. Absorption coefficient : $\dfrac{\text{mass of absorbed water}}{\text{oven dry mass of agr.}} \times 100\% = \dfrac{72 \times 100}{2092} = 3.44\%$

4. Total voids percentage : $\dfrac{\text{total voids volume}}{\text{bulk volume}} \times 100\% = \dfrac{716 \times 100}{1497} = 47.83\%$

5. Porosity % of aggregate : $\dfrac{\text{vol of water poured in originally} - \text{vol of water poured out}}{\text{absolute vol. of saturated aggregate}}$

   $= \dfrac{716 - 644}{853} \times 100\% = 8.44\%$

6. Packing void percentage : $\dfrac{\text{volume of packing voids}}{\text{bulk volume of aggregate}} \times 100\%$

   $= \dfrac{644}{1497} \times 100\% = 43.02\%$

7. (a) Absolute density with pores : $\dfrac{\text{mass of oven dry stone}}{\text{abs vol. of saturated stone}} = \dfrac{2092}{853} = 2.453$ gr/ml

   (b) Absolute density with no pores : $\dfrac{\text{mass of oven dry aggregate}}{\text{abs. vol. of dry aggregate}} = \dfrac{2092}{781} = 2.679$ gr/ml

8. Specific gravity of material : 2.45 as porous material
   2.68 as solid material

Comments :

Compacted dry bulk density	=	1397 kg/m³	→	13.71 kN/m³
Compacted saturated " "	=	1446 kg/m³	→	14.18 kN/m³
Absolute density (at pores)	=	2453 kg/m³	→	24.06 kN/m³

TESTING FOR PHYSICAL PROPERTIES OF AGGREGATES.

Sample Ref. No. 4 : 13.2mm ≤ D ≤ 19.0mm	Cylinder # 2 Volume V = 1487 ml	Date : Tue 17.9.85

Readings taken :

A.	Mass of empty steel cylinder	gr	2637
B.	Mass of cylinder + oven dry stone	gr	4653
	POUR IN WATER AND LET SOAK FOR AT LEAST 24 HOURS.		
C.	Mass of cylinder + saturated stone + water	gr	5374
	EMPTY OUT WATER BY TURNING UPSIDE DOWN ON WIRE MESH.		
D.	Mass of cylinder + saturated stone (I)	gr	4792
	EMPTY OUT STONE, SURFACE DRY BRIEFLY + REFILL CYLINDER TO CHECK *BULKING.		
E.	Mass of cylinder + saturated stone (II)	gr	4763
	REFILL WITH WATER TO CHECK READING C.	gr	OK

Information gained : $\bar{D} = (D+E)/2 = 4777$ gr.

F.	Mass of oven-dry aggregate in cylinder	: B − A	gr	2016
G.	Mass of water in the cylinder	: C − B	gr	721
H.	Mass of the saturated aggregate	: $\bar{D}$ − A	gr	2140
I.	Mass of water absorbed by the aggregate	: $\bar{D}$ − B	gr	124
J.	Mass of the water emptied out	: C − $\bar{D}$	gr	597
K.	Absolute volume of saturated aggregate	: (V − J) / 1 gr/ml	ml	890
L.	Absolute volume of oven-dry aggregate	: (V − G) / 1 gr/ml	ml	766
M.	Total volume of voids : ie packing voids + pores	: G / 1 gr/ml	ml	721

* Report on Bulking of Aggregate : Small % : ~ 3mm — 1%

Other Comments : Contains small % of red brick particles ~ 0.5%.

Form # : ICP85 – 005

Calculation of Physical Properties using the info gained in the experiment.

SAMPLE REFERENCE : Sample # 4 : Coarse Aggregate : 13.2 mm ≤ D ≤ 19.0 mm

Calculations :

1. Dry bulk density (compacted) : $\frac{\text{mass of oven dry stone}}{\text{volume of cylinder}} = \frac{2016}{1487} = 1.356$ gr/ml

2. Saturated bulk density (compacted) : $\frac{\text{mass of saturated stone}}{\text{volume of cylinder}} = \frac{2140}{1487} = 1.439$ gr/ml

3. Absorption coefficient : $\frac{\text{mass of absorbed water}}{\text{oven dry mass of aggr.}} \times 100\% = \frac{124 \times 100}{2016} = 6.15\%$

4. Total voids percentage : $\frac{\text{total voids volume}}{\text{bulk volume}} \times 100\% = \frac{721 \times 100}{1487} = 48.49\%$

5. Porosity % of aggregate : $\frac{\text{vol of water poured in originally} - \text{vol. of water poured out}}{\text{absolute vol. of saturated aggregate}}$

$$= \frac{721 - 597}{890} \times 100\% = 13.93\%$$

6. Packing void percentage : $\frac{\text{volume of packing voids}}{\text{bulk volume of aggregate}} \times 100\%$

$$= \frac{597}{1487} \times 100\% = 40.15\%$$

7. (a) Absolute density with pores : $\frac{\text{mass of oven dry stone}}{\text{abs vol. of saturated stone}} = \frac{2016}{890} = 2.265$ gr/ml

(b) Absolute density with no pores : $\frac{\text{mass of oven dry aggregate}}{\text{abs. vol. of dry aggregate}} = \frac{2016}{766} = 2.632$ gr/ml

8. Specific gravity of material : 2.27 as porous material
2.63 as solid material

Comments :

Compacted dry bulk density	= 1356 kg/m³	→	13.30 kN/m³
" Saturated " "	= 1439 kg/m³	→	14.12 kN/m³
Absolute dry density	= 2265 kg/m³	→	22.22 kN/m³

Form # : ICP85 – 006

TESTING FOR PHYSICAL PROPERTIES OF AGGREGATES.

Sample Ref. No. 4 : 4.75mm → 13.2mm | Cylinder # 2. Volume V = 1487 ml | Date : Th 17·1·85

Readings taken:

A.	Mass of empty steel cylinder	gr	2638
B.	Mass of cylinder + oven dry stone	gr	4545
	POUR IN WATER AND LET SOAK FOR AT LEAST 24 HOURS.		
C.	Mass of cylinder + saturated stone + water	gr	5235
	EMPTY OUT WATER BY TURNING UPSIDE DOWN ON WIRE MESH.		
D.	Mass of cylinder + saturated stone (I)	gr	4770
	EMPTY OUT STONE, SURFACE DRY BRIEFLY & REFILL CYLINDER TO CHECK BULKING.		
E.	Mass of cylinder + saturated stone (II)	gr	4744
	REFILL WITH WATER TO CHECK READING C.	gr	OK

Information gained: $\dot{D} = (D+E)/2 = 4757$ gr

F.	Mass of oven-dry aggregate in cylinder	: B − A	gr	1907
G.	Mass of water in the cylinder	: C − D	gr	690
H.	Mass of the saturated aggregate	: $\dot{D}$ − A	gr	2119
I.	Mass of water absorbed by the aggregate	: $\dot{D}$ − B	gr	212
J.	Mass of the water emptied out	: C − D	gr	478
K.	Absolute volume of saturated aggregate	: (V − J) / 1 gr/ml	ml	1009
L.	Absolute volume of oven-dry aggregate	: (V − G) / 1 gr/ml	ml	797
M.	Total volume of voids : ie. packing voids + pores	: G / 1 gr/ml	ml	690

* Report on Bulking of Aggregate : = 25mm bulking ⇒ 8.3%

Other Comments : Contains brick particles 25/0.3 = 7.5%

Calculation of Physical Properties using the info gained in the experiment.

SAMPLE REFERENCE : Sample # 4 : Coarse aggregate : 4.75mm ≤ ⌀ ≤ 13.2 mm

Calculations :

1. Dry bulk density (compacted) : $\frac{\text{mass of oven dry stone}}{\text{volume of cylinder}} = \frac{1907}{1487} = 1.282 \text{ g/ml}$

2. Saturated bulk density (compacted) : $\frac{\text{mass of saturated stone}}{\text{volume of cylinder}} = \frac{2119}{1487} = 1.425 \text{ g/ml}$

3. Absorption coefficient : $\frac{\text{mass of absorbed water}}{\text{oven dry mass of aggr.}} \times 100\% = \frac{212 \times 100}{1907} = 11.12\%$

4. Total voids percentage : $\frac{\text{total voids volume}}{\text{bulk volume}} \times 100\% = \frac{690 \times 100}{1487} = 46.40\%$

5. Porosity % of aggregate : $\frac{\text{vol. of water poured in originally} - \text{vol. of water poured out}}{\text{absolute vol. of saturated aggregate}}$

   $= \frac{690 - 478}{1009} \times 100\% = 21.01\%$

6. Packing void percentage : $\frac{\text{volume of packing voids}}{\text{bulk volume of aggregate}} \times 100\%$

   $= \frac{478}{1487} \times 100\% = 32.15\%$

7. (a) Absolute density with pores : $\frac{\text{mass of oven dry stone}}{\text{abs vol. of saturated stone}} = \frac{1907}{1009} = 1.890 \text{ g/ml}$

   (b) Absolute density with no pores : $\frac{\text{mass of oven dry aggregate}}{\text{abs. vol. of dry aggregate}} = \frac{1907}{797} = 2.393 \text{ g/ml}$

8. Specific gravity of material : 1.89 as porous material
   2.39 as solid material

Comments :

Compacted dry bulk density	=	1282 kg/m³	→	12.58 kN/m³
Compacted saturated bulk density	=	1425 kg/m³	→	13.98 kN/m³
Absolute density (as porous)	=	1890 kg/m³	→	18.54 kN/m³

Form # : CF85 − 006

TESTING FOR PHYSICAL PROPERTIES OF AGGREGATES.

Sample Ref. No. 5 : 19 – 26.5 mm	Cylinder # 2 Volume V = 1487 ml	Date : Th. 26-01-85

Readings taken :

A. Mass of empty steel cylinder	gr	2633
B. Mass of cylinder + oven dry stone	gr	3888
POUR IN WATER AND LET SOAK FOR AT LEAST 24 HOURS.		
C. Mass of cylinder + saturated stone + water 4892 − 480 = 4412	gr	4892
✱ See reverse for calculations EMPTY OUT WATER BY TURNING UPSIDE DOWN ON WIRE MESH.	adjust this mass by subtracting mass of water above stone.	
D. Mass of cylinder + saturated stone (I)	gr	3965
EMPTY OUT STONE, SURFACE DRY BRIEFLY + REFILL CYLINDER TO CHECK BULKING.		
E. Mass of cylinder + saturated stone (II)	gr	3951
REFILL WITH WATER TO CHECK READING C.	gr	OK

Information gained : $\hat{D} = (D+E)/2 = 3958$ ml

F. Mass of oven-dry aggregate in cylinder : B − A	gr	1255
G. Mass of water in the cylinder up to stone level : C − B	gr	524
H. Mass of the saturated aggregate : $\hat{D}$ − A	gr	1325
I. Mass of water absorbed by the aggregate : $\hat{D}$ − B.	gr	70
J. Mass of the water emptied out from stone level : C − $\hat{D}$	gr	454
K. Absolute volume of saturated aggregate ✱ : $(\overset{1007}{V} - J)/1$ gr/ml	ml	553
L. Absolute volume of oven-dry aggregate ✱ : $(\overset{1007}{V} - G)/1$ gr/ml	ml	483
M. Total volume of voids : ie packing voids + pores ✱ : G / 1 gr/ml	ml	524
✱ Report on Bulking of Aggregate : None		0%
Other Comments :		

Calculation of Physical Properties using the info gained in the experiment.

SAMPLE REFERENCE : Sample # 5 Coarse aggregate : 19.0 ≤ D ≤ 26.5 mm

Calculations :

1. Dry bulk density (compacted) : $\frac{\text{mass of oven dry stone}}{\text{volume of ~~cylinder~~}} = \frac{1255}{1007} = 1.246$ gr/ml

2. Saturated bulk density (compacted) : $\frac{\text{mass of saturated stone}}{\text{volume of cylinder}} = \frac{1325}{1007} = 1.316$ gr/ml

3. Absorption coefficient : $\frac{\text{mass of absorbed water}}{\text{oven dry mass of aggr.}} \times 100\% = \frac{70 \times 100}{1255} = 5.58\%$

4. Total voids percentage : $\frac{\text{total voids volume}}{\text{~~bulk volume~~}} \times 100\% = \frac{524 \times 100}{1007} = 52.03\%$

5. Porosity % of aggregate : $\frac{\text{vol of water poured in originally} - \text{vol. of water poured out}}{\text{absolute vol. of saturated aggregate}}$

$= \frac{524 - 454}{553} \times 100\% = 12.66\%$

6. Packing void percentage : $\frac{\text{volume of packing voids}}{\text{bulk volume of aggregate}} \times 100\%$

$= \frac{454}{1007} \times 100\% = 45.08\%$

7. (a) Absolute density with pores : $\frac{\text{mass of oven dry stone}}{\text{abs vol. of saturated stone}} = \frac{1255}{553} = 2.269$ gr/ml

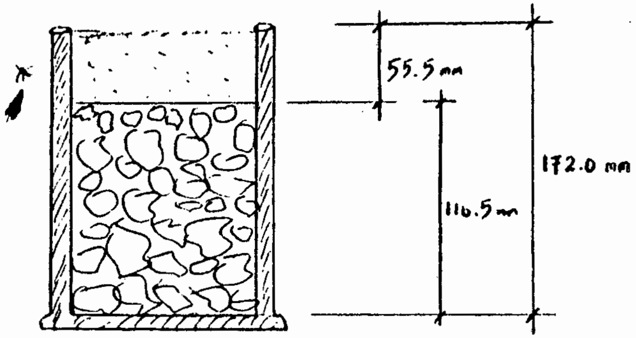
(b) Absolute density with no pores : $\frac{\text{mass of oven dry aggregate}}{\text{abs. vol. of dry aggregate}} = \frac{1255}{483} = 2.598$ gr/ml

8. Specific gravity of material : 2.27 as porous stone
2.60 as solid material.

Comments :

Compacted dry bulk ρ = 1246 kg/m³ → 12.23 kN/m³
" satur. " = 1316 kg/m³ → 12.96 kN/m³
Absolute porous " = 2269 kg/m³ → 22.26 kN/m³

* Calculation of volumes.



Volume of cyl# 2 = 1487 ml

$\therefore \frac{\pi}{4} * \phi^2 * 172.0 = 1487$

$\Rightarrow \phi^2 = \frac{4 * 1487}{\pi * 17.20} = 110.08$

$\Rightarrow \phi = 10.492$ cm.

There was only enough stone to fill the cylinder to within 55.5 mm of the top. i.e. a height of stone in cylinder = 116.5 mm.

By proportion this represents a bulk volume of : $^{116.5}/_{172.0} * 1487$

$\therefore$ bulk volume of aggregate = 1007 ml.

* $\therefore$ the mass of water above this mark that must be corrected for = 480 gr.

$\left(^{55.5}/_{172.0} * 1487 \right) = 480$ gr.

TESTING FOR PHYSICAL PROPERTIES OF AGGREGATES.

Sample Ref. No. 5 : 13-19 mm fraction | Cylinder # 1 Volume V = 1497 ml | Date : Fri 20-9-85

Readings taken :

A.	Mass of empty steel cylinder	gr	2678
B.	Mass of cylinder + oven dry stone	gr	4769
	POUR IN WATER AND LET SOAK FOR AT LEAST 24 HOURS.		
C.	Mass of cylinder + saturated stone + water	gr	5467
	EMPTY OUT WATER BY TURNING UPSIDE DOWN ON WIRE MESH.		
D.	Mass of cylinder + saturated stone (I)	gr	4904
	EMPTY OUT STONE, SURFACE DRY BRIEFLY + REFILL CYLINDER TO CHECK *BULKING.		
E.	Mass of cylinder + saturated stone (II)	gr	4876
	REFILL WITH WATER TO CHECK READING C.	gr	OK

Information gained : $\bar{D} = (D+E)/2 = 4890$ gr

F.	Mass of oven-dry aggregate in cylinder	: B − A	gr	2091
G.	Mass of water in the cylinder	: C − B	gr	698
H.	Mass of the saturated aggregate	: $\bar{D}$ − A	gr	2212
I.	Mass of water absorbed by the aggregate	: $\bar{D}$ − B.	gr	121
J.	Mass of the water emptied out	: C − $\bar{D}$	gr	577
K.	Absolute volume of saturated aggregate	: (V − J) / 1 gr/ml	ml	920
L.	Absolute volume of oven-dry aggregate	: (V − G) / 1 gr/ml	ml	799
M.	Total volume of voids : ie. packing voids + pores	: G / 1 gr/ml	ml	698

* Report on Bulking of Aggregate : Very little, ± 3mm ~ 1%

Other Comments : Contains brick particles and a reddish stone.

Calculation of Physical Properties using the info gained in the experiment.

SAMPLE REFERENCE : Sample # 5 : Coarse aggregate $13.2 \leq D \leq 19.0$ mm

Calculations :

1. Dry bulk density (compacted) : $\frac{\text{mass of oven dry stone}}{\text{volume of cylinder}} = \frac{2091}{1497} = 1.397$ gr/ml

2. Saturated bulk density (compacted) : $\frac{\text{mass of saturated stone}}{\text{volume of cylinder}} = \frac{2212}{1497} = 1.468$ gr/ml

3. Absorption coefficient : $\frac{\text{mass of absorbed water}}{\text{oven dry mass of aggr.}} \times 100\% = \frac{121 \times 100}{2091} = 5.79\%$

4. Total voids percentage : $\frac{\text{total voids volume}}{\text{bulk volume}} \times 100\% = \frac{698 \times 100}{1497} = 46.63\%$

5. Porosity % of aggregate : $\frac{\text{vol of water poured in originally} - \text{vol. of water poured out}}{\text{absolute vol. of saturated aggregate}}$

$$= \frac{698 - 577}{920} \times 100\% = 13.15\%$$

6. Packing void percentage : $\frac{\text{Volume of packing voids}}{\text{bulk volume of aggregate}} \times 100\%$

$$= \frac{577}{1497} \times 100\% = 38.54\%$$

7. (a) Absolute density with pores : $\frac{\text{mass of oven dry stone}}{\text{abs vol. of saturated stone}} = \frac{2091}{920} = 2.273$ gr/ml

   (b) Absolute density with no pores : $\frac{\text{mass of oven dry aggregate}}{\text{abs. vol. of dry aggregate}} = \frac{2091}{799} = 2.617$ gr/ml

8. Specific gravity of material : 2.27 as porous material
   2.62 as solid material

Comments : Compacted dry bulk density = 1397 kg/m³ = 13.70 kN/m³
Compacted saturated bulk density = 1468 kg/m³ = 14.50 kN/m³
Absolute porous density = 2273 kg/m³ = 22.30 kN/m³

TESTING FOR PHYSICAL PROPERTIES OF AGGREGATES.

Sample Ref. No. 5 : 4.75 → 13.2 mm	Cylinder # 2	Volume V = 1487 ml	Date : Fri 20-1-85

Readings taken :

A.	Mass of empty steel cylinder	gr	2437
B.	Mass of cylinder + oven dry stone	gr	4460
	POUR IN WATER AND LET SOAK FOR AT LEAST 24 HOURS.		
C.	Mass of cylinder + saturated stone + water	gr	5340
	EMPTY OUT WATER BY TURNING UPSIDE DOWN ON WIRE MESH.		
D.	Mass of cylinder + saturated stone (I)	gr	4868
	EMPTY OUT STONE. SURFACE DRY BRIEFLY + REFILL CYLINDER TO CHECK *BULKING.		
E.	Mass of cylinder + saturated stone (II)	gr	4840
	REFILL WITH WATER TO CHECK READING C.	gr	ok

Information gained : $\hat{D} = (D+E)/2 = 4854$ gr

F.	Mass of oven-dry aggregate in cylinder	: B − A	gr	2023
G.	Mass of water in the cylinder	: C − B	gr	680
H.	Mass of the saturated aggregate	: $\hat{D}$ − A	gr	2217
I.	Mass of water absorbed by the aggregate	: $\hat{D}$ − B	gr	194
J.	Mass of the water emptied out	: C − $\hat{D}$	gr	486
K.	Absolute volume of saturated aggregate	: (V − J) / 1 gr/ml	ml	1001
L.	Absolute volume of oven-dry aggregate	: (K − G) / 1 gr/ml	ml	807
M.	Total volume of voids : ie packing voids + pores	: G / 1 gr/ml	ml	680

* Report on Bulking of Aggregate : quite substantial ~ 33 mm ~ 11%

Other Comments : Contains brick chips.

Calculation of Physical Properties using the info gained in the experiment.

SAMPLE REFERENCE : Sample # 5 : Coarse aggregate : 4.75 mm → 13.2 mm

Calculations :

1. Dry bulk density (compacted) : $\frac{\text{mass of oven dry stone}}{\text{volume of cylinder}} = \frac{2023}{1487} = 1.360$ gr/ml

2. Saturated bulk density (compacted) : $\frac{\text{mass of saturated stone}}{\text{volume of cylinder}} = \frac{2217}{1487} = 1.491$ gr/ml

3. Absorption coefficient : $\frac{\text{mass of absorbed water}}{\text{oven dry mass of aggr.}} \times 100\% = \frac{194}{2023} \times 100 = 9.59\%$

4. Total voids percentage : $\frac{\text{total voids volume}}{\text{bulk volume}} \times 100\% = \frac{680}{1487} \times 100 = 45.73\%$

5. Porosity % of aggregate : $\frac{\text{vol of water poured in originally} - \text{vol. of water poured out}}{\text{absolute vol. of saturated aggregate}}$

$$= \frac{680 - 486}{1001} \times 100\% = 19.38\%$$

6. Packing void percentage : $\frac{\text{volume of packing voids}}{\text{bulk volume of aggregate}} \times 100\%$

$$= \frac{486}{1487} \times 100\% = 32.68\%$$

7. (a) Absolute density with pores : $\frac{\text{mass of oven dry stone}}{\text{abs vol. of saturated stone}} = \frac{2023}{1001} = 2.021$ gr/ml

(b) Absolute density with no pores : $\frac{\text{mass of oven dry aggregate}}{\text{abs vol. of dry aggregate}} = \frac{2023}{807} = 2.507$ gr/ml

8. Specific gravity of material : 2.02 as porous material.
2.51 as solid material

Comments : Compacted dry bulk ρ = 1360 kg/m³ → 13.35 kN/m³

Compacted saturated ρ = 1491 kg/m³ → 14.63 kN/m³

Absolute porous ρ = 2021 kg/m³ → 19.83 kN/m³

TESTING FOR PHYSICAL PROPERTIES OF AGGREGATES.

Sample Ref. No. 6 : 19 – 26 mm	Cylinder # 1 Volume V = 1497 ml	Date : Thurs 26-09-85

Readings taken :

A. Mass of empty steel cylinder	gr	2634
B. Mass of cylinder + oven dry stone	gr	4783
POUR IN WATER AND LET SOAK FOR AT LEAST 24 HOURS.		
C. Mass of cylinder + saturated stone + water	gr	5495
EMPTY OUT WATER BY TURNING UPSIDE DOWN ON WIRE MESH.		
D. Mass of cylinder + saturated stone (I)	gr	4884
EMPTY OUT STONE, SURFACE DRY BRIEFLY + REFILL CYLINDER TO CHECK *BULKING.		
E. Mass of cylinder + saturated stone (II)	gr	4860
REFILL WITH WATER TO CHECK READING C.	gr	OK

Information gained : $\bar{D} = (D+E)/2 = 4872$ gr

F. Mass of oven-dry aggregate in cylinder	: B − A	gr	2149
G. Mass of water in the cylinder	: C − B	gr	712
H. Mass of the saturated aggregate	: $\bar{D}$ − A	gr	2238
I. Mass of water absorbed by the aggregate	: $\bar{D}$ − B.	gr	89
J. Mass of the water emptied out	: C − $\bar{D}$	gr	623
K. Absolute volume of saturated aggregate	: (V − J) / 1 gr/ml	ml	874
L. Absolute volume of oven-dry aggregate	: (V − G) / 1 gr/ml	ml	785
M. Total volume of voids : ie packing voids + pores	: G / 1 gr/ml	ml	712

* Report on Bulking of Aggregate : None : 0%

Other Comments :

Calculation of Physical Properties using the info gained in the experiment.

SAMPLE REFERENCE : Sample # 6 : Course aggregate : 19 mm ≤ ⌀ ≤ 26.0 mm

Calculations :

1. Dry bulk density (compacted) : $\frac{\text{mass of oven dry stone}}{\text{volume of cylinder}} = \frac{2149}{1497} = 1.436$ g/ml

2. Saturated bulk density (compacted) : $\frac{\text{mass of saturated stone}}{\text{volume of cylinder}} = \frac{2238}{1497} = 1.495$ g/ml

3. Absorption coefficient : $\frac{\text{mass of absorbed water}}{\text{oven dry mass of aggr.}} * 100\% = \frac{89 * 100}{2149} = 4.14\%$

4. Total voids percentage : $\frac{\text{total voids volume}}{\text{bulk volume}} * 100\% = \frac{712 * 100}{1497} = 47.56\%$

5. Porosity % of aggregate : $\frac{\text{vol of water poured in originally} - \text{vol. of water poured out}}{\text{absolute vol. of saturated aggregate}}$

$= \frac{712 - 623}{874} * 100\% = 10.18\%$

6. Packing void percentage : $\frac{\text{volume of packing voids}}{\text{bulk volume of aggregate}} * 100\%$

$= \frac{623}{1497} * 100\% = 41.62\%$

7. (a) Absolute density with pores : $\frac{\text{mass of oven dry stone}}{\text{abs vol. of saturated stone}} = \frac{2149}{874} = 2.459$ g/ml

(b) Absolute density with no pores : $\frac{\text{mass of oven dry aggregate}}{\text{abs. vol. of dry aggregate}} = \frac{2149}{785} = 2.738$ g/ml

8. Specific gravity of material : 2.46 as porous material
2.74 as solid material

Comments :

Compacted dry bulk density = 1436 kg/m³ → 14.08 kN/m³
Compacted saturated " = 1495 kg/m³ → 14.67 kN/m³
Absolute porous density = 2495 kg/m³ → 24.12 kN/m³

TESTING FOR PHYSICAL PROPERTIES OF AGGREGATES.

Sample Ref. No. 6 13 – 19 mm	Cylinder # 2 Volume V = 1497	Date : Wed 25/9/85

Readings taken :

A.	Mass of empty steel cylinder	gr	2680
B.	Mass of cylinder + oven dry stone	gr	4668
	POUR IN WATER AND LET SOAK FOR AT LEAST 24 HOURS.		
C.	Mass of cylinder + saturated stone + water	gr	5404
	EMPTY OUT WATER BY TURNING UPSIDE DOWN ON WIRE MESH.		
D.	Mass of cylinder + saturated stone (I)	gr	4811
	EMPTY OUT STONE, SURFACE DRY BRIEFLY + REFILL CYLINDER TO CHECK *BULKING.		
E.	Mass of cylinder + saturated stone (II)	gr	4780
	REFILL WITH WATER TO CHECK READING C.	gr	OK.

Information gained : $\bar{D} = (D+E)/2 = 4795$ gr.

F.	Mass of oven-dry aggregate in cylinder	: B − A	gr	1988
G.	Mass of water in the cylinder	: C − B	gr	736
H.	Mass of the saturated aggregate	: $\bar{D}$ − A	gr	2115
I.	Mass of water absorbed by the aggregate	: $\bar{D}$ − B	gr	127
J.	Mass of the water emptied out	: C − $\bar{D}$	gr	609
K.	Absolute volume of saturated aggregate	: (V − J) / 1 gr/ml	ml	888
L.	Absolute volume of oven-dry aggregate	: (V − G) / 1 gr/ml	ml	761
M.	Total volume of voids : i.e. packing voids + pores	: G / 1 gr/ml	ml	736

*	Report on Bulking of Aggregate	: None at all	0%

Other Comments : Brick particles seen

Calculation of Physical Properties using the info gained in the experiment.

SAMPLE REFERENCE : Sample # 6 . Coarse aggregate : 13.2 mm ≤ ω ≤ 19.0 mm.

Calculations :

1. Dry bulk density (compacted) : $\frac{\text{mass of oven dry stone}}{\text{volume of cylinder}} = \frac{1988}{1497} = 1.328$ gr/ml

2. Saturated bulk density (compacted) : $\frac{\text{mass of saturated stone}}{\text{volume of cylinder}} = \frac{2115}{1497} = 1.413$ gr/ml

3. Absorption coefficient : $\frac{\text{mass of absorbed water}}{\text{oven dry mass of aggr.}} \times 100\% = \frac{127 \times 100}{1988} = 6.39\%$

4. Total voids percentage : $\frac{\text{total voids volume}}{\text{bulk volume}} \times 100\% = \frac{736 \times 100}{1497} = 49.16\%$

5. Porosity % of aggregate : $\frac{\text{vol. of water poured in originally} - \text{vol. of water poured out}}{\text{absolute vol. of saturated aggregate}}$

$= \frac{736 - 609}{888} \times 100\% = 14.30\%$

6. Packing void percentage : $\frac{\text{volume of packing voids}}{\text{bulk volume of aggregate}} \times 100\%$

$= \frac{609}{1497} \times 100\% = 40.68\%$

7. (a) Absolute density with pores : $\frac{\text{mass of oven dry stone}}{\text{abs vol. of saturated stone}} = \frac{1988}{888} = 2.239$ gr/ml

(b) Absolute density with no pores : $\frac{\text{mass of oven dry aggregate}}{\text{abs. vol. of dry aggregate}} = \frac{1988}{761} = 2.612$ gr/ml

8. Specific gravity of material : 2.24 as porous material
2.61 as solid material

Comments :

Compacted dry bulk density	=	1328 kg/m³	→	13.03 kg/m³
Compacted saturated bulk density	=	1413 kg/m³	→	13.86 kg/m³
Absolute porous density	=	2239 kg/m³	→	21.96 kg/m³

TESTING FOR PHYSICAL PROPERTIES OF AGGREGATES.

Sample Ref. No. 6 | 4.75 → 13.2mm | Cylinder # 2 | Volume V = 1487 | Date : Wed 25.09.85

Readings taken :

A.	Mass of empty steel cylinder	gr	2637
B.	Mass of cylinder + oven dry stone	gr	4549
	POUR IN WATER AND LET SOAK FOR AT LEAST 24 HOURS.		
C.	Mass of cylinder + saturated stone + water.	gr	5250
	EMPTY OUT WATER BY TURNING UPSIDE DOWN ON WIRE MESH.		
D.	Mass of cylinder + saturated stone (I)	gr	4778
	EMPTY OUT STONE, SURFACE DRY BRIEFLY + REFILL CYLINDER TO CHECK BULKING.		
E.	Mass of cylinder + saturated stone (II)	gr	4744
	REFILL WITH WATER TO CHECK READING C.	gr	OK

Information gained : $\bar{D} = (D+E)/2 = 4760$ gr

F.	Mass of oven-dry aggregate in cylinder	: B − A	gr	1912
G.	Mass of water in the cylinder	: C − B	gr	701
H.	Mass of the saturated aggregate	: $\bar{D}$ − A	gr	2123
I.	Mass of water absorbed by the aggregate	: $\bar{D}$ − B.	gr	211
J.	Mass of the water emptied out	: C − $\bar{D}$	gr	490
K.	Absolute volume of saturated aggregate	: (V − J) / 1 gr/ml	ml	997
L.	Absolute volume of oven-dry aggregate	: (V − G) / 1 gr/ml	ml	786
M.	Total volume of voids : ie packing voids + pores	: G / 1 gr/ml	ml	701

* Report on Bulking of Aggregate (4741 − 4626) / 2123 gr × 100% (37mm) = 5.5%

115gr / 2123gr × 100 = 5.5%

Other Comments :

Calculation of Physical Properties using the info gained in the experiment.

SAMPLE REFERENCE : Sample # 6 : Coarse Aggregate 4.75mm ≤ ω ≤ 13.2 mm

Calculations :

1. Dry bulk density (compacted) : $\frac{\text{mass of oven dry stone}}{\text{volume of cylinder}} = \frac{1912}{1487} = 1.286 \text{ gr/ml}$

2. Saturated bulk density (compacted) : $\frac{\text{mass of saturated stone}}{\text{volume of cylinder}} = \frac{2123}{1487} = 1.428 \text{ gr/ml}$

3. Absorption coefficient : $\frac{\text{mass of absorbed water}}{\text{oven dry mass of aggr.}} \times 100\% = \frac{211 \times 100}{1912} = 11.04\%$

4. Total voids percentage : $\frac{\text{total voids volume}}{\text{bulk volume}} \times 100\% = \frac{701 \times 100}{1487} = 47.14\%$

5. Porosity % of aggregate : $\frac{\text{vol of water poured in originally} - \text{vol. of water poured out}}{\text{absolute vol. of saturated aggregate}}$

$$= \frac{701 - 490}{997} \times 100\% = 21.16\%$$

6. Packing void percentage : $\frac{\text{volume of packing voids}}{\text{bulk volume of aggregate}} \times 100\%$

$$= \frac{490}{1487} \times 100\% = 32.95\%$$

7. (a) Absolute density with pores : $\frac{\text{mass of oven dry stone}}{\text{abs vol. of saturated stone}} = \frac{1912}{997} = 1.918 \text{ gr/ml}$

(b) Absolute density with no pores : $\frac{\text{mass of oven dry aggregate}}{\text{abs. vol. of dry aggregate}} = \frac{1912}{786} = 2.433 \text{ gr/ml}$

8. Specific gravity of material : 1.92 as porous stone
2.43 " solid material.

Comments : Compacted dry bulk density = 1286 kg/m³ → 12.61 kN/m³

" saturated " = 1428 kg/m³ → 14.01 kN/m³

Absolute porous density = 1918 kg/m³ → 18.81 kN/m³

TESTING FOR PHYSICAL PROPERTIES OF AGGREGATES.

Sample Ref. No. B : 13.2 ≤ Φ ≤ 19.0 mm	Cylinder # 2	Volume V = 1487 ml	Date : Mo. 11.9.85

Readings taken :

A.	Mass of empty steel cylinder	gr	2638
B.	Mass of cylinder + oven dry stone	gr	4549
	POUR IN WATER AND LET SOAK FOR AT LEAST 24 HOURS.		
C.	Mass of cylinder + saturated stone + water	gr	5325
	EMPTY OUT WATER BY TURNING UPSIDE DOWN ON WIRE MESH.		
D.	Mass of cylinder + saturated stone (I)	gr	4666
	EMPTY OUT STONE, SURFACE DRY BRIEFLY + REFILL CYLINDER TO CHECK *BULKING.		
E.	Mass of cylinder + saturated stone (II)	gr	4652
	REFILL WITH WATER TO CHECK READING C.	gr	OK

Information gained : $\bar{D} = (D+E)/2 = 4659$ gr

F.	Mass of oven-dry aggregate in cylinder	: B − A	gr	1911
G.	Mass of water in the cylinder	: C − B	gr	776
H.	Mass of the saturated aggregate	: $\bar{D}$ − A	gr	2021
I.	Mass of water absorbed by the aggregate	: $\bar{D}$ − B.	gr	110
J.	Mass of the water emptied out	: C − $\bar{D}$	gr	666
K.	Absolute volume of saturated aggregate	: (V − J) / 1 gr/ml	ml	821
L.	Absolute volume of oven-dry aggregate	: (V − G) / 1 gr/ml	ml	711
M.	Total volume of voids : ie packing voids + pores	: G / 1 gr/ml	ml	776

*. Report on Bulking of Aggregate : None — 0 %

Other Comments :

Calculation of Physical Properties using the info gained in the experiment.

SAMPLE REFERENCE : Sample # B : Coarse Aggregate : 13.2 mm ≤ Φ ≤ 19.0 mm

Calculations :

1. Dry bulk density (compacted) : $\frac{\text{mass of oven dry stone}}{\text{volume of cylinder}} = \frac{1911\ gr}{1487\ ml} = 1.285\ gr/ml$

2. Saturated bulk density (compacted) : $\frac{\text{mass of saturated stone}}{\text{volume of cylinder}} = \frac{2021\ gr}{1487\ ml} = 1.359\ gr/ml$

3. Absorption coefficient : $\frac{\text{mass of absorbed water}}{\text{oven dry mass of agg.}} \times 100\,\% = \frac{110 \times 100}{1911} = 5.76\,\%$

4. Total voids percentage : $\frac{\text{total voids volume}}{\text{bulk volume}} \times 100\,\% = \frac{776 \times 100}{1487} = 52.19\,\%$

5. Porosity % of aggregate : $\frac{\text{vol of water poured in originally} - \text{vol. of water poured out}}{\text{absolute vol. of saturated aggregate}}$

   $= \frac{776 - 666}{821} \times 100\,\% = 13.40\,\%$

6. Packing void percentage : $\frac{\text{volume of packing voids}}{\text{bulk volume of aggregate}} \times 100\,\%$

   $= \frac{666}{1487} \times 100\,\% = 44.79\,\%$

7. (a) Absolute density with pores : $\frac{\text{mass of oven dry stone}}{\text{abs vol. of saturated stone}} = \frac{1911}{821} = 2.328\ gr/ml$

   (b) Absolute density with no pores : $\frac{\text{mass of oven dry aggregate}}{\text{abs. vol. of dry aggregate}} = \frac{1911}{711} = 2.688\ gr/ml$

8. Specific gravity of material : 2.33 as porous material.
   2.69 as solid material.

Comments : Compacted dry bulk mass density = 1285 kg/m³ → 12.61 kN/m³
Compacted saturated " " = 1359 kg/m³ → 13.33 kN/m³
Absolute density as porous material = 2328 kg/m³ → 22.83 kN/m³

TESTING FOR PHYSICAL PROPERTIES OF AGGREGATES.

Sample Ref. No. 8 : 4.75 ≤ ∅ ≤ 13.2	Cylinder # 1 Volume V = 1497	Date : Thu 12 09 85

Readings taken :

A.	Mass of empty steel cylinder	gr	2680
B.	Mass of cylinder + oven dry stone	gr	4638
	POUR IN WATER AND LET SOAK FOR AT LEAST 24 HOURS.		
C.	Mass of cylinder + saturated stone + water	gr	5356
	EMPTY OUT WATER BY TURNING UPSIDE DOWN ON WIRE MESH.		
D.	Mass of cylinder + saturated stone (I)	gr	4870
	EMPTY OUT STONE, SURFACE DRY BRIEFLY + REFILL CYLINDER TO CHECK *BULKING.		4846
E.	Mass of cylinder + saturated stone (II)	gr	
	REFILL WITH WATER TO CHECK READING C.	gr	OK

Information gained : $\hat{D} = (D + E)/2 = 4858$ gr

F.	Mass of oven-dry aggregate in cylinder	: B − A	gr	1958
G.	Mass of water in the cylinder	: C − B	gr	718
H.	Mass of the saturated aggregate	: $\hat{D}$ − A	gr	2178
I.	Mass of water absorbed by the aggregate	: $\hat{D}$ − B.	gr	220
J.	Mass of the water emptied out	: C − D	gr	498
K.	Absolute volume of saturated aggregate	: (V − J) / 1 gr/ml	ml	999
L.	Absolute volume of oven-dry aggregate	: (V − G) / 1 gr/ml	ml	779
M.	Total volume of voids : ie packing voids + pores	: G / 1 gr/ml	ml	718

* Report on Bulking of Aggregate	: ~ 25 mm ht of cone	7.35%

Other Comments :

Bulking % = $\frac{160 \times 100}{2178}$ %

by mass : $\frac{4700 - 268}{4700 - 2680}$

160 gr couldn't fit again

Calculation of Physical Properties using the info gained in the experiment.

SAMPLE REFERENCE : Sample # 8 : Coarse aggregate : 4.75 mm ≤ ∅ ≤ 13.2 mm

Calculations :

1. Dry bulk density (compacted) : $\frac{\text{mass of oven dry stone}}{\text{volume of cylinder}} = \frac{1958 \text{ gr}}{1497 \text{ ml}} = 1.308 \text{ gr/ml}$

2. Saturated bulk density (compacted) : $\frac{\text{mass of saturated stone}}{\text{volume of cylinder}} = \frac{2178 \text{ gr}}{1497 \text{ ml}} = 1.455 \text{ gr/ml}$

3. Absorption coefficient : $\frac{\text{mass of absorbed water}}{\text{oven dry mass of aggr.}} \times 100\% = \frac{220 \times 100}{1958} = 11.24\%$

4. Total voids percentage : $\frac{\text{total voids volume}}{\text{bulk volume}} \times 100\% = \frac{718 \times 100}{1497} = 47.96\%$

5. Porosity % of aggregate : $\frac{\text{vol of water poured in originally} - \text{vol. of water poured out}}{\text{absolute vol. of saturated aggregate}}$

   $= \frac{718 - 498}{999} \times 100\% = 22.02\%$

6. Packing void percentage : $\frac{\text{volume of packing voids}}{\text{bulk volume of aggregate}} \times 100\%$

   $= \frac{498}{1497} \times 100\% = 33.27\%$

7. (a) Absolute density with pores : $\frac{\text{mass of oven dry stone}}{\text{abs vol. of saturated stone}} = \frac{1958 \text{ gr}}{999 \text{ ml}} = 1.960 \text{ gr/ml}$

   (b) Absolute density with no pores : $\frac{\text{mass of oven dry aggregate}}{\text{abs. vol. of dry aggregate}} = \frac{1958 \text{ gr}}{779 \text{ ml}} = 2.513 \text{ gr/ml}$

8. Specific gravity of material : 1.96 as porous material
   2.51 as solid material

Comments : Compacted bulk mass density (dry) = 1308 kg/m³ → ρ_{dry} = 12.83 kN/m³

Compacted bulk " " (saturated) = 1455 kg/m³ → ρ_{sat} = 14.27 kN/m³

Absolute mass density of porous stone = 1960 kg/m³ → ρ_{abs} = 19.23 kN/m³

TESTING FOR PHYSICAL PROPERTIES OF AGGREGATES.

Sample Ref. No. 9 : 13.2m ≤ O ≤ 19.0m | Cylinder # 1 Volume V = 1497 ml | Date : We 11·9·85

Readings taken:

A.	Mass of empty steel cylinder	gr	2678
B.	Mass of cylinder + oven dry stone	gr	4545

POUR IN WATER AND LET SOAK FOR AT LEAST 24 HOURS.

C.	Mass of cylinder + saturated stone + water	gr	5327

EMPTY OUT WATER BY TURNING UPSIDE DOWN ON WIRE MESH.

D.	Mass of cylinder + saturated stone (I)	gr	4704

EMPTY OUT STONE, SURFACE DRY BRIEFLY + REFILL CYLINDER TO CHECK *BULKING.

E.	Mass of cylinder + saturated stone (II)	gr	4682

REFILL WITH WATER TO CHECK READING C. gr OK

Information gained: $\dot{D} = (D+E)/2 = 4693$ gr

F.	Mass of oven-dry aggregate in cylinder	B − A	gr	1867
G.	Mass of water in the cylinder	C − B	gr	782
H.	Mass of the saturated aggregate	$\dot{D}$ − A	gr	2015
I.	Mass of water absorbed by the aggregate	$\dot{D}$ − B.	gr	148
J.	Mass of the water emptied out	C − $\dot{D}$	gr	634
K.	Absolute volume of saturated aggregate	(V − J) / 1 gr/ml	ml	863
L.	Absolute volume of oven-dry aggregate	(V − G) / 1 gr/ml	ml	715
M.	Total volume of voids : ie packing voids + pores	G / 1 gr/ml	ml	782

* Report on Bulking of Aggregate : Bulked very slightly, indeed. ~ %

Other Comments :

Calculation of Physical Properties using the info gained in the experiment.

SAMPLE REFERENCE : Sample # 9 : Coarse Aggregate : 13.2mm ≤ O ≤ 19.0 mm

Calculations :

1. Dry bulk density (compacted) :
$$\frac{\text{mass of oven dry stone}}{\text{volume of cylinder}} = \frac{1867\text{ gr}}{1497\text{ ml}} = 1.247\ \text{gr/ml}$$

2. Saturated bulk density (compacted) :
$$\frac{\text{mass of saturated stone}}{\text{volume of cylinder}} = \frac{2015\text{ gr}}{1497\text{ ml}} = 1.346\ \text{gr/ml}$$

3. Absorption coefficient (by mass) :
$$\frac{\text{mass of absorbed water}}{\text{oven dry mass of aggr.}} \times 100\% = \frac{148 \times 100}{1867} = 7.93\%$$

4. Total voids percentage :
$$\frac{\text{total voids volume}}{\text{bulk volume}} \times 100\% = \frac{782 \times 100}{1497} = 52.24\%$$

5. Porosity % of aggregate :
$$\frac{\text{vol of water poured in originally} - \text{vol. of water poured out}}{\text{absolute vol. of saturated aggregate}}$$
$$= \frac{782 - 634}{863} \times 100\% = 17.15\%$$

6. Packing void percentage :
$$\frac{\text{volume of packing voids}}{\text{bulk volume of aggregate}} \times 100\%$$
$$= \frac{634}{1497} \times 100\% = 42.35\%$$

7. (a) Absolute density with pores :
$$\frac{\text{mass of oven dry stone}}{\text{abs vol. of saturated stone}} = \frac{1867\text{ gr}}{863\text{ ml}} = 2.163\ \text{gr/ml}$$

(b) Absolute density with no pores :
$$\frac{\text{mass of oven dry aggregate}}{\text{abs. vol. of dry aggregate}} = \frac{1867\text{ gr}}{715\text{ ml}} = 2.611\ \text{gr/ml}$$

8. Specific gravity of material : 2.16 as porous material
2.61 as solid material

Comments : Compacted dry bulk mass density = 1247 kg/m³ → dry bulk density = 12.23 kN/m³

Compacted saturated bulk " " = 1346 kg/m³ → sat. bulk " = 13.20 kN/m³

Absolute density as porous aggr = 2163 kg/m³ → absolute bulk ρ = 21.22 kN/m³

TESTING FOR PHYSICAL PROPERTIES OF AGGREGATES.

Sample Ref. No. 9 : 4.75 ≤ O ≤ 13.2 mm | Cylinder # 2 Volume V = 1487 ml | Date : Tue 10-01-85

Readings taken :

A.	Mass of empty steel cylinder	gr	2637
B.	Mass of cylinder + oven dry stone	gr	4662

POUR IN WATER AND LET SOAK FOR AT LEAST 24 HOURS.

C.	Mass of cylinder + saturated stone + water.	gr	5349

EMPTY OUT WATER BY TURNING UPSIDE DOWN ON WIRE MESH.

D.	Mass of cylinder + saturated stone (I)	gr	4830

EMPTY OUT STONE, SURFACE DRY BRIEFLY + REFILL CYLINDER TO CHECK *BULKING.

E.	Mass of cylinder + saturated stone (II)	gr	4810

REFILL WITH WATER TO CHECK READING C. gr OK

Information gained : $\hat{D} = (D+E)/2 = 4820$ gr

F.	Mass of oven-dry aggregate in cylinder	: B − A	gr	2025
G.	Mass of water in the cylinder	: C − B	gr	687
H.	Mass of the saturated aggregate	: $\hat{D}$ − A	gr	2183
I.	Mass of water absorbed by the aggregate	: $\hat{D}$ − B.	gr	158
J.	Mass of the water emptied out	: C − $\hat{D}$	gr	529
K.	Absolute volume of saturated aggregate	: (V − J) / 1 gr/ml	ml	958
L.	Absolute volume of oven-dry aggregate	: (V − G) / 1 gr/ml	ml	800
M.	Total volume of voids : ie. packing voids + pores	: G / 1 gr/ml	ml	687

* Report on Bulking of Aggregate : YES : − 12mm 0.3 x 12 %

Other Comments :

Calculation of Physical Properties using the info gained in the experiment.

SAMPLE REFERENCE : Sample # 9 : Coarse aggregate : 4.75 ≤ O ≤ 13.2 mm.

Calculations :

1. Dry bulk density (compacted) : $\frac{\text{mass of oven dry stone}}{\text{volume of cylinder}} = \frac{2025\ \text{gr}}{1487\ \text{ml}} = 1.362\ \text{gr/ml}$

2. Saturated bulk density (compacted) : $\frac{\text{mass of saturated stone}}{\text{volume of cylinder}} = \frac{2183\ \text{gr}}{1487\ \text{ml}} = 1.468\ \text{gr/ml}$

3. Absorption coefficient : $\frac{\text{mass of absorbed water}}{\text{oven dry mass of aggr.}} \times 100\,\% = \frac{158 \times 100}{2025} = 7.80\%$

4. Total voids percentage : $\frac{\text{total voids volume}}{\text{bulk volume}} \times 100\,\% = \frac{687 \times 100}{1487} = 46.20\%$

5. Porosity % of aggregate : $\frac{\text{vol of water poured in originally} - \text{vol. of water poured out}}{\text{absolute vol. of saturated aggregate}}$

$= \frac{687 - 529}{958} \times 100\,\% = 16.49\,\%$

6. Packing void percentage : $\frac{\text{volume of packing voids}}{\text{bulk volume of aggregate}} \times 100\,\%$

$= \frac{529}{1487} \times 100\,\% = 35.57\%$

7. (a) Absolute density with pores : $\frac{\text{mass of oven dry stone}}{\text{abs vol. of saturated stone}} = \frac{2025\ \text{gr}}{958\ \text{ml}} = 2.114\ \text{gr/ml}$

   (b) Absolute density with no pores : $\frac{\text{mass of oven dry aggregate}}{\text{abs. vol. of dry aggregate}} = \frac{2025\ \text{gr}}{800\ \text{ml}} = 2.531\ \text{gr/ml}$

8. Specific gravity of material : 2.11 as porous material
   2.53 as solid material.

Comments : Compacted dry bulk mass density = 1362 kg/m³ → dry bulk density : 13.36 kN/m³

Compacted saturated bulk mass ρ : 1468 kg/m³ → sat. bulk density : 14.40 kN/m³

Absolute density of porous material : 2114 kg/m³ → 20.74 kN/m³

TESTING FOR PHYSICAL PROPERTIES OF AGGREGATES.

Sample Ref. No. 10 : 19.0mm ≤ l ≤ 20 | Cylinder # 1 Volume V 1497 ml | Date : Fri 6.09.85

Readings taken :

A. Mass of empty steel cylinder — gr 2680

B. Mass of cylinder + oven dry stone — gr 4724

POUR IN WATER AND LET SOAK FOR AT LEAST 24 HOURS.

C. Mass of cylinder + saturated stone + water — gr 5450

EMPTY OUT WATER BY TURNING UPSIDE DOWN ON WIRE MESH.

D. Mass of cylinder + saturated stone (I) — gr 4813

EMPTY OUT STONE. SURFACE DRY BRIEFLY + REFILL CYLINDER TO CHECK *BULKING.

E. Mass of cylinder + saturated stone (II) — gr 4799

REFILL WITH WATER TO CHECK READING C. ∴ OK — gr 5447

Information gained : let $\hat{D} = (D+E)/2 = 4806$ gr

F.	Mass of oven-dry aggregate in cylinder	: $B - A$	gr	2044
G.	Mass of water in the cylinder	: $C - B$	gr	726
H.	Mass of the saturated aggregate	: $\hat{D} - A$	gr	2126
I.	Mass of water absorbed by the aggregate	: $\hat{D} - B$	gr	82
J.	Mass of the water emptied out	: $C - \hat{D}$	gr	644
K.	Absolute volume of saturated aggregate	: $(V - J)/1$ gr/ml	ml	853
L.	Absolute volume of oven-dry aggregate	: $(V - G)/1$ gr/ml	ml	771
M.	Total volume of voids : ie packing voids + pores	: $G/1$ gr/ml	ml	726

* Report on Bulking of Aggregate : none

Other Comments : Estimate of original coarse aggregate size :

Calculation of Physical Properties using the info gained in the experiment.

SAMPLE REFERENCE : Sample # 10 : Coarse Aggregate : 19.0mm ≤ ∅ ≤ 26.0 mm

Calculations :

1. Dry bulk density (compacted) : $\frac{\text{mass of oven dry stone}}{\text{volume of cylinder}} = \frac{2044 \text{ gr}}{1497 \text{ ml}} = 1.365 \text{ gr/ml}$

2. Saturated bulk density (compacted) : $\frac{\text{mass of saturated stone}}{\text{volume of cylinder}} = \frac{2126 \text{ gr}}{1497 \text{ ml}} = 1.420 \text{ gr/ml}$

3. Absorption coefficient : $\frac{\text{mass of absorbed water}}{\text{oven dry mass of aggr.}} \times 100\% = \frac{82 \times 100}{2044} = 4.01\%$

4. Total voids percentage : $\frac{\text{total voids volume}}{\text{bulk volume}} \times 100\% = \frac{726 \times 100}{1497} = 48.50\%$

5. Porosity % of aggregate : $\frac{\text{vol of water poured in originally} - \text{vol. of water poured out}}{\text{absolute vol. of saturated aggregate}}$

$$= \frac{726 - 644}{853} \times 100\% = 9.61\%$$

6. Packing void percentage : $\frac{\text{volume of packing voids}}{\text{bulk volume of aggregate}} \times 100\%$

$$= \frac{644}{1497} \times 100\% = 43.02\%$$

7. (a) Absolute density with pores : $\frac{\text{mass of oven dry stone}}{\text{abs vol. of saturated stone}} = \frac{2044 \text{ gr}}{853 \text{ ml}} = 2.396 \text{ gr/ml}$

(b) Absolute density with no pores : $\frac{\text{mass of oven dry aggregate}}{\text{abs. vol. of dry aggregate}} = \frac{2044 \text{ gr}}{771 \text{ ml}} = 2.651 \text{ gr/ml}$

8. Specific gravity of material : 2.40 as material with pores
2.65 as fully solid material.

Comments : Bulk dry mass density = 2.044 kg / 0.001497 m³ = 1365 kg/m³

∴ Dry compacted bulk density = 1365 × 9.81/1000 = 13.39 kN/m³

also : Saturated mass bulk density = 1420 kg/m³ → Saturated bulk density = 13.93 kN/m³

also Absolute density = 2396 kg/m³ = 23.51 kN/m³

TESTING FOR PHYSICAL PROPERTIES OF AGGREGATES.

Sample Ref. No. 10 : 13.2mm 1-1 19.0mm	Cylinder # 2 Volume V 1487 ml	Date : Fr. 6 09.05

Readings taken :

A.	Mass of empty steel cylinder	gr	2639
B.	Mass of cylinder + oven dry stone	gr	4700

POUR IN WATER AND LET SOAK FOR AT LEAST 24 HOURS.

C.	Mass of cylinder + saturated stone + water	gr	5410

EMPTY OUT WATER BY TURNING UPSIDE DOWN ON WIRE MESH.

D.	Mass of cylinder + saturated stone (I)	gr	4811

EMPTY OUT STONE, SURFACE DRY BRIEFLY + REFILL CYLINDER TO CHECK *BULKING. 4795

E.	Mass of cylinder + saturated stone (II)	gr	

REFILL WITH WATER TO CHECK READING C. OK gr 5418

Information gained : $\hat{D} = (D+E)/2 = 4803$ gr

F.	Mass of oven-dry aggregate in cylinder	: B − A	gr	2061
G.	Mass of water in the cylinder	: C − B	gr	710
H.	Mass of the saturated aggregate	: $\hat{D}$ − A	gr	2164
I.	Mass of water absorbed by the aggregate	: $\hat{D}$ − B.	gr	103
J.	Mass of the water emptied out	: C − $\hat{D}$	gr	607
K.	Absolute volume of saturated aggregate	: (V − J) / 1 gr/ml	ml	880
L.	Absolute volume of oven-dry aggregate	: (V − G) / 1 gr/ml	ml	777
M.	Total volume of voids : ie. packing voids + pores	: G / 1 gr/ml	ml	710

* Report on Bulking of Aggregate : Bulked slightly ~ 8mm %

Other Comments :

Calculation of Physical Properties using the info gained in the experiment.

SAMPLE REFERENCE : Sample # 10 : Coarse aggregate : 13.2mm ≤ D ≤ 19.0 mm

Calculations :

1\. Dry bulk density (compacted) :

$$\frac{\text{mass of oven dry stone}}{\text{volume of cylinder}} = \frac{2061 \text{ gr}}{1487 \text{ ml}} = 1.386 \text{ gr/ml}$$

2\. Saturated bulk density (compacted) :

$$\frac{\text{mass of saturated stone}}{\text{volume of cylinder}} = \frac{2164 \text{ gr}}{1487 \text{ ml}} = 1.455 \text{ gr/ml}$$

3\. Absorption coefficient :

$$\frac{\text{mass of absorbed water}}{\text{oven dry mass of agg.}} \times 100\% = \frac{103 \times 100}{2061} = 5.00\%$$

4\. Total voids percentage :

$$\frac{\text{total voids volume}}{\text{bulk volume}} \times 100\% = \frac{710 \times 100}{1487} = 47.75\%$$

5\. Porosity % of aggregate :

$$\frac{\text{vol of water poured in originally} - \text{vol. of water poured out}}{\text{absolute vol. of saturated aggregate}}$$

$$= \frac{710 - 607}{880} \times 100\% = 11.70\%$$

6\. Packing void percentage :

$$\frac{\text{volume of packing voids}}{\text{bulk volume of aggregate}} \times 100\%$$

$$= \frac{607}{1487} \times 100\% = 40.82\%$$

7\. (a) Absolute density with pores :

$$\frac{\text{mass of oven dry stone}}{\text{abs vol. of saturated stone}} = \frac{2061 \text{ gr}}{880 \text{ ml}} = 2.342 \text{ gr/ml}$$

(b) Absolute density with no pores :

$$\frac{\text{mass of oven dry aggregate}}{\text{abs. vol. of dry aggregate}} = \frac{2061 \text{ gr}}{777 \text{ ml}} = 2.653 \text{ gr/ml}$$

8\. Specific gravity of material : 2.34 as material with pores
2.65 as solid material.

Comments : Compacted bulk mass density of dry stone = 1386 kg/m³

⇒ Compacted bulk density of dry aggregate = 13.60 kN/m³

also : Saturated bulk mass density = 1455 kg/m³ ; Sat. bulk density = 14.28 kN/m³

also : Absolute density = 2342 kg/m³ ≡ 22.98 kN/m³

TESTING FOR PHYSICAL PROPERTIES OF AGGREGATES.

Sample Ref. No. 10 : 4.75 mm ≤ O ≤ 13.2 mm | Cylinder # 1 Volume V 1497 ml | Date : Tue 10-01-85

Readings taken:

A.	Mass of empty steel cylinder	gr	2678
B.	Mass of cylinder + oven dry stone	gr	4624

POUR IN WATER AND LET SOAK FOR AT LEAST 24 HOURS.

C.	Mass of cylinder + saturated stone + water	gr	5330

EMPTY OUT WATER BY TURNING UPSIDE DOWN ON WIRE MESH.

D.	Mass of cylinder + saturated stone (I)	gr	4808

EMPTY OUT STONE, SURFACE DRY BRIEFLY + REFILL CYLINDER TO CHECK *BULKING.

E.	Mass of cylinder + saturated stone (II)	gr	4797

REFILL WITH WATER TO CHECK READING C. gr OK

Information gained: $\hat{D} = (D+E)/2 = 4803$ gr

F.	Mass of oven-dry aggregate in cylinder	:	B − A	gr	1946
G.	Mass of water in the cylinder	:	C − B	gr	706
H.	Mass of the saturated aggregate	:	$\hat{D}$ − A	gr	2125
I.	Mass of water absorbed by the aggregate	:	$\hat{D}$ − B.	gr	179
J.	Mass of the water emptied out	:	C − $\hat{D}$	gr	527
K.	Absolute volume of saturated aggregate	:	(V − J) / 1 gr/ml	ml	970
L.	Absolute volume of oven-dry aggregate	:	(V − G) / 1 gr/ml	ml	791
M.	Total volume of voids : ie packing voids + pores	:	G / 1 gr/ml	ml	706

* Report on Bulking of Aggregate : slightly : ~~[illegible]~~ i.e. ≈ 5.2 %

Other Comments :

Calculation of Physical Properties using the info gained in the experiment.

Sample Reference : Sample # 10 ; Coarse aggregate : 4.75 mm ≤ O ≤ 13.2 mm

Calculations :

1. Dry bulk density : (compacted) : $\frac{\text{mass of oven dry stone}}{\text{volume of cylinder}} = \frac{1946 \text{ gr}}{1497 \text{ ml}} = 1.300 \text{ gr/ml}$

2. Saturated bulk density (compacted) : $\frac{\text{mass of saturated stone}}{\text{volume of cylinder}} = \frac{2125 \text{ gr}}{1497 \text{ ml}} = 1.420 \text{ gr/ml}$

3. Absorption coefficient : $\frac{\text{mass of absorbed water}}{\text{oven dry mass of aggr.}} \times 100\% = \frac{179 \times 100}{1946} = 9.20\%$

4. Total voids percentage : $\frac{\text{total voids volume}}{\text{bulk volume}} \times 100\% = \frac{706 \times 100}{1497} = 47.16\%$

5. Porosity % of aggregate : $\frac{\text{vol of water poured in originally} - \text{vol. of water poured out}}{\text{absolute vol. of saturated aggregate}}$

$$= \frac{706 - 527}{970} \times 100\% = 18.45\%$$

6. Packing void percentage : $\frac{\text{volume of packing voids}}{\text{bulk volume of aggregate}} \times 100\%$

$$= \frac{527}{1497} \times 100\% = 35.20\%$$

7. (a) Absolute density with pores : $\frac{\text{mass of oven dry stone}}{\text{abs vol. of saturated stone}} = \frac{1946}{970} = 2.006 \text{ gr/ml}$

(b) Absolute density with no pores : $\frac{\text{mass of oven dry aggregate}}{\text{abs vol. of dry aggregate}} = \frac{1946}{791} = 2.460 \text{ gr/ml}$

8. Specific gravity of material : 2.01 as porous material.
2.46 as solid material.

Comments : Compacted bulk mass density of dry stone = 1300 kg/m³

→ " bulk density " " " = 12.75 kN/m³

\+ Saturated bulk mass density = 1420 kg/m³ ; Sat. bulk density = 13.93 kN/m³

\+ Absolute density = 2006 kg/m³ ≡ 19.68 kN/m³

TESTING FOR PHYSICAL PROPERTIES OF AGGREGATES.

Sample Ref. No. Stockpile 19-26 mm	Cylinder # 2 Volume V = 1487 ml	Date : 25-02-86

Readings taken :

A.	Mass of empty steel cylinder	gr	2635
B.	Mass of cylinder + oven dry stone	gr	4696
	POUR IN WATER AND LET SOAK FOR AT LEAST 24 HOURS.		
C.	Mass of cylinder + saturated stone + water	gr	5408
	EMPTY OUT WATER BY TURNING UPSIDE DOWN ON WIRE MESH.		
D.	Mass of cylinder + saturated stone (I)	gr	4812
	EMPTY OUT STONE, SURFACE DRY BRIEFLY + REFILL CYLINDER TO CHECK *BULKING.		
E.	Mass of cylinder + saturated stone (II)	gr	4798
	REFILL WITH WATER TO CHECK READING C. OK	gr	OK

Information gained : $\bar{D} = (D+E)/2 = 4805$ gr

F.	Mass of oven-dry aggregate in cylinder	: $B - A$	gr	2061
G.	Mass of water in the cylinder	: $C - B$	gr	712
H.	Mass of the saturated aggregate	: $\bar{D} - A$	gr	2170
I.	Mass of water absorbed by the aggregate	: $\bar{D} - B$.	gr	109
J.	Mass of the water emptied out	: $C - \bar{D}$	gr	603
K.	Absolute volume of saturated aggregate	: $(V - J)/1$ gr/ml	ml	884
L.	Absolute volume of oven-dry aggregate	: $(V - G)/1$ gr/ml	ml	775
M.	Total volume of voids : ie packing voids + pores	: $G/1$ gr/ml	ml	712

*	Report on Bulking of Aggregate	: None.	0%

Other Comments :

Calculation of Physical Properties using the info gained in the experiment.

SAMPLE REFERENCE : Mix Design Stockpile 19-26 mm stone.

Calculations :

1. Dry bulk density (compacted) : $\frac{\text{mass of oven dry stone}}{\text{volume of cylinder}} = \frac{2061}{1487} = 1.386$ gr/ml

2. Saturated bulk density (compacted) : $\frac{\text{mass of saturated stone}}{\text{volume of cylinder}} = \frac{2170}{1487} = 1.459$ g/ml

3. Absorption coefficient : $\frac{\text{mass of absorbed water}}{\text{oven dry mass of aggr.}} \times 100\% = \frac{109 \times 100}{2061} = 5.29\%$

4. Total voids percentage : $\frac{\text{total voids volume}}{\text{bulk volume}} \times 100\% = \frac{712 \times 100}{1487} = 47.88\%$

5. Porosity % of aggregate : $\frac{\text{vol of water poured in originally} - \text{vol of water poured out}}{\text{absolute vol. of saturated aggregate}}$

   $= \frac{712 - 603}{884} \times 100\% = 12.33\%$

6. Packing void percentage : $\frac{\text{volume of packing voids}}{\text{bulk volume of aggregate}} \times 100\%$

   $= \frac{603}{1487} \times 100\% = 40.55\%$

7. (a) Absolute density with pores : $\frac{\text{mass of oven dry stone}}{\text{abs vol. of saturated stone}} = \frac{2061}{884} = 2.331$ g/ml

   (b) Absolute density with no pores : $\frac{\text{mass of oven dry aggregate}}{\text{abs. vol. of dry aggregate}} = \frac{2061}{775} = 2.659$ g/ml

8. Specific gravity of material : 2.33 as porous material.
   2.66 as solid material.

Comments :

Compacted dry bulk density	= 1386 kg/m³	→	13.60 kN/m³
Compacted saturated " "	= 1459 kg/m³	→	14.31 kN/m³
Absolute porous density	= 2331 kg/m³	→	22.87 kN/m³

TESTING FOR PHYSICAL PROPERTIES OF AGGREGATES.

Sample Ref. No. Stockpile 13 - 19mm | Cylinder # 1 Volume V = 1497 ml | Date : 25-02-86

Readings taken :

A.	Mass of empty steel cylinder	gr	2676
B.	Mass of cylinder + oven dry stone	gr	4685
	POUR IN WATER AND LET SOAK FOR AT LEAST 24 HOURS.		
C.	Mass of cylinder + saturated stone + water	gr	5410
	EMPTY OUT WATER BY TURNING UPSIDE DOWN ON WIRE MESH.		
D.	Mass of cylinder + saturated stone (I)	gr	4833
	EMPTY OUT STONE. SURFACE DRY BRIEFLY + REFILL CYLINDER TO CHECK *BULKING.		
E.	Mass of cylinder + saturated stone (II)	gr	4810
	REFILL WITH WATER TO CHECK READING C.	gr	OK

Information gained : $\hat{D} = (4810 + 4833)/2 = 4821$ gr

F.	Mass of oven-dry aggregate in cylinder	$B - A$	gr	2009
G.	Mass of water in the cylinder	$C - B$	gr	725
H.	Mass of the saturated aggregate	$\hat{D} - A$	gr	2145
I.	Mass of water absorbed by the aggregate	$\hat{D} - B$.	gr	136
J.	Mass of the water emptied out	$C - \hat{D}$	gr	589
K.	Absolute volume of saturated aggregate	$(V - J)/1$ gr/ml	ml	908
L.	Absolute volume of oven-dry aggregate	$(V - G)/1$ gr/ml	ml	772
M.	Total volume of voids : ie packing voids + pores	$G/1$ gr/ml	ml	725

* Report on Bulking of Aggregate : None 0%

Other Comments :

Calculation of Physical Properties using the info gained in the experiment.

SAMPLE REFERENCE : Mix Design Stockpile . 13.2 - 19.0 mm stone

Calculations :

1. Dry bulk density (compacted) : $\dfrac{\text{mass of oven dry stone}}{\text{volume of cylinder}} = \dfrac{2009}{1497} = 1.342$ gr/ml

2. Saturated bulk density (compacted) : $\dfrac{\text{mass of saturated stone}}{\text{volume of cylinder}} = \dfrac{2145}{1497} = 1.433$ gr/ml

3. Absorption coefficient : $\dfrac{\text{mass of absorbed water}}{\text{oven dry mass of aggr.}} \times 100\,\% = \dfrac{136 \times 100}{2009} = 6.77\%$

4. Total voids percentage : $\dfrac{\text{total voids volume}}{\text{bulk volume}} \times 100\,\% = \dfrac{725 \times 100}{1497} = 48.43\%$

5. Porosity % of aggregate : $\dfrac{\text{vol of water poured in originally} - \text{vol. of water poured out}}{\text{absolute vol. of saturated aggregate}}$

$$= \frac{725 - 589}{908} \times 100\,\% = 14.98\,\%$$

6. Packing void percentage : $\dfrac{\text{Volume of packing voids}}{\text{bulk volume of aggregate}} \times 100\,\%$

$$= \frac{589}{1497} \times 100\,\% = 39.35\,\%$$

7. (a) Absolute density with pores : $\dfrac{\text{mass of oven dry stone}}{\text{abs vol. of saturated stone}} = \dfrac{2009}{908} = 2.213$ gr/ml

(b) Absolute density with no pores : $\dfrac{\text{mass of oven dry aggregate}}{\text{abs. vol. of dry aggregate}} = \dfrac{2009}{772} = 2.602$ gr/ml

8. Specific gravity of material : 2.21 as porous material.
2.60 as solid material.

Comments :
Compacted dry bulk density = 1342 kg/m³ ⇒ 13.17 kN/m³
Compacted saturated " " = 1433 kg/m³ ⇒ 14.06 kN/m³
Absolute porous density = 2013 kg/m³ ⇒ 21.71 kN/m³

TESTING FOR PHYSICAL PROPERTIES OF AGGREGATES.

Sample Ref. No. Mix Design Stockpile 9.5 – 13.2 mm	Cylinder # 1 Volume V = 1497 ml	Date : 27-02-86

Readings taken :

A.	Mass of empty steel cylinder	gr	2678
B.	Mass of cylinder + oven dry stone	gr	4687
	POUR IN WATER AND LET SOAK FOR AT LEAST 24 HOURS.		
C.	Mass of cylinder + saturated stone + water.	gr	5383
	EMPTY OUT WATER BY TURNING UPSIDE DOWN ON WIRE MESH.		
D.	Mass of cylinder + saturated stone (I)	gr	4884
	EMPTY OUT STONE. SURFACE DRY BRIEFLY + REFILL CYLINDER TO CHECK *BULKING.		
E.	Mass of cylinder + saturated stone (II)	gr	4854
	REFILL WITH WATER TO CHECK READING C.	gr	ok

Information gained : $\hat{D} = (D+E)/2 = 4869$ gr

F.	Mass of oven-dry aggregate in cylinder	: $B - A$	gr	2009
G.	Mass of water in the cylinder	: $C - B$	gr	696
H.	Mass of the saturated aggregate	: $\hat{D} - A$	gr	2191
I.	Mass of water absorbed by the aggregate	: $\hat{D} - B$.	gr	182
J.	Mass of the water emptied out	: $C - D$	gr	514
K.	Absolute volume of saturated aggregate	: $(V - J) / 1$ gr/ml	ml	983
L.	Absolute volume of oven-dry aggregate	: $(V - G) / 1$ gr/ml	ml	801
M.	Total volume of voids : ie packing voids + pores	: $G / 1$ gr/ml	ml	696

* Report on Bulking of Aggregate : Slight bulking ~ 13 mm.

Other Comments :

Calculation of Physical Properties using the info gained in the experiment.

SAMPLE REFERENCE : Mix Design Stockpile : 9.5 – 13.2 mm. stone.

Calculations :

1. Dry bulk density (compacted) : $\frac{\text{mass of oven dry stone}}{\text{volume of cylinder}} = \frac{2009}{1497} = 1.342\ \text{gr/ml}$

2. Saturated bulk density (compacted) : $\frac{\text{mass of saturated stone}}{\text{volume of cylinder}} = \frac{2191}{1497} = 1.464\ \text{gr/ml}$

3. Absorption coefficient : $\frac{\text{mass of absorbed water}}{\text{oven dry mass of aggr.}} \times 100\,\% = \frac{182 \times 100}{2009} = 9.06\,\%$

4. Total voids percentage : $\frac{\text{total voids volume}}{\text{bulk volume}} \times 100\,\% = \frac{696 \times 100}{1497} = 46.49\,\%$

5. Porosity % of aggregate : $\frac{\text{vol of water poured in originally} - \text{vol. of water poured out}}{\text{absolute vol. of saturated aggregate}}$

$= \frac{696 - 514}{983} \times 100\,\% = 18.51\,\%$

6. Packing void percentage : $\frac{\text{volume of packing voids}}{\text{bulk volume of aggregate}} \times 100\,\%$

$= \frac{514}{1497} \times 100\,\% = 34.34\,\%$

7. (a) Absolute density with pores : $\frac{\text{mass of oven dry stone}}{\text{abs vol. of saturated stone}} = \frac{2009}{983} = 2.044\ \text{gr/ml}$

(b) Absolute density with no pores : $\frac{\text{mass of oven dry aggregate}}{\text{abs. vol. of dry aggregate}} = \frac{2009}{801} =$

8. Specific gravity of material : 2.04 as porous material
2.51 as solid material.

Comments :

Compacted dry bulk density	= 1342 kg/m³	→	13.17 kN/m³
Compacted saturated " "	= 1464 kg/m³	→	14.36 kN/m³
Absolute porous density	= 2044 kg/m³	→	20.05 kN/m³

TESTING FOR PHYSICAL PROPERTIES OF AGGREGATES.

Sample Ref. No. Mix Design Stockpile 6.7 - 9.5 mm	Cylinder # 2 Volume V = 1487 ml	Date : 27-02-86

Readings taken :

A.	Mass of empty steel cylinder	gr	2636
B.	Mass of cylinder + oven dry stone	gr	4571
	POUR IN WATER AND LET SOAK FOR AT LEAST 24 HOURS.		
C.	Mass of cylinder + saturated stone + water	gr	5265
	EMPTY OUT WATER BY TURNING UPSIDE DOWN ON WIRE MESH.		
D.	Mass of cylinder + saturated stone (I)	gr	4784
	EMPTY OUT STONE, SURFACE DRY BRIEFLY + REFILL CYLINDER TO CHECK *BULKING.		
E.	Mass of cylinder + saturated stone (II)	gr	4754
	REFILL WITH WATER TO CHECK READING C.	gr	OK

Information gained : $\hat{D} = (D + E)/2 = 4769$ gr

F.	Mass of oven-dry aggregate in cylinder	: B - A	gr	1935
G.	Mass of water in the cylinder	: C - B	gr	694
H.	Mass of the saturated aggregate	: $\hat{D}$ - A	gr	2133
I.	Mass of water absorbed by the aggregate	: $\hat{D}$ - B.	gr	198
J.	Mass of the water emptied out	: C - $\hat{D}$	gr	496
K.	Absolute volume of saturated aggregate	: (V - J) / 1 gr/ml	ml	991
L.	Absolute volume of oven-dry aggregate	: (V - G) / 1 gr/ml	ml	793
M.	Total volume of voids : ie packing voids + pores	: G / 1 gr/ml	ml	694

* Report on Bulking of Aggregate : bulked to - 18 mm

Other Comments :

Calculation of Physical Properties using the info gained in the experiment.

SAMPLE REFERENCE : Mix Design Stockpile : 6.7 to 9.5 mm stone.

Calculations :

1. Dry bulk density (compacted) : $\frac{\text{mass of oven dry stone}}{\text{volume of cylinder}} = \frac{1935}{1487} = 1.301\ \text{gr/ml}$

2. Saturated bulk density (compacted) : $\frac{\text{mass of saturated stone}}{\text{volume of cylinder}} = \frac{2133}{1487} = 1.434\ \text{gr/ml}$

3. Absorption coefficient : $\frac{\text{mass of absorbed water}}{\text{oven dry mass of aggr.}} \times 100\,\% = \frac{198 \times 100}{1935} = 10.23\,\%$

4. Total voids percentage : $\frac{\text{total voids volume}}{\text{bulk volume}} \times 100\,\% = \frac{694 \times 100}{1487} = 46.67\,\%$

5. Porosity % of aggregate : $\frac{\text{vol of water poured in originally} - \text{vol. of water poured out}}{\text{absolute vol. of saturated aggregate}}$

$= \frac{694 - 496}{991} \times 100\,\% = 19.98\,\%$

6. Packing void percentage : $\frac{\text{volume of packing voids}}{\text{bulk volume of aggregate}} \times 100\,\%$

$= \frac{496}{1487} \times 100\,\% = 33.36\,\%$

7. (a) Absolute density with pores : $\frac{\text{mass of oven dry stone}}{\text{abs vol. of saturated stone}} = \frac{1935}{991} = 1.953\ \text{gr/ml}$

(b) Absolute density with no pores : $\frac{\text{mass of oven dry aggregate}}{\text{abs. vol. of dry aggregate}} = \frac{1935}{793} = 2.440\ \text{gr/ml}$

8. Specific gravity of material : 1.95 as porous material
2.44 as solid material.

Comments :

Compacted dry bulk density	=	1301 kg/m³	→	12.77 kN/m³
Compacted saturated " "	=	1434 kg/m³	→	14.07 kN/m³
Absolute porous density	=	1 953 kg/m³	→	19.15 kN/m³

TESTING FOR PHYSICAL PROPERTIES OF AGGREGATES.

Sample Ref. No. Mix Design Stockpile 4.75 - 6.7 mm stone | Cylinder # 1 Volume V = 1497 ml | Date : 05-05-[illegible]

Readings taken:

A.	Mass of empty steel cylinder	gr	2678
B.	Mass of cylinder + oven dry stone	gr	4582
	POUR IN WATER AND LET SOAK FOR AT LEAST 24 HOURS.		
C.	Mass of cylinder + saturated stone + water	gr	5305
	EMPTY OUT WATER BY TURNING UPSIDE DOWN ON WIRE MESH.		
D.	Mass of cylinder + saturated stone (I)	gr	4893
	EMPTY OUT STONE. SURFACE DRY BRIEFLY + REFILL CYLINDER TO CHECK *BULKING.		
E.	Mass of cylinder + saturated stone (II)	gr	4863
	REFILL WITH WATER TO CHECK READING C.	gr	OK

Information gained: $\hat{D} = (D + E)/2 = 4878$ gr

F.	Mass of oven-dry aggregate in cylinder	: B - A	gr	1904
G.	Mass of water in the cylinder	: C - B	gr	723
H.	Mass of the saturated aggregate	: $\hat{D}$ - A	gr	2200
I.	Mass of water absorbed by the aggregate	: $\hat{D}$ - B.	gr	296
J.	Mass of the water emptied out	: C - $\hat{D}$	gr	427
K.	Absolute volume of saturated aggregate	: (V - J) / 1 gr/ml	ml	1070
L.	Absolute volume of oven-dry aggregate	: (V - G) / 1 gr/ml	ml	774
M.	Total volume of voids : ie packing voids + pores	: G / 1 gr/ml	ml	723

* Report on Bulking of Aggregate : 140gr of sat. agg wouldn't fit i.e. 6.4%

Other Comments :

Calculation of Physical Properties using the info gained in the experiment.

SAMPLE REFERENCE : Mix Design Stockpile 4.75 - 6.70 mm chips

Calculations :

1. Dry bulk density (compacted) :
$$\frac{\text{mass of oven dry stone}}{\text{volume of cylinder}} = \frac{1904}{1497} = 1.272 \ \text{g/ml}$$

2. Saturated bulk density (compacted) :
$$\frac{\text{mass of saturated stone}}{\text{volume of cylinder}} = \frac{2200}{1497} = 1.470 \ \text{gr/ml}$$

3. Absorption coefficient :
$$\frac{\text{mass of absorbed water}}{\text{oven dry mass of agg.}} \times 100\,\% = \frac{296 \times 100}{1904} = 15.55\,\%$$

4. Total voids percentage :
$$\frac{\text{total voids volume}}{\text{bulk volume}} \times 100\,\% = \frac{723 \times 100}{1497} = 48.30\,\%$$

5. Porosity % of aggregate :
$$\frac{\text{vol. of water poured in originally} - \text{vol. of water poured out}}{\text{absolute vol. of saturated aggregate}}$$
$$= \frac{723 - 427}{1070} \times 100\,\% = 27.66\,\%$$

6. Packing void percentage :
$$\frac{\text{volume of packing voids}}{\text{bulk volume of aggregate}} \times 100\,\%$$
$$= \frac{427}{1497} \times 100\,\% = 28.52\,\%$$

7. (a) Absolute density with pores :
$$\frac{\text{mass of oven dry stone}}{\text{abs vol. of saturated stone}} = \frac{1904}{1070} = 1.779 \ \text{gr/ml}$$

(b) Absolute density with no pores :
$$\frac{\text{mass of oven dry aggregate}}{\text{abs. vol. of dry aggregate}} = \frac{1904}{774} = 2.460 \ \text{g/ml}$$

8. Specific gravity of material : 1.78 as porous material.
2.46 as solid material.

Comments :

Compacted dry bulk density : 1272 kg/m³ → 12.48 kN/m³

" saturated " " : 1470 kg/m³ → 14.42 kN/m³

Absolute porous density : ~~2460~~ 1780 kg/m³ → ~~24.13~~ 17.45 kN/m³

Calculation of the Overall Absorption, Porosity and Absolute Density for each sample tested.

"Mix design stockpile" sample :

(i) overall absorption coefficient

$$= \left\{ \frac{abs\,1 + abs\,2 + abs\,3 + abs\,4 + abs\,5}{Mass1 + Mass2 + Mass\,3 + Mass4 + Mass\,5} \right\} \times 100\%$$

$$= \left\{ \frac{109 + 136 + 182 + 198 + 296}{2061 + 2009 + 2009 + 1935 + 1904} \right\} \times 100\%$$

$$= 9.29\%$$

(ii) overall Porosity

$$= \left\{ \frac{abs1 + abs2 + abs\,3 + abs\,4 + abs\,5}{aV1 + aV2 + aV_3 + aV_4 + aV_5} \right\} \times 100\%$$

$$= \left\{ \frac{109 + 136 + 182 + 198 + 296}{884 + 908 + 983 + 991 + 1070} \right\} \times 100\%$$

$$= 19.04\%$$

(iii) overall absolute porous density

$$= \left\{ \frac{M_1 + M_2 + M_3 + M_4 + M_5}{aV_1 + aV_2 + aV_3 + aV_4 + aV_5} \right\}$$

$$= \left\{ \frac{2061 + 2009 + 2009 + 1935 + 1904}{884 + 908 + 983 + 991 + 1070} \right\}$$

$$= 2.051 \text{ gram / millilitre} \quad \text{or} \quad 2051 \text{ kg}/m^3$$

$$\therefore SG_{porous} = 2.051.$$

Sample # 1 :

(i) overall absorption coefficient

$$= \left\{ \frac{120 + 133 + 197}{1932 + 1982 + 1919} \right\} \times 100\%$$

$$= 7.71\%$$

(ii) overall Porosity

$$= \left\{ \frac{120 + 133 + 197}{842 + 875 + 967} \right\} \times 100\%$$

$$= 16.77\%$$

(iii) overall absolute porous density

$$= \left\{ \frac{1932 + 1982 + 1919}{842 + 875 + 967} \right\}$$

$$= 2.173 \text{ gram / millilitre}$$

$$= 2173 \text{ kg }/m^3$$

$$\therefore SG_{Porous} = 2.173$$

Sample # 4 :

(i) overall absorption coefficient

$$= \left(\frac{72 + 124 + 212}{2092 + 2016 + 1907} \right) * 100\ \%$$

$$= 6.78\ \%$$

(ii) overall porosity

$$= \left(\frac{72 + 124 + 212}{853 + 890 + 1009} \right) \times 100\ \%$$

$$= 14.83\ \%$$

(iii) overall absolute porous density

$$= \left(\frac{2092 + 2016 + 1907}{853 + 890 + 1009} \right)$$

$$= 2.186\ \mathrm{gr/ml} \quad \text{or} \quad 2186\ \mathrm{kg/m^3}$$

Sample # 5 :

(i) overall absorption coefficient

$$= \left(\frac{70 + 121 + 194}{1255 + 2091 + 2023} \right) \times 100\ \%$$

$$= 7.17\ \%$$

(ii) overall porosity

$$= \left(\frac{70 + 121 + 194}{553 + 920 + 1001} \right) \times 100\ \%$$

$$= 15.56\ \%$$

(iii) overall absolute porous density

$$= \left(\frac{1255 + 2091 + 2023}{553 + 920 + 1001} \right)$$

$$= 2.170\ \mathrm{gr/ml} \quad \text{or} \quad 2170\ \mathrm{kg/m^3}$$

Sample # 6 :

(i) overall absorption coefficient

$$= \left(\frac{89 + 127 + 211}{2149 + 1988 + 1912} \right) \times 100\ \%$$

$$= 7.06\ \%$$

(ii) overall porosity

$$= \left(\frac{89 + 127 + 211}{874 + 888 + 997} \right) \times 100\ \%$$

$$= 15.48\ \%$$

(iii) overall porous absolute density

$$= \left(\frac{2149 + 1988 + 1912}{874 + 888 + 997} \right)$$

$$= 2.192\ \mathrm{gr/ml}$$

$$= 2192\ \mathrm{kg/m^3}$$

$$\therefore\ SG_{\text{porous}} = 2.192.$$

Sample # 8 :

(i) overall absorption coefficient

$$= \left(\frac{82 + 110 + 220}{2135 + 1911 + 1958} \right) \times 100\%$$

$$= 6.86\%$$

(ii) overall porosity

$$= \left(\frac{82 + 110 + 220}{866 + 821 + 999} \right) \times 100\%$$

$$= 15.34\%$$

(iii) overall absolute porous density

$$= \left(\frac{2135 + 1911 + 1958}{866 + 821 + 999} \right)$$

$$= 2.235 \ {}^{gr}/{ml} \quad \text{or} \quad 2235 \ {}^{kg}/{m^3}$$

Sample # 9 :

(i) overall absorption coefficient

$$= \left(\frac{148 + 158 + -}{1867 + 2025 + -} \right) \times 100\%$$

$$= 7.86\%$$

(ii) overall porosity

$$= \left(\frac{148 + 158 + /}{863 + 958 + /} \right) \times 100\%$$

$$= 16.80\%$$

(iii) overall absolute porous density

$$= \left(\frac{1867 + 2025 + -}{863 + 958 + -} \right)$$

$$= 2.137 \ {}^{gr}/{ml} \quad \text{or} \quad 2137 \ {}^{kg}/{m^3}$$

Sample # 10 :

(i) overall absorption coefficient

$$= \left(\frac{82 + 103 + 179}{2044 + 2061 + 1946} \right) \times 100\%$$

$$= 6.02\%$$

(ii) overall porosity

$$= \left(\frac{82 + 103 + 179}{853 + 880 + 970} \right) \times 100\%$$

$$= 13.47\%$$

(iii) overall absolute porous density

$$= \left(\frac{2044 + 2061 + 1946}{853 + 880 + 970} \right)$$

$$= 2.239 \ {}^{gr}/{ml} \quad \text{or} \quad 2239 \ {}^{kg}/{m^3}.$$

APPENDIX A5

1. BS812 specification for the determination of the 10% Fines Crushing Value
2. Determination of the 10% FACT Values for the recycled aggregates

DETERMINATION OF AGGREGATE CRUSHING VALUE

34. *a*. **General.** The aggregate crushing value gives a relative measure of the resistance of an aggregate to crushing under a gradually applied compressive load. With aggregate of an aggregate crushing value of 30 or higher the result may be anomalous, and in such cases the ten per cent fines value (Clause 35) should be determined instead.

The standard aggregate crushing test shall be made as described in Subclauses *b* to *f* on aggregate passing a ½ in (12·70 mm) and retained on a ⅜ in (9·52 mm) BS test sieve. If required, or if the standard size of aggregate is not available, the test shall be made according to Subclause *g*.

b. **Apparatus.** The following apparatus is required for the standard test:

(i) An open-ended steel cylinder of nominal 6 in (15 cm) internal diameter, with plunger and baseplate, of the general form and dimensions shown in Fig. 12. The surfaces in contact with the aggregate shall be machined and case-hardened, or otherwise treated, so as to have a hardness value of not less than 650, in accordance with BS 427*, and shall be maintained in a smooth condition.

(ii) A straight metal tamping rod of circular cross section, ⅝ in (16 mm) diameter and 18 in to 24 in (45 cm to 60 cm) long. One end shall be rounded.

(iii) A balance of 3 kg capacity and accurate to 1 g.

(iv) BS test sieves of sizes ½ in (12·70 mm), ⅜ in (9·52 mm) and No. 7 (2·40 mm).

(v) A compression testing machine capable of applying a load of 40 ton (40·64 tonne) and which can be operated to give a uniform rate of loading so that this load is reached in ten minutes. The accuracy of the machine shall comply with the requirements of BS 1610† for a Grade A or a Grade B machine. The machine may be used with or without a spherical seating.

(vi) For measuring the sample, a cylindrical metal measure of sufficient rigidity to retain its form under rough usage and having an internal diameter of 4½ in (11·5 cm) and an internal depth of 7 in (18·0 cm).

c. **Preparation of test sample.** The material for the standard test shall consist of aggregate passing a ½ in (12·70 mm) and retained on a ⅜ in (9·52 mm) BS test sieve and shall be thoroughly separated on these sieves before testing.

The aggregate shall be tested in a surface-dry condition. If dried by heating the period of drying shall not exceed four hours, the temperature shall not exceed 110°C and the aggregate shall be cooled to room temperature before testing.

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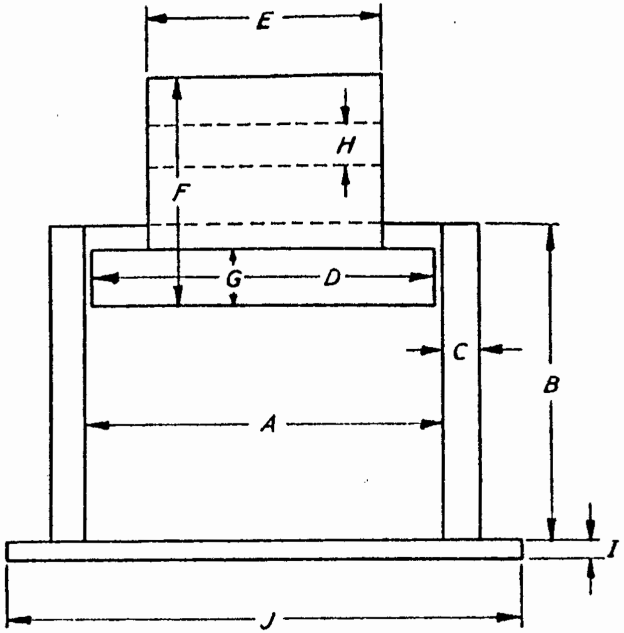
* BS 427, 'Method for Vickers hardness test', Part 1, 'Testing of metals'.

† BS 1610, 'Methods for the load verification of testing machines'.



KEY TO DIMENSIONS

Letter	Dimensions for	Nominal 6 in internal diameter cylinder		Nominal 3 in internal diameter cylinder	
	CYLINDER	in	mm	in	mm
A	Internal diameter	6 1/16 ± 1/64	154·0 ± 0·4	3 1/32 ± 1/64	77·0 ± 0·4
B	Internal depth	5 to 5½	127·0 to 139·7	2¾ to 3¼	70·0 to 82·5
C	Wall thickness	≮ ⅝	≮ 16·0	≮ 5/16	≮ 8·0
	PLUNGER				
D	Diameter of piston	6 ± 1/64	152·4 ± 0·4	3 ± 1/64	76·2 ± 0·4
E	Diameter of stem	3¾ to 6	95·2 to 152·4	1⅞ to 3	47·6 to 76·2
F	Overall length of piston plus stem	4 to 4½	101·6 to 114·3	2½ to 3	63·5 to 76·2
G	Depth of piston	≮ 1	≮ 25·4	≮ ¾	≮ 19·0
H	Diameter (nominal) of hole	¾	19·0	⅜	9·5
	BASEPLATE				
I	Thickness (nominal)	¼	6·5	¼	6·5
J	Length of each side of square	8 to 9	200 to 230	4¼ to 4½	110 to 115

Fig. 12. Outline form and principal dimensions of cylinder and plunger apparatus for aggregate crushing test

The quantity of aggregate shall be such that the depth of the material in the cylinder shall, after tamping as described in Subclause *d*, be 4 in (10 cm).

The appropriate quantity may be found conveniently by filling the cylindrical measure in three layers of approximately equal depth, each layer being tamped 25 times with the rounded end of the tamping rod and finally levelled off, using the tamping rod as a straightedge.

The weight of material comprising the test sample shall be determined (weight A) and the same weight of sample shall be taken for the repeat test.

d. **Test procedure.** The cylinder of the test apparatus shall be put in position on the baseplate, and the test sample added in thirds, each third being subjected to 25 strokes from the tamping rod. The surface of the aggregate shall be carefully levelled and the plunger inserted so that it rests horizontally on this surface care being taken to ensure that the plunger does not jam in the cylinder.

The apparatus, with the test sample and plunger in position, shall then be placed between the platens of the testing machine and loaded at as uniform a rate as possible so that the total load is reached in ten minutes. The total load shall be 40 ton (40·64 tonne).

The load shall be released and the whole of the material removed from the cylinder without further breaking of the sample and sieved on the No. 7 (2·40 mm) BS test sieve until no further significant amount passes in one minute. The fraction passing the sieve shall be weighed (weight B).

In all of these operations care shall be taken to avoid loss of the fines. Two tests shall be made.

e. **Calculations.** The ratio of the weight of fines formed to the total sample weight in each test shall be expressed as a percentage, the result being recorded to the first decimal place:

$$\text{Aggregate crushing value} = \frac{B}{A} \times 100$$

where A = weight in grammes of surface-dry sample,

B = weight in grammes of the fraction passing the No. 7 (2·40 mm) BS test sieve.

f. **Reporting of results.** The mean of the two results shall be reported to the nearest whole number as the aggregate crushing value.

g. **Determination of aggregate crushing value for non-standard sizes of aggregate.** (i) *General.* If required, or if the standard size is not available, tests may be made on aggregates of other sizes larger than the standard up to a size which passes a 1 in (25·40 mm) BS test sieve, using the standard apparatus. Alternatively, tests may be made on aggregates smaller than the standard down to a size which is retained on a No. 7 (2·40 mm) BS test sieve, using either the standard apparatus or that described in Subclause *g*(ii) which is referred to as the smaller apparatus.

Owing to the non-homogeneity of aggregates the results of tests on non-standard sizes will not be comparable with those obtained in the standard test. In general, the smaller sizes of aggregate will give a lower aggregate crushing value and the larger sizes a higher value, but the relationship between the values obtained will vary from one aggregate to another. However, the results obtained with the smaller apparatus have been found to be slightly higher than those with the standard apparatus and the errors for the smaller sizes of aggregate tested in the smaller apparatus are therefore compensatory.

(ii) *Apparatus.* The smaller apparatus shall be as follows:

A. An open-ended steel cylinder, with plunger and baseplate, generally as described in Subclause *b*(i), with a nominal internal diameter of 3 in (7·5 cm). The general form and dimensions of the cylinder and of the plunger are shown in Fig. 12.

B. A straight metal tamping rod of circular cross section ⁵⁄₁₆ in (8 mm) diameter and 12 in (30 cm) long. One end shall be rounded.

C. A balance of 500 g capacity and accurate to 0·2 g.

D. BS test sieves of appropriate sizes as given in Table 13.

E. A compression testing machine generally as described in Subclause *b*(v) except that it shall be capable of applying a load of 10 ton (10·16 tonne), and of being operated to give a uniform rate of loading so that this load is reached in 10 minutes.

F. A cylindrical metal measure generally as described in Subclause *b*(vi) except that it shall have an internal diameter of 2¼ in (6 cm) and an internal depth of 3½ in (9 cm).

(iii) *Preparation of test sample.* The material for tests on non-standard sizes shall consist of aggregate passing and retained on corresponding BS test sieves given in Table 13.

The procedure shall in other respects follow that given in Subclause *c* except that in tests with the smaller apparatus the quantity shall be such that the depth of material in the nominal 3 in (7·5 cm) internal diameter cylinder shall be 2 in (5 cm) after tamping with the smaller rod. The appropriate quantity may be found conveniently by using the smaller measure and tamping rod, but otherwise as described in Subclause *c*.

(iv) *Test procedure.* Tests on non-standard sizes shall follow the procedure given in Subclause *d* except that, when using the smaller apparatus, the smaller tamping rod shall be used and the total load shall be 10 ton (10·16 tonne). Particular care shall be taken with the larger sizes of aggregate to ensure that the plunger does not jam in the cylinder. The material removed from the cylinder shall be sieved on the appropriate sieve given in the ' For separating fines ' column in Table 13.

(v) *Calculations.* Calculations for tests on non-standard sizes shall follow the method given in Subclause *e*, substituting in the description of weight ' B ' the test sieve of appropriate size.

(vi) *Reporting of results.* Results of tests on non-standard sizes shall be reported as in Subclause *f* with, additionally, a report on the size of the aggregate tested and, if smaller than the standard size, the nominal size of the cylinder used in the test.

DETERMINATION OF THE TEN PER CENT FINES VALUE

35. *a.* **General.** The ten per cent fines value gives a measure of the resistance of an aggregate to crushing which is applicable to both weak and strong aggregates.

The standard ten per cent fines test shall be made as described in Subclauses *b* to *f* on aggregate passing a ½ in (12·70 mm) and retained on a ⅜ in (9·52 mm) BS test sieve. If required, or if the standard size of aggregate is not available, the test shall be made according to Subclause *g*.

b. **Apparatus.** The following apparatus is required for the standard test:

(i) An open-ended steel cylinder with plunger and baseplate, as described in Subclause 34*b*(i).

(ii) A tamping rod as described in Subclause 34*b*(ii).

(iii) A balance as described in Subclause 34*b*(iii),

(iv) BS test sieves as described in Subclause 34*b*(iv).

(v) A compression testing machine as described in Subclause 34*b*(v), except that the load which is to be applied may vary from ½ ton to 50 ton (½ tonne to 51 tonne).

(vi) A cylindrical metal measure as described in Subclause 34*b*(vi).

(vii) If required (see Note in Subclause *d*), a means of measuring to the nearest 0·05 in (1 mm) the reduction in distance between the platens of the testing machine during the test (e.g. a dial gauge).

c. **Preparation of test sample.** The preparation of the test sample shall be as described in Subclause 34*c* except that, in the case of weak materials, particular care shall be taken not to break the particles when filling the measure and the cylinder.

d. **Test procedure.** The cylinder of the test apparatus shall be put in position on the baseplate and the test sample added in thirds, each third being subjected to 25 strokes from the tamping rod, particular care being taken in the case of weak materials not to break the particles. The surface of the aggregate shall be carefully levelled and the plunger inserted so that it rests horizontally on this surface, care being taken to ensure that the plunger does not jam in the cylinder.

The apparatus, with the test sample and plunger in position, shall then be placed between the platens of the testing machine. Load shall be applied at as uniform a rate as possible so as to cause a total penetration of the plunger in ten minutes of about:

0·60 in (15 mm) for rounded or partially rounded aggregates (e.g. uncrushed gravels);

0·80 in (20 mm) for normal crushed aggregates;

0·95 in (24 mm) for honeycombed aggregates (e.g. some slags);

these figures may be varied according to the extent of the rounding or honeycombing.

NOTE. When an aggregate impact testing machine (Clause 33) is available, the load required for the first ten per cent fines test can be estimated by means of the following formula more conveniently than by the use of the dial gauge:

$$\text{Required load (ton)} = \frac{400}{\text{Aggregate impact value}}$$

This value of load will nearly always give a percentage fines within the required range of 7·5–12·5.

The maximum load applied to produce the required penetration shall be recorded. The load shall be released and the whole of the material removed from the cylinder without further breaking of the sample, and sieved on the No. 7 (2·40 mm) BS test sieve until no further significant amount passes in one minute. The fraction passing the sieve shall be weighed, and this weight expressed as a percentage of the weight of the test sample. Normally this percentage fines will fall within the range 7·5–12·5, but if it does not, a further test shall be made loading to a maximum value adjusted as seems appropriate to bring the percentage fines within the range of 7·5–12·5. (The formula given in Subclause 35*e* may be used for calculating the load required.)

In all of these operations care shall be taken to avoid loss of the fines. A repeat test shall be made at the maximum load that gives a percentage fines within the range 7·5–12·5.

e. **Calculations.** The mean percentage fines from the two tests at this maximum load shall be used in the following formula to calculate the load required to produce ten per cent fines:

$$\text{Load required to produce ten per cent fines} = \frac{14x}{y + 4}$$

where x = maximum load in ton,

y = mean percentage fines from two tests at x ton load.

f. **Reporting of results.** The load required to produce ten per cent fines shall be reported, to the nearest whole number for loads of 10 ton (10·2 tonne) or more or to the nearest 0·5 ton for loads of less than 10 ton (10·2 tonne), as the ten per cent fines value.

g. **Determination of the ten per cent fines value for non-standard sizes of aggregate.** (i) *General*. If required, or if the standard size is not available, tests may be made on aggregates of other sizes which pass a 1 in (25·40 mm) and are retained on a No. 7 (2·40 mm) BS test sieve. Because of the lack of experience of testing sizes other than the standard it has not been possible to give any indication as to how the results obtained on non-standard sizes would compare with those obtained in the standard test as in the case of the aggregate crushing value.

(ii) *Apparatus*. The apparatus shall be as described in Subclauses 35*b*(i), (ii), (iii), (v), (vi) and (vii).

BS test sieves of appropriate sizes shall be as given in Table 13.

(iii) *Preparation of test sample*. The material for tests on non-standard sizes shall consist of aggregate passing and retained on corresponding BS test sieves given in Table 13.

The procedure shall in other respects follow that given in Subclause *c*.

(iv) *Test procedure*. Tests on non-standard sizes shall follow the procedure given in Subclause *d*; it should be noted that the penetration of the plunger may not accord with the values given in Subclause *d*.

(v) *Calculations.* Calculations for tests on non-standard sizes shall follow the method given in Subclause *e*.

(vi) *Reporting of results.* Results of tests on non-standard sizes shall be reported as in Subclause *f* with, additionally, a report on the size of the aggregate tested.

DETERMINATION OF CRUSHING STRENGTH

36. *a.* **General.** When aggregates are not available, this test may be used to give a direct measure of the stress in lbf/in² (kgf/cm²) at ultimate failure of a rock under a slowly increasing compressive load.

b. **Apparatus.** (i) A compression testing machine the accuracy of which shall comply with BS 1610*, for a Grade A or B machine, and which shall include at least one platen having a spherical seating of not more than 1 in (2·5 cm) radius.

(ii) A well-ventilated oven thermostatically controlled to maintain a temperature of 105 ± 5°C.

c. **Test specimens.** The test specimens shall be cylinders of 1 ± 0·025 in (25·40 ± 0·63 mm) mean diameter and of 1 ± 0·025 in (25·40 ± 0·63 mm) mean height. In any one specimen the diameter shall not vary by more than 0·01 in (0·25 mm) and the height by not more than 0·005 in (0·13 mm). The end faces shall be at right angles to the cylindrical axis and shall be lapped plane to an accuracy of 0·001 in (0·025 mm).

In the preparation of the test specimens, the rock shall not be subjected to any treatment (such as chipping with a hammer) liable to induce incipient fracture. A copious flow of cold water shall be used throughout all grinding, drilling and sawing operations, to ensure that the aggregate is not damaged by overheating.

The test specimens shall be dried for four hours in the oven at a temperature of 105 ± 5°C and cooled before test.

If no planes of structural weakness are apparent, three specimens shall be tested. If planes of structural weakness are apparent, four specimens shall be tested, of which two shall have the planes at right angles to the axis of the cylinder.

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* BS 1610, ' Methods for the load verification of testing machines '.

d. **Procedure.** The mean diameter and height of each specimen shall be measured to an accuracy of 0·001 in (0·025 mm). The specimen shall be placed centrally between the steel platens without packing.

Each test shall be a direct compression test in which the load is applied to the ends of the cylindrical test specimen at a rate of about 5 ton (5·1 tonne) per minute. In making each test the final load necessary to produce crushing of the specimen shall be observed.

e. **Calculations.** The crushing strength shall be calculated in pounds-force per square inch from the final load and the mean cross-sectional area of the specimen.

f. **Reporting of results.** The value of the crushing strength for each individual specimen, and the average crushing strength shall be reported to the nearest 100 lbf/in² (7 kgf/cm²). Any peculiar condition of a test specimen which might affect the result of the test, such as the presence of seams, fissures, etc., shall be noted in the report.

DETERMINATION OF AGGREGATE ABRASION VALUE

37. *a.* **General.** This test gives a measure of the resistance of aggregates to surface wear by abrasion.

b. **Apparatus.** (i) An abrasion machine consisting essentially of a flat circular cast iron or steel grinding lap not less than 2 ft (60 cm) in diameter, which can be rotated in a horizontal plane at a speed of 28 to 30 rev/min and which is provided with the following accessories (see Figs. 13 and 14):

At least two trays for holding the test samples, made from ⅛ in (3 mm) mild steel plate and of *internal* dimensions 3¾ × 2¼ × 5/16 in (95 × 57 × 8 mm) (referred to below as the ' larger trays ').

Means for locating two of the larger trays with their centre points 10¼ in (26 cm) from the centre of the lap, diametrically opposite to each other and with their longer sides lying in the direction of rotation of the lap. The trays must be free to move in a vertical direction but restrained from moving in the horizontal plane.

A weight with a rounded base for pressing the test samples against the surface of the lap, having means for adjusting the weight to 2 kg ± 10 g.

Means for feeding sand continuously on the lap in front of each test sample at the rate of 1½–2 lb (680–900 g) per min, and for removing and recovering the sand after it has passed under the test samples.

(ii) BS test sieves ½ in (12·70 mm), ⅜ in (9·52 mm) and Nos. 18 (850 microns), 25 (600 microns), 36 (420 microns), 52 (300 microns) and 100 (150 microns).

(iii) A hotplate not less than 5 in (13 cm) square, giving a surface temperature of about 100°C.

10% FINES CRUSHING TEST.

Sample description : Sample # 1 : 13·2 mm – 19·0 mm fraction.

Maximum load reached : $x = 153$ kN

Displacement of piston : $\delta = 25{\cdot}0$ mm

Sieve analysis :

fraction :	mass:	mass:
> 6.70 mm	2978	3252 gr
4.75 – 6.70 mm	107	
2.38 - 4.75 mm	167	
≤ 2.38 mm	265	265 gr
Total mass of sample :	3517	3517 gr

Percentage of fines produced : $y = 7{\cdot}53$ %

Amount of aggregate remaining in original size fraction = not taken gr

= – %

10% FACT value = $\dfrac{14x}{y+4}$ = 186 kN.

10% FINES CRUSHING TEST.

Sample description : Sample # 4 : 13·2 mm – 19·0 mm fraction.

Maximum load reached : x = 166.0 kN

Displacement of piston : δ = 27.0 mm

Sieve analysis :

fraction :	mass:	mass:
> 6.70 mm	2962	3244 gr
4.75 – 6.70 mm	120	
2.38 – 4.75 mm	162	
≤ 2.38 mm	308	308 gr
Total mass of sample :	3552 gr	3552 gr

Percentage of fines produced : y = 8.76 %

Amount of aggregate remaining in original size fraction = not taken gr

= – %

10% FACT value = $\frac{14x}{y+4}$ = 182 kN

10% FINES CRUSHING TEST.

Sample description : Sample # 4 : 19.0 mm - 26.5 mm fraction

Maximum load reached : x = 256 kN

Displacement of piston : δ = 30.0 mm

Sieve analysis :

fraction :	mass:	mass:
> 6.70 mm	-	3445 gr
4.75 - 6.70 mm	-	
2.38 - 4.75 mm	-	
≤ 2.38 mm	291	291 gr
Total mass of sample :	3736 gr	3736 gr

Percentage of fines produced : y = 7.79 %

Amount of aggregate remaining in original size fraction = not taken gr

= — %

10% FACT value = $\frac{14x}{y+4}$ = 304 kN

10% FINES CRUSHING TEST.

Sample description : Sample # 5 : 13.2 mm to 19.0 mm

Maximum load reached : x = 215 kN

Displacement of piston : δ = 30.0 mm

Sieve analysis :

fraction :	mass:	mass:
> 6.70 mm	2887	3267 gr
4.75 - 6.70 mm	146	
2.38 - 4.75 mm	234	
≤ 2.38 mm	413	413 gr
Total mass of sample :	3680 gr	3680 gr

Percentage of fines produced : y = 11.22 %

Amount of aggregate remaining in original size fraction = not taken gr

= — %

10% FACT value = $\frac{14x}{y+4}$ = 198 kN

10% Fines Crushing Test.

Sample description : Sample #6 : 13.2mm – 19.0mm fraction

Maximum load reached : x = 181 kN

Displacement of piston : δ = 30.0 mm

Sieve analysis :

fraction :	mass:	mass:
> 6.70 mm	2600	2966 gr
4.75 – 6.70 mm	151	
2.38 – 4.75 mm	215	
≤ 2.38 mm	479	479 gr
Total mass of sample :	3445 gr	3445 gr

Percentage of fines produced : y = 13.90 %

Amount of aggregate remaining in original size fraction = not taken gr

= — %

10% FACT value $= \dfrac{14x}{y+4} =$ **142 kN**

10% FINES CRUSHING TEST.

Sample description : Sample #8 : 13·2 mm – 19·0 mm fraction.

Maximum load reached : $x = 259$ kN

Displacement of piston : $\delta = 30.0$ mm

Sieve analysis :

fraction :	mass :	mass :
> 6.70 mm	2764	3073 gr
4.75 – 6.70 mm	165	
2.38 – 4.75 mm	144	
≤ 2.38 mm	388	388 gr
Total mass of sample :	3461 gr	3461 gr

Percentage of fines produced : $y = 11{\cdot}21\ \%$

Amount of aggregate remaining in original size fraction = 1750 gr

= 51 %

10% FACT value = $\dfrac{14x}{y+4}$ = 238 kN

10% FINES CRUSHING TEST.

Sample description : Sample # 9 : 13·2 mm - 19·0 mm fraction.

Maximum load reached : x = 200 kN

Displacement of piston : δ = 30.0 mm

Sieve analysis :

fraction :	mass :	mass :
> 6.70 mm	2522	2949 gr
4.75 - 6.70 mm	163	
2.38 - 4.75 mm	264	
≤ 2.38 mm	421 gr	421 gr
Total mass of sample :	3370 gr	3370 gr

Percentage of fines produced : y = 12.49 %

Amount of aggregate remaining in original size fraction = 1110 gr

= 33 %

10% FACT value $= \dfrac{14\,x}{y+4}$ = 170 kN

10% FINES CRUSHING TEST.

Sample description : Sample # 10 : 13·2mm - 19·0mm fraction.

Maximum load reached : x = 222 kN

Displacement of piston : δ = 29·5 mm

Sieve analysis :

fraction :	mass:	mass:
> 6.70 mm	2834	3181 gr
4.75 - 6.70 mm	137	
2.38 - 4.75 mm	210	
≤ 2,38 mm	452	452 gr
Total mass of sample :	3633 gr	3633 gr

Percentage of fines produced : y = 12·44 %

Amount of aggregate remaining in original size fraction = 1962 gr

= 54 %

10% FACT value = $\frac{14x}{y+4}$ = 189 kN

10% FINES CRUSHING TEST.

Sample description : Stockpile of Recycled aggregate 13·2 mm - 19·0 mm fraction. } Test 1

Maximum load reached : $x = 153$ kN

Displacement of piston : $\delta = 26.0$ mm

Sieve analysis :

fraction :	mass:	mass:
> 6.70 mm	2675	3041 gr
4.75 - 6.70 mm	174	
2.38 - 4.75 mm	192	
≤ 2.38 mm	390	390 gr
Total mass of sample :	3431 gr	3431 gr

Percentage of fines produced : $y = 11{\cdot}37\ \%$

Amount of aggregate remaining in original size fraction = 1706 gr

= 50 %

* **10% FACT value** $= \dfrac{14x}{y+4} =$ 139 kN

---

* A second test produced a value of 192 kN ⇒ mean FACT value = 165 kN

10% FINES CRUSHING TEST.

Sample description : Recycled aggregate Stockpile
13·2 mm - 19·0 mm fraction } TEST 2

Maximum load reached : $x = 179$ kN

Displacement of piston : $\delta = 27{\cdot}0$ mm

Sieve analysis :

fraction :	mass:	mass:
> 6.70 mm	2709	3107 gr
4.75 - 6.70 mm	180	
2.38 - 4.75 mm	218	
≤ 2.38 mm	308	308 gr
Total mass of sample :	3415 gr	3415 gr

Percentage of fines produced : $y = 9.02$ %

Amount of aggregate remaining in original size fraction = 1636 gr

= 48 %

$$*\text{10\% FACT value} = \frac{14x}{y+4} = \underline{192\ \text{kN}}$$

---

* The first test produced the value of 139 kN ⇒ mean 10% FACT = 165 kN

10% FINES CRUSHING TEST.

Sample description : Recycled aggregate Stockpile
9.5mm – 13.2 mm fraction } TEST 1

Maximum load reached : $x = 135$ kN

Displacement of piston : $\delta = 26.0$ mm

Sieve analysis :

fraction :	mass:	mass:
> 6.70 mm	–	2926 gr
4.75 – 6.70 mm	–	
2.38 – 4.75 mm	–	
≤ 2.38 mm	–	439 gr
Total mass of sample :	–	3365 gr

Percentage of fines produced : $y = 13.05\,\%$

Amount of aggregate remaining in original size fraction = 1679 gr

= 50 %

*10% FACT value $= \dfrac{14x}{y+4} =$ 111 kN

---

* The value produced in the second test was 106 kN ∴ mean 10% FACT = 108 kN

10% FINES CRUSHING TEST.

Sample description : Recycled aggregate Stockpile
9.5 mm – 13.2 mm fraction } TEST 2

Maximum load reached : $x = 118$ kN

Displacement of piston : $\delta = 25.0$ mm

Sieve analysis :

fraction :	mass:	mass:
> 6.70 mm	-	2952 gr
4.75 – 6.70 mm	-	
2.38 – 4.75 mm	-	
≤ 2.38 mm	-	385 gr
Total mass of sample :	-	3337 gr

Percentage of fines produced : $y = 11.54$ %

Amount of aggregate remaining in original size fraction = 1799 gr

= 54 %

* **10% FACT value** = $\frac{14x}{y+4}$ = 106 kN

---

* The value in the first test was 111 kN ∴ the mean 10% FACT value = 108 kN

APPENDIX A6

1. Details of the Wet Batched Recycled Concrete Mixes made

2. Record of the Moisture Content of the Klipheuwel sand used in these mixes

3. Correlation of the Actual and Theoretical Mortar Excess Values found for this mix series

Mix Design with Rubble Aggregate. Mix Code 100 - 20 #1

1. Batched Materials.

	calculated kg/m³	batched gr	adjustment gr	* adjustment gr	FINAL gr
rubble stone (saturated)	1884	8500			8500
klipheuwel sand (air dry)	441	1990		-2	1988
rapid hardening cement	120	541			541
water	120	541		+2	543

2. Details of first batch: Comments:

slump = collapse, say 150 mm

V.B. = 1 sec, not applicable really

Mortar excess = h = 75 mm ; d = -43 mm M.C = +34.7%

3. Adjustment of mix to give ≐ 70 mm slump. (I attempt only!)

4. Details of second mix. Comments:

Slump =

V.B. =

mortar excess =

5. * Water content of sand : M.C = 0.10%

Sand 22/4 ∴ add 2 gr of water

6. Tested cubes :

Cubes not cast

Too little mortar.

cube #	mass	crushing force	density	strength
1.				
2.				
3.				
4.				
5.				

Mix Design with Rubble Aggregate. Mix Code 100 - 30 #2

1. Batched Materials.

	calculated kg/m³	batched gr	adjustment gr	* adjustment gr	FINAL gr
rubble stone (saturated)	1571	8500	+ 1990		10 490
klipheuwel sand (air dry)	631	3414	+ 800	-4	4210
rapid hardening cement	150	812			812
water	150	812		+4	816

2. Details of first batch: Comments

Slump = the water was about 190 ml too much

V.B. =

Mortar excess =

3. Adjustment of mix to give ≐ 70 mm slump. (I attempt only!)

Attempt to remove 190 ml water i.e. add 800 gr sand
1990 gr saturated stone

4. Details of second mix. Comments:

Slump = either stands (20mm) or collapses, say 50mm

V.B. = 1.8 sec

mortar excess = exactly zero, but mix segregates though
i.e. the sand sinks.

5. * Water content of sand :

Sand 22/4 M.C = 0.10% add 4 gr of water

6. Tested cubes :

cube #	mass gr	crushing force kN	density	strength
1.	2327	118	2327	11.8
2.	2321	119	2321	11.9
3.	2338	108	2338	10.8
4.	2360	121	2360	12.1
5.	–	–	–	–
			2337	11.6

effective c/w = 1.00

Mix Design with Rubble Aggregate.

#4

Mix Code: 100 - 50 ✓

1. Batched Materials.

	calculated kg/m³	batched gr	adjustment gr	* adjustment gr	FINAL gr
rubble stone (saturated)	1104	7000	✓	✓	7000
klipheuwel sand (air dry)	1034	6556	✓	-7	6549
rapid hardening cement	160	1014	✓	✓	1014
water	160	1014	✓	+7	1021

2. Details of first batch:

Comments: Runny + Sandy appearance. Segregation occurs

Slump = 50mm

V.B. = 2 sec

Mortar excess = d = 29mm
h = 49mm

m.e = 14.7 ~~[illegible]~~ %

3. Adjustment of mix to give ÷ 70 mm slump. (1 attempt only!)

4. Details of second mix.

Comments:

Slump =

V.B. =

mortar excess =

5. * Water content of sand : m.c = 0.01%

Sand 22/4

6. Tested cubes:

cube #	mass	crushing force	density	strength
1.	2326	126	2326	12.6
2.	2344	141	2344	14.1
3.	2350	134	2350	13.4
4.	2333	122	2333	12.2
5.	✓	✓	✓	✓
			2338	13.1 MPa

effective c/w = 0.99
w/c = 1.01

Mix Design with Rubble Aggregate.

Mix Code: 100 - 40 #3

1. Batched Materials.

	calculated kg/m³	batched gr	adjustment gr	* adjustment gr	FINAL gr
rubble stone (saturated)	1329	8000	+ 480		8480
klipheuwel sand (air dry)	830	4996	+ 300	-5	5291
rapid hardening cement	158	951			951
water	158	951		+ 5	956

2. Details of first batch:

Comments:

Slump = 150 mm or so.

V.B. =

Mortar excess =

3. Adjustment of mix to give ÷ 70 mm slump. (1 attempt only!)

Add sand equivalent to about 10 l of water ⇒ 50 kg/m³ sand
+ 300 gr sand
+ 480 gr saturated stone

4. Details of second mix.

Comments:

Slump = 30 mm with stone interference ∴ actual about 60 mm

V.B. = not taken initially, later 2 sec.

mortar excess = d = 12 mm
h = 51 mm

m.e = 8.1 %

5. * Water content of sand :

Sand 22/4

m.c. = 0.10% ∴ add 5 gr water

6. Tested cubes:

cube #	mass	crushing force	density	strength
1.		122	2341	12.2
2.		115	2358	11.5
3.		116	2348	11.6
4.		126	2369	12.6
5.		✓	✓	✓
			2354	12.0

effective c/w = 0.99
w/c = 1.01

Mix Design with Rubble Aggregate.

#6
Mix Code 125 - 20 ✓

1. Batched Materials.

	calculated kg/m³	batched gr	adjustment gr	* adjustment gr	FINAL gr
rubble stone (saturated)	1853	8500	/	/	8500
klipheuwel sand (air dry)	434	1991	/	-2	1989
rapid hardening cement	154	706	/	/	706
water	123	564	/	+2	566

2. Details of first batch:

Comments:

slump = runny 150mm or so

V.B. =

Mortar excess = h = 78
d = -30 mm

∴ M.E. = - 24%

3. Adjustment of mix to give ≑ 70 mm slump. (1 attempt only!)

4. Details of second mix.

Comments:

Slump =

V.B. =

mortar excess =

5.* Water content of sand : M.C. = 0.07%

sand 15/4

adjust by 2gr.

6. Tested cubes:

not cast

would be impossible.

cube #	mass	crushing force	density	strength
1.				
2.				
3.				
4.				
5.				

effective c/w = 1.25

Mix Design with Rubble Aggregate.

#5
Mix Code 100 - 60 ✓

1. Batched Materials.

	calculated kg/m³	batched gr	adjustment gr	* adjustment gr	FINAL gr
rubble stone (saturated)	861	6500	/	/	6500
klipheuwel sand (air dry)	1209	9127	/	-6	9121
rapid hardening cement	175	1321	/	/	1321
water	175	1321	/	+6	1327

2. Details of first batch:

Comments

slump = 50mm

V.B. = 2.3 sec.

Mortar excess = d = 23 mm
h = 22 mm

∴ M.E. = 12.9%

3. Adjustment of mix to give ≑ 70 mm slump. (1 attempt only!)

4. Details of second mix.

Comments:

Slump =

V.B. =

mortar excess =

5.* Water content of sand : M.C = 0.07%

sand 15/4

adjust by 6gr

6. Tested cubes:

All failures in paste

not coarse aggr. seen

cube #	mass gr	crushing force kN	density kg/m³	strength MPa
1.	2323	122	2323	12.2
2.	2333	122	2333	12.2
3.	2331	121	2331	12.1
4.	2337	121	2337	12.1
5.	/	/	/	/
			2331	12.1 MPa

effective c/w = 1.00

Mix Design with Rubble Aggregate.

#8
Mix Code 125 - 40 ✓

1. Batched Materials.

	calculated kg/m³	batched gr	adjustment gr	* adjustment gr	FINAL gr
rubble stone (saturated)	1300	8000	+ 1143	/	9143
klipheuwel sand (air dry)	802	4997	+ 714	-4	5707
rapid hardening cement	201	1237	/	/	1237
water	161	991	/	+4	995

2. Details of first batch:

Comments:

slump = > 150 mm
V.B. =
Mortar excess =

3. Adjustment of mix to give ÷ 70 mm slump. (1 attempt only!)

Add lots of sand : 714gr
+ 1143 stone

4. Details of second mix.

Comments:

slump = 50mm Stone interference actual sl = 20 mm
V.B. = 2.8sec but visibly a great deal more
mortar excess = d = 12mm
h = 39mm
m.e = 7.5%

5. Water content of sand : M.C = 0.07%

* sand 15/4
adjust by 4 gr

6. Tested cubes :

cube #	mass	crushing force	density kg/m³	strength
1.	2349	158	2349	15.8
2.	2362	156	2362	15.6
3.	2357	159	2357	15.9
4.	2359	145	2359	14.5
5.	/	/	/	/
			2357	15.4 MPa

erratic load curve

effective c/w = 1.24

Mix Design with Rubble Aggregate.

#7
Mix Code 125 - 30 ✓

1. Batched Materials.

	calculated kg/m³	batched gr	adjustment gr	* adjustment gr	FINAL gr
rubble stone (saturated)	1534	8500	+ 1992	/	10 492
klipheuwel sand (air dry)	616	3413	+ 800	- 3	4210
rapid hardening cement	194	1075	/	/	1075
water	155	859	/	+ 3	862

2. Details of first batch:

Comments

slump = very high
V.B. =
Mortar excess =

3. Adjustment of mix to give ÷ 70 mm slump. (1 attempt only!)

Add lots of sand : try 800gr sand
+ 1992gr stone

4. Details of second mix.

Comments:

slump = measured ~~actual~~ = 15mm but actual ~ 40mm
V.B. = /
mortar excess = d = 5mm
h = 19mm
m.e. = 2.8%

5. * Water content of sand : M.C = 0.07%

Sand 15/4
adjust by 3gr

6. Tested cubes :

cube #	mass	crushing force	density	strength
1.	2361	191	2361	19.1
2.	2337	193	2337	19.3
3.	2395	185	2395	18.5
4.	2340	185	2340	18.5
5.	/	/	/	/
			2358	18.8 MPa

effective c/w = 1.05

Mix Design with Rubble Aggregate.

#10
Mix Code 125-60

1. Batched Materials.

	calculated kg/m³	batched gr	adjustment gr	* adjustment gr	FINAL gr
rubble stone (saturated)	845	6500	+285	/	6785
Klipheuwel sand (air dry)	1187	9131	+415	-7	9539
rapid hardening cement	219	1685	/	/	1685
water	175	1346	/	+7	1353

2. Details of first batch:

Comments:

Slump · 95mm

V.B. ·

Mortar excess ·

3. Adjustment of mix to give ≈ 70 mm slump. (1 attempt only!)

Reduce water by 8 litres

⇒ add sand 54 kg/m³

stone 37 kg/m³

4. Details of second mix.

Comments: Coarse sand segregation

Slump = 50 mm

V.B. = 1.8 sec

mortar excess = h = 17mm, d = 22 mm ∴ m.e = 12.1%

5.* Water content of sand : m.c = 0.07%

sand 15/4

adjust by adding 7 gr water from sand.

6. Tested cubes:

cube #	mass gr	crushing force kN	density kg/m³	strength MPa
1.	2376	182	2376	18.2
2.	2336	169	2336	16.9
3.	2339	175	2339	17.5
4.	2339	175	2339	17.5
5.	/	/	/	/
			2347	17.5 MPa

effective c/w = 1.25

Mix Design with Rubble Aggregate.

#9
Mix Code 125-50

1. Batched Materials.

	calculated kg/m³	batched gr	adjustment gr	* adjustment gr	FINAL gr
rubble stone (saturated)	1080	7500	+368	/	7868
Klipheuwel sand (air dry)	1012	7028	+347	-5	7370
rapid hardening cement	204	1417	/	/	1417
water	163	1132	/	+5	1137

2. Details of first batch:

Comments:

Slump · ~100 mm

V.B. ·

Mortar excess ·

3. Adjustment of mix to give ≈ 70 mm slump. (1 attempt only!)

Add -8 l/m³ water i.e. add sand = 50 kg/m³

stone = 53 kg/m³

4. Details of second mix.

Comments:

Slump = 60mm

V.B. = n/t 2.2sec

mortar excess = d = 17mm

h = 30mm

m.e. = 10.1%

5.* Water content of sand :

sand 15/4

M.C = 0.07% → adjust by 5gr

6. Tested cubes:

cube #	mass gr	crushing force kN	density kg/m³	strength MPa
1.	2357	161	2357	16.1
2.	2366	179	2366	17.9
3.	2361	165	2361	16.5
4.	2357	165	2357	16.5
5.	/	/	/	/
			2360	16.7 MPa

effective c/w = 1.25

Mix Design with Rubble Aggregate.

\# 12
Mix Code 150 - 30 ✓

1. Batched Materials.

	calculated	batched	adjustment	*adjustment	FINAL
rubble stone (saturated)	1486	9000	+ 235	/	9235
klipheuwel sand (air dry)	597	3616	+ 220	-5	3831
rapid hardening cement	245	1484	/	/	1484
water	163	987	/	+5	992

try to remove 10 ℓ/m³ i.e add 36.6 kg/m³ sand

2. Details of first batch.

Comments

Slump = 85mm

V.B. = 2 secs

Mortar excess = not taken, ~0% it seemed

Mortar excess seemed about 0%

3. Adjustment of mix to give ≑ 70 mm slump. (1 attempt only!)

Added 220 gr of sand + 235 gr of saturated stone.
Mix stiffened up well and first slump measurement gave 60mm
when the mould collapsed / toppled over. Next attempt almost toppled
but didn't and very low slump resulted ~ 15mm, slump definitely more!

4. Details of second mix.

Comments:

Slump = 30 mm

V.B. = 8-9 sec

mortar excess = d = 5mm, h = 60mm ⇒ m.e = 3.6%
(d = 3mm m.e ≑ 2.2%) (possibly even less)

5. * Water content of sand : M.C = 0.18%

Sand 18/3

add 5 gr to water from sand

6. Tested cubes :

cube #	mass gr	crushing force kN	density kg/m³	strength MPa
1.	2361	212	2361	21.2
2.	2407	218	2407	21.8
3.	2364	214	2364	21.4
4.	2365	213	2365	21.3
5.	/	/	/	/
			2374 gr	21.4 MPa

effective c/w = 1484/992 = 1.50

Mix Design with Rubble Aggregate.

\# 11
Mix Code 150 - 20 ✓

1. Batched Materials.

	calculated kg/m³	batched gr	adjustment gr	*adjustment gr	FINAL gr
rubble stone (saturated)	1699	8500	+ 854	/	9354
klipheuwel sand (air dry)	398	1991	+ 200	- 4	2187
rapid hardening cement	245	1226	/	/	1226
water	163	815	/	+ 4	819

2. Details of first batch.

Comments mortar deficiency visible
very liquid mortar, though

Slump = 150mm (inexact)

V.B. = not taken

Mortar excess = not taken

3. Adjustment of mix to give ≑ 70 mm slump. (1 attempt only!)

add 15 kg/m³ water in sand + stone i.e 37 gr of one, no!
added 300 gr sand + ~~1280~~ stone 854 gr s

4. Details of second mix.

Comments:

Slump = still collapses 150mm or so

V.B. = not taken

mortar excess = deficiency d = -10mm h = 68mm m.d = 7.6%

5. * Water content of sand : M.C = 0.20%

sand 19/3

∴ add 4 gr from sand to water.

6. Tested cubes :

Why such low strength?

Original mix very liquid and the sand not well graded so segregation occurs (seen in m.e. test) and the cube's uniformity is badly impaired.

cube #	mass kg	crushing force kN	density kg/m³	strength MPa
1.	2317	156	2317	15.6
2.	2355	158	2355	15.8
3.	2390	159	2390	15.9
4.	2329	154	2329	15.4
5.	/	/	/	/
			2348	15.7 MPa

∴ effective c/w = 1226/819 = 1.50

Mix Design with Rubble Aggregate.

\# 13 **Mix Code** 150 - 40 ✓

1. Batched Materials.

	calculated	batched	adjustment	*adjusted	FINAL
rubble stone (saturated)	1274	9000	N/A	/	9000
klipheuwel sand (air dry)	796	5623		- 7	5616
rapid hardening cement	245	1731		/	1731
water	163	1151		+ 7	1158

2. Details of first batch:

Slump = 52mm

V.B. = 4.7 sec

Mortar excess = D = 199mm ; d = 15mm ; h = 58mm ⇒ m.e = 9.3%

Comments: Seemed like a perfectly good workable concrete with sand content perhaps slightly too much

3. Adjustment of mix to give ± 70 mm slump. (1 attempt only!)

not required as all mixes must fall between 50 and 70mm slump

4. Details of second mix: N/A

Comments:

Slump =

V.B. =

mortar excess =

5. *Water content of sand : W.C = 0.13% ∴ add 7gr to water

Sand 18/3

6. Tested cubes:

cube #	mass gr	crushing force kN	density kg/m³	strength MPa
1.	2385	199	2385	19.9
2.	2358	192	2358	19.2
3.	2379	115	0 2379	11.5
4.	2370	200	2370	20.0
5.	/	/	/	/
		MEAN	2373	19.7 MPa

outlier

Something went wrong distinctly so ignore

effective C/W ratio = 1731/1158 = 1.49

Mix Design with Rubble Aggregate.

\# 13 TRIAL MIX **Mix Code** 150 - 40

1. Batched Materials.

	calculated	batched gr	adjustment	*adjusted	FINAL
rubble stone (saturated)	1257	9000	+ 800		9800
klipheuwel sand (air dry)	785	5621	+ 500	- 122	6121
rapid hardening cement	255	1826	i.e. reduced water by		1826
water	170	1217	108 gr.	+ 122	1217

effectively reduced this to 155 kg/m³

2. Details of first batch:

Slump = 102mm

V.B. = not taken

Mortar excess = not taken

(FG 12; K 1.225)

Comments: The water demand of 170 kg/m³ is too high and need to *reduce it to get slump from 100mm to ± 60mm say need to reduce water by 8 kg/m³

3. Adjustment of mix to give ± 70 mm slump. (1 attempt only!)

Added 500gr sand & 800gr saturated stone

4. Details of second mix.

Comments:

Slump = 20mm

V.B. = not taken

mortar excess = 22^{d}mm / 33^{h}mm D = ⇒ m.e =

5. *Water content of sand : say 2% , ∴ add water = 0.02 × (5621 + 500) =

Sand 18/3

6. Tested cubes:

cube #	mass	crushing force	density	strength
1.				
2.				
3.				
4.				
5.				

Will use water requirement of sand as 163 kg/m³ instead of the previous estimation of 170.

This could be largely due to the moisture content. P.T.O

225 -20

	calculated	batched gr	adjustment gr	adjustment gr	FINAL gr
	~~422~~	8500			
(air dry)	~~377~~ 413	1984			
hardening cement	~~307~~ 277	1334			
water	123	~~854~~ 592			

by experience : water demand = 123 kg/m³

2. Details of first batch : Comments

Slump •

V.B. •

Mortar excess •

Mix was not made because it would be impractical concrete as previous 20% sand mixes have shown.

3. Adjustment of mix to give ± 70 mm slump. (1 attempt only !)

4. Details of second mix : Comments :

Slump =

V.B =

mortar excess =

5. Water content of sand

6. Tested cubes

cube #	mass	crushing force	density	strength
1.				
2.				
3.				
4.				
5.				

Mix Design with Rubble Aggregate.

#27

Mix Code 225 - 30

1. Batched Materials.

	calculated kg/m³	batched gr	adjustment gr	*adjustment gr	FINAL gr
rubble stone (saturated)	1487	8500	/	/	8500
klipheuwel sand (air dry)	~~586~~ 573	3413	/	-2	3411
rapid hardening cement	~~387~~ 356	~~2892~~ 2121	/	/	2121
water	~~163~~ 158	~~963~~ 941	/	+2	943

by experience for ~ 60 mm slump need 158 litres of water

adjust

2. Details of first batch. Comments

Slump • 65 mm

V.B. • 15 sec

Mortar excess • d = 4 mm ; h = 62 mm m.e = 2,9%

3. Adjustment of mix to give ± 70 mm slump. (1 attempt only !)

4. Details of second mix. Comments :

Slump =

V.B =

mortar excess =

5.* Water content of sand m.c = 0.07%

Sand 07/4 add to water

6. Tested cubes : 4 pm

cube #	mass	crushing force	density	strength
1.	2371	329	2371	32.9
2.	2346	330	2346	33.0
3.	2371	316	2371	31.6
4.	2364	323	2364	32.3
5.	/	/	/	/
			2363	32.4

Cubes were quite difficult to cast, seems to be the limit for heavy vibro-compacted concrete.!

effective c/w = 2.25

Mix Design with Rubble Aggregate.

\# 15

Mix Code 150 - 60 ✓

1. Batched Materials.

	calculated kg/m³	batched gr	adjustment gr	*adjustment gr	FINAL gr
rubble stone (saturated)	850	8500	/	/	8500
klipheuwel sand (air dry)	1193	11930	/	-24	11906
rapid hardening cement	245	2450	+ 90	/	2540
water	163	1630	+ 60	+ 24	1714

2. Details of first batch.

Comments Mix visibly oversanded, but of good consistency

Slump = 25 mm

V.B. = 3.0 seconds

Mortar excess = not taken

3. Adjustment of mix to give ± 70 mm slump. (1 attempt only!)

Add about 6 kg/m³ of water ie 60 ml water
+ 90 gr cement

4. Details of second mix.

Comments:

Slump = 45 mm

V.B. = 2.4 sec

mortar excess = d = 26 mm, h = 22 mm ∴ m.e = ~~[illegible]%~~ 15.0%

5. *Water content of sand

m.c = 0.20 %

sand 14/3

add 24 gr water from sand

6. Tested cubes:

Excellent finish on cubes

cube #	mass gr	crushing force kN	density kg/m³	strength MPa
1.	2366	232	2366	23.2
2	2348	226	2348	22.6
3.	2362	240	2362	24.0
4.	2343	236	2343	23.6
5.	/	/	/	/
			2355	23.3 MPa

effective c/ω = 2540/1714 = 1.48

Mix Design with Rubble Aggregate.

\# 14

Mix Code 150 - 50 ✓

1. Batched Materials.

	calculated	batched	adjustment	*adjustment	FINAL
rubble stone (saturated)	1062	9000	N/A	/	9000
klipheuwel sand (air dry)	995	8432	/	- 11	8421
rapid hardening cement	245	2076	/	/	2076
water	163	1381	/	+ 11	1392

2. Details of first batch.

Comments A [illegible] liking concrete again. Good workability, but slightly too much mortar

Slump = 60 mm

V.B. = 2.6 sec

Mortar excess = D = 199 mm, d = 20 mm, h = 5 mm → m.e = 10.3%

3. Adjustment of mix to give ± 70 mm slump. (1 attempt only!)

Not required

4. Details of second mix. N/A

Comments:

Slump =

V.B. =

mortar excess =

5. *Water content of sand

ω.c = 0.13% → add 11 gr to water

sand 18/3

6. Tested cubes:

cube #	mass gr	crushing force kN	density kg/m³	strength MPa
1.	2362	207	2362	20.7
2	2345	213	2345	21.3
3.	2369	215	2369	21.5
4	2358	194	2358	19.4
5.	/	/	/	/
		MEAN:	2359	20.7 MPa

effective c/ω ratio = 2076/1392 = 1.49

Mix Design with Rubble Aggregate.

#17
Mix Code 175 - 30 ✓

1. Batched Materials

	kg/m³ calculated	batched gr	adjustment gr	* adjusted gr	FINAL gr
rubble stone (saturated)	1462	8500	+ 249	–	8749
klipheuwel sand (air dry)	587	3413	+ 100	- 4	3509
rapid hardening cement	285	1657	–	–	1657
water	163	948	–	+ 4	952

2. Details of first batch

Comments Runny mix

Slump = 120 mm or over

V.B. = 1½ sec

Mortar excess = not taken

3. Adjustment of mix to give ± 70 mm slump (1 attempt only!)

Add 100gr of sand + 249gr of stone

4. Details of second mix

Comments: Still quite a wet mix, although dominated by stone

Slump = 90 mm +

V.B. = 2 sec

mortar excess = h = 63mm, d = 7mm   M.C = 5.1%

5. * Water content of sand : M.C = 0.11%

Sand 20/3   add 4gr to water

6. Tested cubes

cube #	mass gr	crushing force kN	density kg/m³	strength MPa
1.	2380	264	2370	26.4
2	2363	265	2361	26.5
3.	2352	273	2350	27.3
4.	2400	265	2398	26.5
5.	–	–	–	–
	(1-2gcol)		2372	26.7 MPa

effective c/w = 1657/952 = 1.74

Mix Design with Rubble Aggregate.

#16
Mix Code 175 - 20 ✓

1. Batched Materials

	kg/m³ calculated	batched gr	adjustment gr	* adjusted gr	FINAL gr
rubble stone (saturated)	1670	8500	+ 2560	–	11 060
klipheuwel sand (air dry)	391	1990	+ 600	- 3	2587
rapid hardening cement	285	1451	–	–	1451
water	163	830	–	+ 3	833

2. Details of first batch

Comments

Slump = far too high & runny

V.B. = x

Mortar excess = x

3. Adjustment of mix to give ± 70 mm slump (1 attempt only!)

Add sand to remove ± 200-300ml of water

say 250ml water i.e. add 600gr of sand

+ 2560gr of stone

4. Details of second mix

Comments: Better, but still quite runny

Slump = +130 mm

V.B. = 1½ sec

mortar excess = h = 42mm   d = -22.3mm   Mortar deficiency = 14%

5. * Water content of sand : W.C = 0.10%

Sand 25/3   add 3gr to water

6. Tested cubes

cube #	mass gr	crushing force kN	density kg/m³	strength MPa
1.	2345	208	2345	20.8
2.	2345	196	2345	19.6
3.	2311	191	2311	19.1
4.	2345	202	2345	20.2
5.	–	–	–	–
			2337	19.9 MPa

effective c/w = 1.74

Mix Design with Rubble Aggregate.

#19
Mix Code 175 - 50 ✓

1. Batched Materials.

	calculated kg/m³	batched gr	adjustment gr	* adjustment gr	FINAL gr
rubble stone (saturated)	1044	8500	–		8500
klipheuwel sand (air dry)	978	7963	–	- 9	7954
rapid hardening cement	285	2320	–		2320
water	163	1327	–	+ 9	1336

2. Details of first batch:

Comments: good looking mix
nice workability for hand pl.

Slump = 50 mm
V.B. = 2.8 sec
Mortar excess = h = 47 mm ; d = 18 mm   M.E = 11.5%

3. Adjustment of mix to give ± 70 mm slump. (1 attempt only!)

N/A

4. Details of second mix. N/A

Comments: N/A

Slump =
V.B. =
mortar excess =

5. * Water content of sand : M.C = 0.11%   add

Sand 20/3

6. Tested cubes :

cube #	mass gr	crushing force kN	density kg/m³	strength MPa
1.	2350	294	2350	29.4
2.	2357	281	2357	28.1
3.	2374	289	2374	28.9
4.	2377	290	2377	29.0
5.	–	–	–	–
			2365	28.8

effective c/w = 2329/1336 = 1.74

Mix Design with Rubble Aggregate.

#18
Mix Code 175 - 40 ✓

1. Batched Materials.

	calculated kg/m³	batched gr	adjustment gr	* adjustment gr	FINAL gr
rubble stone (saturated)	1252	8000	–	–	8000
klipheuwel sand (air dry)	782	4997	–	-5	4992
rapid hardening cement	285	1821	+ 77	–	1898
water	163	1042	+ 44	+ 5	1091

2. Details of first batch.

Comments

Slump = 30-40 mm
V.B. = 4.5 sec
Mortar excess = not taken

3. Adjustment of mix to give ± 70 mm slump. (1 attempt only!)

Add about 5 l/m³ of water
i.e. add ~~32~~ ml + ~~54~~ gr cement
44 ml + 77 cement

4. Details of second mix.

Comments:

Slump = 35 mm
V.B. = 2.6 sec
mortar excess = h = 55 mm ; d = 20   M.E = 13.9%

5. * Water content of sand : W.C = 0.10%

Sand 25/3
add 0.001 × (4997) ≈ 5 gr

6. Tested cubes :

cube #	mass gr	crushing force kN	density kg/m³	strength MPa
1.	2400	291	2400	29.1
2.	2402	291	2402	29.1
3.	2379	279	2379	27.9
4.	2375	291	2375	29.1
5.	–	–	–	–
			2389	28.8 MPa

effective c/w ratio = 1.74

Mix Design with Rubble Aggregate.

#21
Mix Code 200 - 20 ✓

1. Batched Materials.

	calculated kg/m	batched gr	adjustment gr	* adjustment gr	FINAL gr
rubble stone (saturated)	1641	8000	9000		9000
klipheuwel sand (air dry)	384	1872	2106	-2	2104
rapid hardening cement	326 -86	1589 -419	1316		1316
water	163 -43	795 -210	658	+2	660

2. Details of first batch.

Comments

Slump =

V.B. =

Mortar excess =

Previous experience has shown that for too much water it [illegible] and so reduce water requirement down to 120 litre

3. Adjustment of mix to give ± 70 mm slump. (1 attempt only!)

4. Details of second mix.

Comments:

Slump = 150 mm

V.B. = //

mortar excess = d = -16mm ; h = 72mm   M.C = -12.6%

5. Water content of sand

M.C = 0.10%

∝ Sand 26/3

add 2gr to water

6. Tested cubes:

(seem to shrink)

cube #	mass	crushing force	density	strength
1.	2357	225	2357	22.5
2.	2332	221	2332	22.1
3.	2336	215	2336	21.5
4.	2331	212	2331	21.3
5.	–	–	–	–
			2339	21.8

effective c/w = 1316/660 = 1.99

Mix Design with Rubble Aggregate.

20
Mix Code 175 - 60 ✓

1. Batched Materials.

	calculated	batched	adjustment	* adjustment	FINAL
rubble stone (saturated)	835	7500	–	–	7500
klipheuwel sand (air dry)	1173	10 536	–	-11	10 525
rapid hardening cement	285	2560	+301	–	2861
water	163	1464	+172	+11	1647

2. Details of first batch.

Comments

Slump = zero

V.B. = not taken

Mortar excess = N.C

3. Adjustment of mix to give ± 70 mm slump. (1 attempt only!)

Add about 15 kg/m³ water

i.e. add 172ml water + 301 cement

(172)

4. Details of second mix.

Comments: nice smooth mix even though sl = 70 it is quite stiff like clay

Slump = 70 mm

V.B. = 1.8 sec

mortar excess = h = 40 ; d = 25

M.C = 15.7%

5. * Water content of sand

: M.C = 0.10%

SAND 25/3

add to water

6. Tested cubes:

cube #	mass gr	crushing force kN	density kg/m³	strength MPa
1.	2373	306	2373	30.6
2.	2365	297	2365	29.7
3.	2360	310	2360	31.0
4.	2365	306	2365	30.6
5.	–	–	–	–
			2366	30.5 MPa

effective c/w ratio = 1.74

Mix Design with Rubble Aggregate.

#23
Mix Code 200 - 40 ✓

1. Batched Materials.

	calculated kg/m³	batched gr	adjustment gr	*adjustment gr	FINAL gr
rubble stone (saturated)	1231	8000	–	–	8000
klipheuwel sand (air dry)	768	4991	–	-5	4986
rapid hardening cement	326	2119	–	–	2119
water	163	1059	–	+5	1065

2. Details of first batch:

Comments: fairly runny mix
high c/w ratio and roughness of stone keeps slump down

Slump = 65mm
V.B. = 4.3 sec
Mortar excess = d = 14 ; h = 49 ⇒ M.E = 9.3%

3. Adjustment of mix to give ± 70 mm slump. (1 attempt only!)

N/A

4. Details of second mix. N/A

Comments:

Slump =
V.B. =
mortar excess =

5.* Water content of sand

M.C = 0.10%
Sand 26/3
⇒ add 5gr

6. Tested cubes:

cube #	mass gr	crushing force kN	density kg/m³	strength MPa
1.	2386	340	2386	34.0
2.	2386	328	2386	32.8
3.	2382	332	2382	33.2
4.	2386	336	2386	33.6
5.	–	–	–	–
			2385	33.4 MPa

effective c/w ratio = 1.99

Mix Design with Rubble Aggregate.

#22
Mix Code 200 - 30 ✓

1. Batched Materials.

	calculated kg/m³	batched gr	adjustment gr	*adjustment gr	FINAL gr
rubble stone (saturated)	1436	8000	+ 748	–	8748
klipheuwel sand (air dry)	576	3209	+ 300	-4	3505
rapid hardening cement	326	1816	–	–	1816
water	163	908	–	+4	912

2. Details of first batch:

Comments

Slump = 115mm
V.B. = not taken
Mortar excess = not taken

3. Adjustment of mix to give ± 70 mm slump. (1 attempt only!)

Add 300gr sand + 748 gr of stone

4. Details of second mix.

Comments:

Slump = 50mm ([illegible] [illegible])
V.B. = 2 sec
mortar excess = d = 6mm ; h = 63mm ⇒ M.E = 4.4%

5.* Water content of sand

M.C = 0.10%
Sand 26/3
add 4gr to water

6. Tested cubes:

cube #	mass gr	crushing force kN	density kg/m³	strength MPa
1.	2385	323	2385	32.3
2.	2393	321	2393	32.1
3.	2403	323	2403	32.3
4.	2380	321	2380	32.1
5.	–	–	–	–
			2390	32.2 MPa

effective c/w = 1816/912 = 1.99

#24

Mix Design with Rubble Aggregate.

Mix Code 200 - 50 ✓

1. Batched Materials.

	calculated kg/m³	batched gr	adjustment gr	* adjustment gr	FINAL gr
rubble stone (saturated)	1026	7500	–	7	7500
klipheuwel sand (air dry)	961	7025	–	-7	7018
rapid hardening cement	326	2383	–	–	2383
water	163	1192	–	+7	1197

2. Details of first batch.

Comments

Slump = 55 mm

V.B. = 3.5 sec

Mortar excess = d = 7mm ; h = 32mm ⇒ m.e. = 10.2%

3. Adjustment of mix to give ± 70 mm slump. (1 attempt only!)

N/A

4. Details of second mix.

Comments:

Slump =

V.B. =

mortar excess =

5.* Water content of sand

M.C = 0.10 %

Sand 26/3

add 7gr.

6. Tested cubes:

cube #	mass gr	crushing force kN	density kg/m³	strength MPa
1.	2409	375	2409	37.5
2.	2406	369	2406	36.9
3.	2395	356	2395	35.6
4.	2408	364	2408	36.4
5.	–	–	–	–
			2405	36.6 MPa

effective c/w = $2383/1197$ = 1.99

#25

Mix Design with Rubble Aggregate.

Mix Code 200 - 60 ✓

1. Batched Materials.

	calculated kg/m³	batched gr	adjustment gr	* adjustment gr	FINAL gr
rubble stone (saturated)	820	7000	–	–	7000
klipheuwel sand (air dry)	1153	9843	–	-10	9833
rapid hardening cement	326	2783	+350	–	3133
water	163	1391	+175	+10	1576

2. Details of first batch.

Comments

Slump = very low, probably 10mm + less

V.B. = not t

Mortar excess = not t

3. Adjustment of mix to give ± 70 mm slump. (1 attempt only!)

Added 175ml water + 350 cement

4. Details of second mix.

Comments:

Slump = 65mm

V.B. = 2.0 sec

mortar excess = d = 25mm ; h = 39mm ⇒ m.e. = 15.2%

5.* Water content of sand

M.C = 0.10 %

Sand 26/3

add 10gr to water from sand

6. Tested cubes:

cube #	mass gr	crushing force kN	density kg/m³	strength MPa
1.	2396	394	2396	39.4
2.	2369	386	2369	38.6
3.	2366	391	2366	39.1
4.	2357	389	2357	38.9
5.	–	–	–	–
			2372	39.0 MPa

effective c/w ratio = 1.99

Mix Design with Rubble Aggregate.

#28

Mix Code 225-40 ✓

1. Batched Materials.

	calculated kg/m³	batched gr	adjustment gr	*adjustment gr	FINAL gr
rubble stone (saturated)	1208	8000	/	/	8000
klipheuwel sand (air dry)	755	5000	/	-4	4996
rapid hardening cement	367	2430	/	/	2430
water	163	1079	/	+4	1083

2. Details of first batch.

Comments: Very slight segregation
nice stony but still workable
Seems to be optimum for hand placing
& light vibro comp.

Slump = 60 mm

V.B. = 3.2 sec

Mortar excess = h = 47mm ; d = 18mm   m.e % = 11.2%

3. Adjustment of mix to give ± 70 mm slump. (1 attempt only !)

4. Details of second mix.

Comments:

Slump =

V.B. =

mortar excess =

5.* Water content of sand

m.c = 0.07%

Sand 07/3

add to water : 4g

6. Tested cubes : 3pm

cube #	mass	crushing force	density	strength
1.	2412	355	2412	35.5
2.	2405	359	2405	35.9
3.	2393	359	2393	35.9
4.	2396	352	2396	35.2
5.	/	/	/	/
			2402	35.6 MPa

effective c/w = 2.24

Mix Design with Rubble Aggregate.

#29

Mix Code 225-50 ✓

1. Batched Materials.

	calculated kg/m³	batched gr	adjustment gr	*adjustment gr	FINAL gr
rubble stone (saturated)	1008	7500	/	/	7500
klipheuwel sand (air dry)	944	7024	/	-5	7019
rapid hardening cement	367	2731	/	/	2731
water	163	1213	/	+5	1218

2. Details of first batch.

Comments: nice workability ; Stiffy
m.e ok ; for nice working
no segregation in m.e test

Slump = 55 mm

V.B. = 2.7 sec

Mortar excess = h = 27mm ; d = 22mm   m.e = 12.8%

3. Adjustment of mix to give ± 70 mm slump. (1 attempt only !)

4. Details of second mix.

Comments:

Slump =

V.B. =

mortar excess =

5.* Water content of sand

m.c = 0.07%

sand 07/4

add to water : 6gr

6. Tested cubes : 2 pm.

quick failures
i.e. load drops off
suddenly
→ brittle fracture ?
the aggregate?

cube #	mass	crushing force	density	strength
1.	2389	415	2389	41.5
2.	2397	402	2397	40.2
3.	2389	411	2389	41.1
4.	2389	404	2389	40.4
5.	/	/	/	/
			2391	40.8 MPa

effective c/w = 2.24

Mix Design with Rubble Aggregate.

Mix Code 225-60 #30

1. Batched Materials.

	calculated kg/m³	batched gr	adjustment	* adjustment gr	FINAL gr
rubble stone (saturated)	783	7000			7000
klipheuwel sand (air dry)	1101	9818		-7	9811
rapid hardening cement	393	3513			3513
water	175	1560		+7	1567

2. Details of first batch:

Comments:

slump = 55 mm

V.B. = 2.8 sec

Mortar excess = d = 24 mm ; h = 39 mm ; M.e = 15.0 %

3. Adjustment of mix to give ≈ 70 mm slump. (1 attempt only !)

4. Details of second mix.

Comments:

Slump =

V.B. =

mortar excess =

5. Water content of sand : m.c = 0.07%

* sand 07/4

add 7gr of water from sand

6. Tested cubes :

cube #	mass gr	crushing force	density	strength
1.	2353	448	2353	44.8
2.	2396	465	2396	46.5
3.	2395	453	2395	45.3
4.	2372	452	2372	45.2
5.				
			2379	45.4 (MPa)

effective c/w = 2.24.

Mix Design with Rubble Aggregate.

#32

Mix Code 250-30 ✓

1. Batched Materials.

	calculated kg/m³	batched gr	adjustment gr	* adjustment gr	FINAL gr
rubble stone (saturated)	1413	8500	/	/	8500
klipheuwel sand (air dry)	567	3411	/	-5	3406
rapid hardening cement	388	2334	/	/	2334
water	155	932	/	+5	937

2. Details of first batch:

Comments: Runny mix

slump = 60 mm

Stones cannot slide : measured ~ 25mm actually

V.B. = /

Mortar excess = d = 3mm ; h = 60 mm ; M.e = 2.0%

(no segregation)

3. Adjustment of mix to give ≈ 70 mm slump. (1 attempt only !)

(NOTE THAT MIX # 31 was not made)

4. Details of second mix.

Comments:

Slump =

V.B. =

mortar excess =

5. Water content of sand : m.c = 0.15%

sand 09/4

adjust by 5gr.

6. Tested cubes :

Cubes cast ok, mortar just enough (heavy vibro-comp:)

cube #	mass	crushing force	density	strength
1.	2379	409	2379	40.9
2.	2386	405	2366	40.5
3.	2884	429	2384	42.9
4.	2377	417	2377	41.7
5.	/	/	/	/
			2377	41.5 MPa

effective c/w = 2.49

Mix Design with Rubble Aggregate.

#33
Mix Code 250 - 40 ✓

1. Batched Materials.

	calculated kg/m³	batched gr	adjustment gr	*adjustment gr	FINAL gr
rubble stone (saturated)	7190	8000	/	/	8000
klipheuwel sand (air dry)	743	4995	/	-7	4988
rapid hardening cement	405	2723	/	/	2723
water	162	1089	/	+7	1096

2. Details of first batch:

Comments: Nice texture

slump = 60mm
V.B. = 1.9 sec
Mortar excess = d = 13mm ; h = 45mm m.e. = 8.4%

3. Adjustment of mix to give ≈ 70 mm slump. (1 attempt only!)

4. Details of second mix.

Comments:

Slump =
V.B. =
mortar excess =

5. *Water content of sand : m.c. = 0.15%

Sand 9/4
adjust by 7gr

6. Tested cubes:

cube #	mass	crushing force	density	strength
1.	2405	485	2405	48.5
2.	2395	480	2395	48.0
3.	2410	486	2410	48.6
4.	2412	472	2412	47.2
5.	/	/	/	/
			2406	48.1 MPa

effective c/w = 2.48

Mix Design with Rubble Aggregate.

#34
Mix Code 250 - 50 ✓

1. Batched Materials.

	calculated kg/m³	batched gr	adjustment gr	*adjustment gr	FINAL gr
rubble stone (saturated)	989	7500	/	/	7500
klipheuwel sand (air dry)	927	7030	/	-11	7019
rapid hardening cement	408	3094	/	/	3094
water	163	1236	/	+11	1247

2. Details of first batch:

Comments:

slump = 60 mm
V.B. = 2.7 sec
Mortar excess = h = 22mm ; d = 25mm ; m.e. = 14.1%

3. Adjustment of mix to give ≈ 70 mm slump. (1 attempt only!)

4. Details of second mix.

Comments:

Slump =
V.B. =
mortar excess =

5. *Water content of sand : adjust by 7030 × 0.15%

= 11gr
Sand 09/4

6. Tested cubes:

cube #	mass	crushing force	density	strength
1.	2386	522	2386	52.2
2.	2394	500	2394	50.0
3.	2396	492	2396	49.2
4.	2406	498	2406	49.8
5.	/	/	/	/
			2396	50.3 MPa

ewc = 2.40

Mix Design with Rubble Aggregate.

#35
Mix Code 250 - 60

1. Batched Materials.

	calculated kg/m^3	batched gr	adjustment gr	* adjustment gr	FINAL gr
rubble stone (saturated)	767	6500	/	/	6500
klipheuwel sand (air dry)	1078	9136	/	-14	9122
rapid hardening cement	438	3712	+250	/	3962
water	175	1483	+100	+14	1597

2. Details of first batch:

Comments : too stiff.

slump = 35mm
V.B. = 2.8 sec
Mortar excess = N/T

3. Adjustment of mix to give ≈ 70 mm slump. (1 attempt only!)

Add 5 l/m^3 water ∴ add 50gr water
(double this)

4. Details of second mix.

Comments :

Slump = 60mm
V.B. = 2.0 sec
mortar excess = h = 31mm ; d = 25mm m.e = 15.6%

5. * Water content of sand : adjust by 9136 × 0.15 %

Sand 09/4 = 14gr

6. Tested cubes :

cube #	mass	crushing force	density	strength
1.	2407	556	2407	55.6
2.	2375	516	2375	51.6
3.	2390	518	2390	51.8
4.	2395	522	2395	52.2
5.	/	/	/	/
			2392	52.8 MPa

effective c/w = 2.48

Mix Design with Rubble Aggregate.

Mix Code 275 - 30 #37

1. Batched Materials.

	calculated kg/m^3	batched gr	adjustment gr	* adjustment gr	FINAL gr
rubble stone (saturated)	1377	8000			8000
klipheuwel sand (air dry)	553	3213		-3	3210
rapid hardening cement	435	2527			2527
water	158	918		+3	921

2. Details of first batch:

Comments : fairly liquid mix

slump = 25mm, but stone are holding it up, say 60 mm
V.B. = 1.7 sec
Mortar excess = d = 3mm , h = 64 mm , m.e. = 2.2%

3. Adjustment of mix to give ≈ 70 mm slump. (1 attempt only!)

4. Details of second mix.

Comments :

Slump =
V.B. =
mortar excess =

5. Water content of sand : M.C = 0.10 %

* Sand 24/4 adjust by 2 gr

6. Tested cubes :

cube #	mass	crushing force	density	strength
1.	2402	520	2402	52.0
2.	2399	536	2399	53.6
3.	2398	528	2398	52.8
4.	2411	518	2411	51.8
5.	–	–	–	–
			2403	52.5

(MPa)

effective c/w = 2.74
w/c = 0.36

Mix Design with Rubble Aggregate.

Mix Code 275 - 40 # 38

1. Batched Materials.

	calculated kg/m³	batched g	adjustment g	* adjustment g	FINAL gr
rubble stone (saturated)	1162	7500			7500
klipheuwel sand (air dry)	726	4686		-5	4681
rapid hardening cement	451	2911	+ 137		3048
water	164	1059	+ 50	+ 5	1114

2. Details of first batch:

Comments:

slump = 40 mm
V.B. = 3.2 sec
Mortar excess = N/T

3. Adjustment of mix to give ≈ 70 mm slump. (1 attempt only !)

Add about 7 L/m³ water = i.e. 50 g water
+ 137 g cement

4. Details of second mix.

Comments:

Slump = 55 mm
V.B. = 3.0 sec.
mortar excess = d = 10 mm , h = 39 mm ⇒ m.e = 6.3%

5. Water content of sand : M.C = 0.10%

* sand 24/4
∴ add 5 gr water from sand

6. Tested cubes :

cube #	mass	crushing force	density	strength
1.	2428	580	2428	58.0
2.	2395	596	2395	59.6
3.	2412	600	2412	60.0
4.	2413	600	2413	60.0
5.				
			2413	59.4 MPa

effective c/w = 2.74
w/c = 0.37

Mix Design with Rubble Aggregate.

Mix Code 275 - 50 # 39

1. Batched Materials.

	calculated kg/m³	batched gr	adjustment	* adjustment g	FINAL gr
rubble stone (saturated)	963	7000			7000
klipheuwel sand (air dry)	902	6557		-7	6550
rapid hardening cement	457	3322			3322
water	166	1207		+ 7	1214

2. Details of first batch:

Comments:

Slump = 45 mm
V.B. = 3.5 sec
Mortar excess = d = 15 ; h = 30 mm m.e = 8.9 %

3. Adjustment of mix to give ≈ 70 mm slump. (1 attempt only !)

4. Details of second mix.

Comments:

Slump =
V.B. =
mortar excess =

5. Water content of sand : M.C = 0.10%

* Sand 24/4
∴ adjust by 7 grammes

6. Tested cubes :

cube #	mass	crushing force	density	strength
1.	2422	616	2422	61.6
2.	2434	610	2434	61.0
3.	2413	612	2413	61.2
4.	2390	629	2390	62.9
5.	–	–	–	–
			2415	61.7
				(MPa)

effective c/w = 2.74
w/c = 0.37

Mix Design with Rubble Aggregate.

Mix Code 275 - 60 #40

1. Batched Materials.

	calculated kg/m³	batched	adjustment	* adjusted	FINAL gr
rubble stone (saturated)	728	6000			6000
klipheuwel sand (air dry)	1023	8431		-6	8425
rapid hardening cement	512	4220			4220
water	186	1533		+6	1539

2. Details of first batch:

Comments:

slump = 55 mm

V.B. = 2.0 sec

Mortar excess = d = 25 mm, h = 8 mm me = 13.1%

3. Adjustment of mix to give ≐ 70 mm slump. (1 attempt only !)

4. Details of second mix.

Comments:

slump =

V.B. =

mortar excess =

5. Water content of sand : M/C = 0.07%

* sand 15/4. adjust by 6 gr

6. Tested cubes :

cube #	mass	crushing force	density	strength
1.	2377	614	2377	61·4
2.	2378	624	2378	62·4
3.	2378	636	2378	63·6
4.	2385	600	2385	60·0
5.	-	-	-	-
			2380	61·8
				(MPa)

effective c/w = 2.74

Mix Design with Rubble Aggregate.

Mix Code 300 - 30 #42

1. Batched Materials.

	calculated kg/m³	batched g	adjustment g	* adjusted g	FINAL gr
rubble stone (saturated)	1326	7500			7500
klipheuwel sand (air dry)	532	3009		-3	3006
rapid hardening cement	495	2800			2800
water	165	933		+3	936

2. Details of first batch:

Comments

slump = 20 mm but held up by stones ; actual probably 60 mm

V.B. = 1.9 sec

Mortar excess = d = 4½ mm ; h = 43 mm m.e = 2.9%

3. Adjustment of mix to give ≐ 70 mm slump. (1 attempt only !)

4. Details of second mix.

Comments:

slump =

V.B. =

mortar excess =

5. Water content of sand : M.C = 0.10%

* sand 24/4 adjust by 3 gr

6. Tested cubes :

cube #	mass	crushing force	density	strength
1.	2406	590	2406	59·0
2.	2417	596	2417	59·6
3.	2379	584	2379	58·4
4.	2404	592	2404	59·2
5.				
			2402	59·0
				(MPa)

effective c/w = 2.99
w/c = 0.33

Mix Design with Rubble Aggregate. Mix Code 300 - 40 #43

1. Batched Materials.

	calculated kg/m³	batched g	adjustment g	* adjustment g	FINAL g
rubble stone (saturated)	1104	7000			7000
klipheuwel sand (air dry)	689	4369		−4	4365
rapid hardening cement	525	3329			3329
water	175	1110		+4	1114

2. Details of first batch: Comments:

Slump = 45mm

V.B. = 4.1 sec

Mortar excess = h = 44 mm ; d = 11 mm ; m.c = 7,1 %

3. Adjustment of mix to give ÷ 70 mm slump. (1 attempt only!)

Note that mixes 44, 45 and 41 were not done as they were considered impractical (41) and unnecessary (44 & 45)

4. Details of second mix. Comments:

Slump =

V.B. =

mortar excess =

5. Water content of sand : m.c = 0.10 %

* sand 2414 adjust by 4 gr

6. Tested cubes:

cube #	mass	crushing force	density	strength
1.	2412	618	2412	61·8
2.	2386	606	2386	60·6
3.	2436	596	2436	59·6
4.	2421	640	2421	64·0
5.				
			2414	61·5 MPa

effective c/w = 2.99

w/c = 0.33

Date	Used in Mixes	Weight of Pan. (gram)	Weight of pan+ sand (gram)	Weight of Pan + dry sand. (gram)	Moisture Content. %
18/3	13 ; 14 : 12 : trial mix	212	4087	4082	0.13
19/3	11 ; 15	214	2235	2231	0.20
20/3	17 ; 19	212	2989	2986	0.11
25/3	16 ; 18 ; 20	212	2406	2404	0.09
26/3	25 ; 24 ; 23	208	3082	3079	0.10
7/4	30 ; 29 ; 28 ; 27	213	3121	3119	0.07
9/4	35 ; 34 ; 33 ; 32	208	2840	2838	0.15
15/4	10 ; 9 ; 8 ; 7 ; 6 ; 5 ; 40	209	3219	3217	0.07
22/4	1 ; 2 ; 3 ; 4	210	3314	3311	0.10
24/4	39 ; 38 ; 37 ; 42 ; 43	212	3202	3199	0.10

Record of the Moisture Content of the Klipheuwel sand used in the series of recycled concrete mixes.

Statistical Correlation of the Actual Mortar Excess with the Theoretical Mortar Excess.

A linear regression analysis will be performed on the mortar excess data generated by the series of recycled concrete mixes undertaken in PHASE 2 of this thesis. The equations used by this regression analysis are shown in Section 4.3.2.1. The following two factors may upset the accuracy of the regression somewhat :

(i) Rich mixes are sticky and do not allow the stones to sink freely through the mortar – the measured mortar excess will thus be underestimated somewhat.

(ii) Lean mixes allow segregation to occur : the sand sinks to the bottom of the container and the stones are pushed apart upsetting the actual mortar excess to some degree.

The bi-variate sample is :

A.m.e.	T.m.e.	A.m.e.	T.m.e	A.m.e.	T.m.e	A.m.e.	T.m.e.	Regr. Coefficients
-34·7	-14·3	0·0	-2·5	8·1	16·2	14·7	39·3	Correlation coefficient r = 0.735
12·9	75·7	-24·0	-13·0	2·8	-0·8	7·5	16·7	
10·1	40·8	12·1	77·2	-7·6	-7·8	3·6	6·2	
9·3	22·1	10·3	44·5	15·0	79·6	-14·0	-8·4	
5·1	7·0	13·9	25·3	11·5	46·8	15·7	86·1	
-12·6	-9·2	4·4	7·2	9·3	26·1	10·2	49·2	a = 21.615 b = 2.278
15·2	89·8	2·9	10·0	11·2	28·2	12·8	51·7	
15·0	91·9	2·0	11·1	8·4	30·1	14·1	54·4	
15·6	100·2	2·2	13·6	6·3	34·7	8·9	58·3	
13·1	106·1	2·9	17·6	7·1	39·4	—	—	

The value of r is 0.735 which indicates that a fair correlation exists. The regression line fitted to the data has the following equation :

$$tme = 2.28 * ame + 21.62 \quad \text{-------} \ (i)$$

$$\text{or} \quad ame = 0 \cdot 44 * tme - 9 \cdot 49 \quad \text{------} \ (ii)$$

APPENDIX A7

1. BS1881 specification for the determination of the Elastic Modulus of a Concrete

2. Determination of the Modulus of Elasticity for the Recycled Concretes

3. TEST FOR THE STATIC MODULUS OF ELASTICITY BY MEANS OF AN EXTENSOMETER

NOTE. For the methods of making and curing moulded specimens see the clause describing the making and curing of test cylinders in Part 3 of this standard. For the method of preparing cores from hardened concrete see the clause on the preparation and compression testing of cores drilled from concrete in Part 4 of this standard.

3.1 Apparatus

3.1.1 ***Compression testing machine.*** The testing machine shall comply with the requirements for the compression testing machine in the clause describing the test for compressive strength of test cubes in Part 4 of this standard and in addition shall be capable of maintaining the load at any desired value.

3.1.2 ***Extensometers.*** Two extensometers shall be provided. They shall have a gauge length of not less than 100 mm and not more than half the length of the specimen and shall conform to either Grade A or Grade B of BS 3846[*].

3.2 Procedure

3.2.1 ***Determination of test load***

3.2.1.1 *Test on moulded specimen.* Immediately before the modulus of elasticity test, the three cubes shall be tested in accordance with the requirements of the clause describing the test for compressive strength of test cubes in Part 4 of this standard, and the value C, given by one third of the average compressive strength, shall be calculated to the nearest 1 MN/m^2.

3.2.1.2 *Tests on drilled core.* The value of C shall be estimated from the strength of similar specimens or a knowledge of the properties of the concrete.

3.2.2 ***Attachment of extensometers.*** Immediately on removing the specimen from the water, whilst it is still wet, the extensometers shall be attached on opposite sides of the specimen and parallel to its axis, in such a way that the gauge points are symmetrical about the middle of the specimen and are not nearer to either end of the specimen than a distance equal to half its diameter. When a square prism is used in place of a cylinder the gauge points of the extensometer shall not be nearer to either end than half the width. The extensometers shall be fixed with the recording points at the same end.

Cylinders.
150 mm diam
300 mm long

a ≥ 75.

GL ≤ 150mm

3.2.3 ***Placing the specimen in the testing machine.*** The bearing surfaces of the testing machine and of any auxiliary platens shall be wiped clean and any loose sand or other material removed from the ends of the specimen. The specimen shall be placed in the machine and its axis carefully aligned with the centre of thrust of the spherically seated platen. As the latter is brought to bear on the specimen the movable portion shall be rotated gently by hand so that uniform seating is obtained. No packing other than auxiliary steel platens shall be used between the ends of the specimens and the platens of the testing machine.

---

[*] BS 3846, 'Methods for calibration and grading of extensometers for testing of metals'.

3.2.4 ***Preliminary loading.*** The load shall be applied without shock and increased continuously at a rate of approximately 15 MN/m^2 per minute until an average stress of $(C+2)$ MN/m^2 is reached. The load shall be maintained at this figure for at least one minute and shall then be reduced gradually to an average stress of 1 MN/m^2, when extensometer readings shall be taken. The load shall be applied a second time at the same rate until an average stress of $(C+1)$ MN/m^2 is reached. The load shall be maintained at this figure while extensometer readings are taken. The load shall then be reduced gradually to an average stress of 1 MN/m^2 and readings again taken.

3.2.5 ***Loading.*** The load shall then be applied a third time at the same rate and extensometer readings taken at ten approximately equal increments of stress up to an average stress of $(C+1)$ MN/m^2. Readings shall be taken at each stage of loading with as little delay as possible. If the average strains observed on the second and third loadings differ by more than 5%, the loading cycle shall be repeated until the difference in strain between consecutive readings at $(C+1)$ MN/m^2 does not exceed 5%.

3.3 Calculation. The strains at the various stages of loading in the last cycle shall be calculated separately for each extensometer and the results shall be plotted against the corresponding stress. Straight lines shall be drawn through the points for each extensometer. The slopes of these two lines shall be determined and the average value shall be found. If the difference between the individual values for slope is less than 15% of the average value, this average value expressed to the nearest 500 MN/m^2 shall be recorded as the modulus of elasticity of the concrete. If the difference is greater than 15%, the specimen shall be re-centered in the testing machine and the test repeated. If the difference after re-centering and testing is still greater than 15% of the average value, the result of the test shall be discarded.

?

0,5 GPa

3.4 Report. The following information shall be included in the report on each specimen:

(1) date of test,
(2) identification mark, description and nominal size of specimen,
(3) age of specimen, if known,
(4) static modulus of elasticity,
(5) value of C, and
(6) remarks, e.g. number of loading cycles or whether re-centered.

4. TEST FOR THE DYNAMIC MODULUS OF ELASTICITY BY AN ELECTRODYNAMIC METHOD

NOTE 1. For the methods of making and curing moulded beams see the clause describing the making and curing of test beams in Part 3 of this standard. For the method of preparing beams sawn from hardened concrete see Part 4 of this standard.

ELASTIC MODULUS OF RECYCLED CONCRETE.

Specimens tested : MIX 1

Concrete age : 7days

gauge factor = $1.02 \times 10^{-5} \times 8/6 = 1.36 \times 10^{-5}$

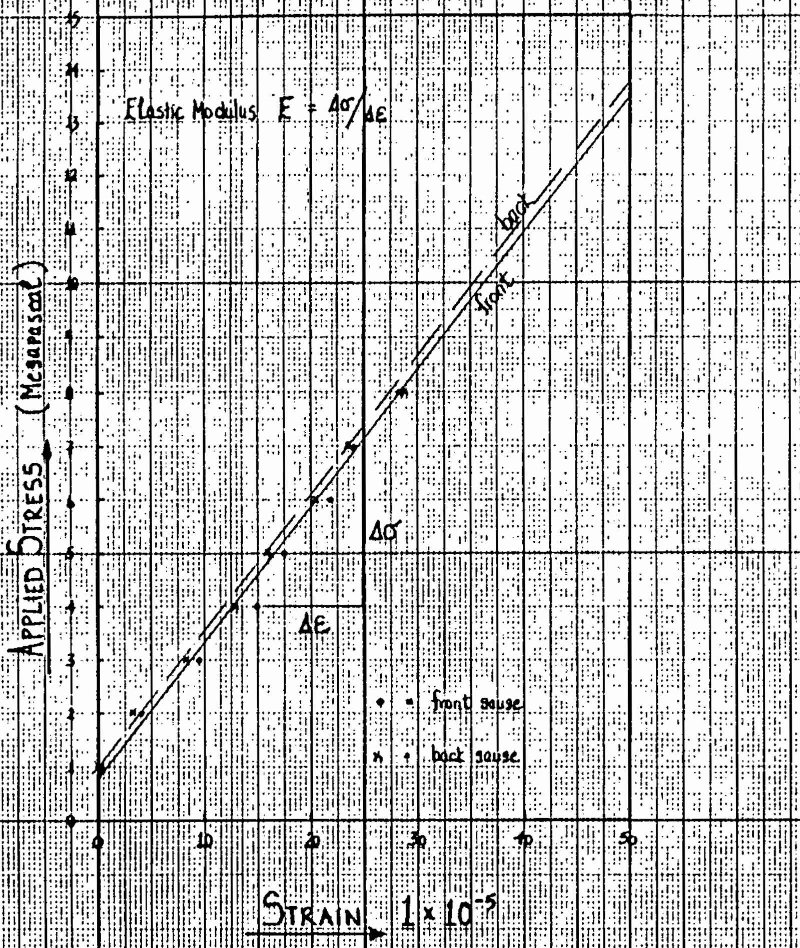
Specimens cast on : 24.11.86

tested on : 1.12.86

		cylinder 1						cylinder 2					
Stress	Force	Front Gauge : 1.1			Back Gauge 1.1			Front Gauge 1.2			Back Gauge : 1.2		
(MPa)	(kN)	Reading	Strain	Corrected Strain	Reading	Strain	Corrected Strain	Reading	Strain	Corrected Strain	Reading	Strain	Corrected Strain
				$\times 10^{-5}$			$\times 10^{-5}$			$\times 10^{-5}$			$\times 10^{-5}$
1.0	8.5	992.0	0.00	0.00	997.5	0.0	0.00	975.0	0.0	0.00	991.5	0.0	0.00
2.0	17.0	989.1	2.9	3.94	995.1	2.4	3.26	973.9	1.1	1.50	990.2	1.3	1.77
3.0	25.5	985.0	7.0	9.52	991.5	6.0	8.16	971.6	3.4	4.62	985.0	6.5	8.84
4.0	34.0	981.0	11.0	14.96	988.3	9.2	12.51	967.0	8.0	10.88	982.4	9.1	12.38
5.0	42.5	979.2	12.8	17.41	986.0	11.5	15.64	963.6	11.4	15.50	978.7	12.8	17.41
6.0	51.0	976.1	15.9	21.62	982.6	14.9	20.26	960.0	15.0	20.40	974.7	16.8	22.85
7.0	59.5	974.2	17.8	24.21	980.1	17.4	23.66	954.2	20.8	28.29	971.0	20.5	27.88
8.0	68.0	971.2	20.8	28.29	976.5	21.0	28.56	953.7	21.3	28.97	968.0	23.5	31.96
9.0	76.5	—	—	—	—	—	—	—	—	—	—	—	—
10.0	85.0												
11.0	93.5												
12.0	102.0												
13.0	110.5												
14.0	119.0												

MODULUS OF ELASTICITY OF RECYCLED CONCRETE

Mix 1 : cylinder 1.1 @ 7 days



lines fitted by linear regression analysis : E_{front} = 24.558 GPa

E_{back} • 24.563 GPa

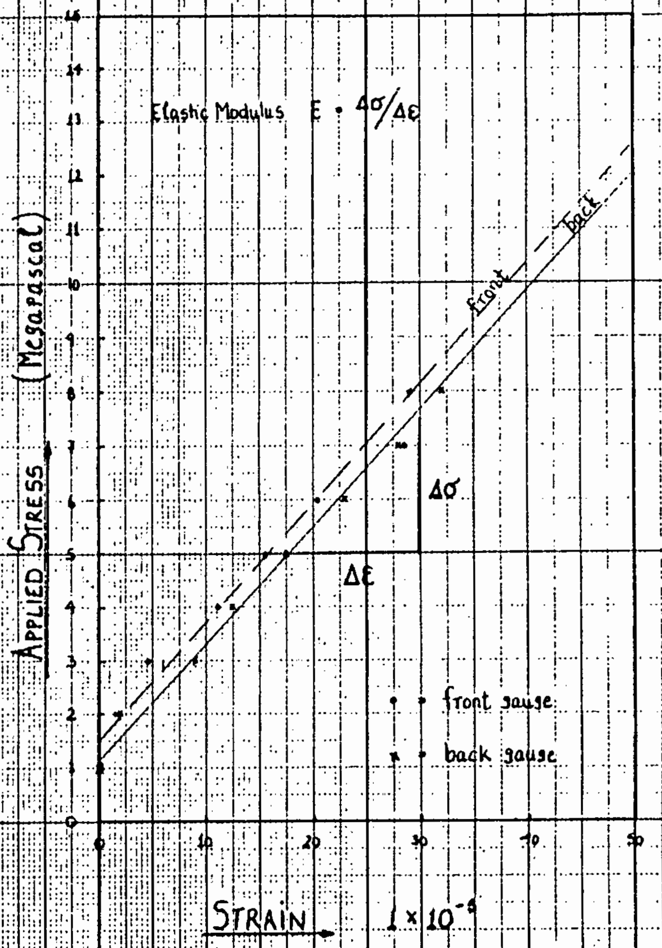
mean slope $\bar{E}$ = 24.561 GPa

diffrence front to back = 0.005 GPa

% diffrence from mean = 0.02 % < 15% ∴ accept values

MODULUS OF ELASTICITY

Mix 1 : cylinder 1.2 @ 7 days



Lines fitted by regression analysis : E_{front} • 21.101 GPa

E_{back} • 20.803 GPa

mean slope $\bar{E}$ • 20.952 GPa

diffirence front to back • 0.298 GPa

% diffirence from the mean • 1.42 % ∴ accept values

ELASTIC MODULUS OF RECYCLED CONCRETE.

Specimens tested : MIX 1

concrete age : 28 days

gause factor = $1.02 \times 10^{-5} \times 8/6 = 1.36 \times 10^{-5}$

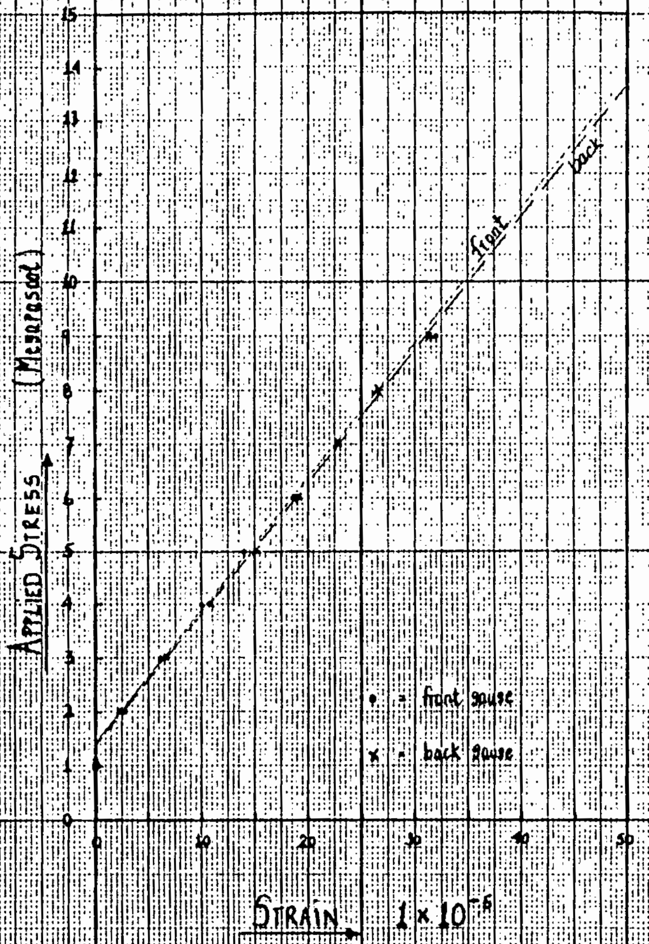
Specimens cast on : 24.11.86

tested on : 22.12.86

		cylinder 1						cylinder 2					
Stress	Force	Front Gause : 1.1			Back Gause 1.1			Front Gause 1.2			Back Gause : 1.2		
(MPa)	(kN)	Reading	Strain	Corrected Strain x 10^{-5}	Reading	Strain	Corrected Strain x 10^{-5}	Reading	Strain	Corrected Strain x 10^{-5}	Reading	Strain	Corrected Strain x 10^{-5}
1.0	8.5	980.5	0.0	0.00	978.0	0.0	0.00	973.8	0.0	0.00	985.2	0.0	0.00
2.0	17.0	978.6	1.9	2.58	976.3	1.7	2.31	970.7	3.1	4.22	983.0	2.2	2.99
3.0	25.5	976.0	4.5	6.12	973.2	4.8	6.53	966.4	7.4	10.06	980.0	5.2	7.07
4.0	34.0	973.1	7.4	10.06	970.0	8.0	10.88	963.0	10.8	14.69	977.2	8.0	10.88
5.0	42.5	970.2	10.3	14.01	966.9	11.1	15.10	960.0	13.8	18.77	974.2	11.0	14.96
6.0	51.0	967.0	13.5	18.36	964.0	14.0	19.04	957.1	16.7	22.71	971.1	14.1	19.18
7.0	59.5	963.8	16.7	22.71	961.3	16.7	22.71	954.0	19.8	26.93	967.5	17.7	24.07
8.0	68.0	961.0	19.5	26.52	958.5	19.5	26.52	951.0	22.8	31.01	964.2	21.0	28.56
9.0	76.5	957.0	23.5	31.96	955.0	23.0	31.28	948.4	25.4	34.54	961.0	24.2	32.91
10.0	85.0	—	—	—	—	—	—	—	—	—	—	—	—
11.0	93.5												
12.0	102.0												
13.0	110.5												
14.0	119.0												

MODULUS OF ELASTICITY

Mix 1 cylinder 1.1 @ 28 days



lines fitted by regression analysis : E_{front} = 24.763 GPa

E_{back} = 25.128 GPa

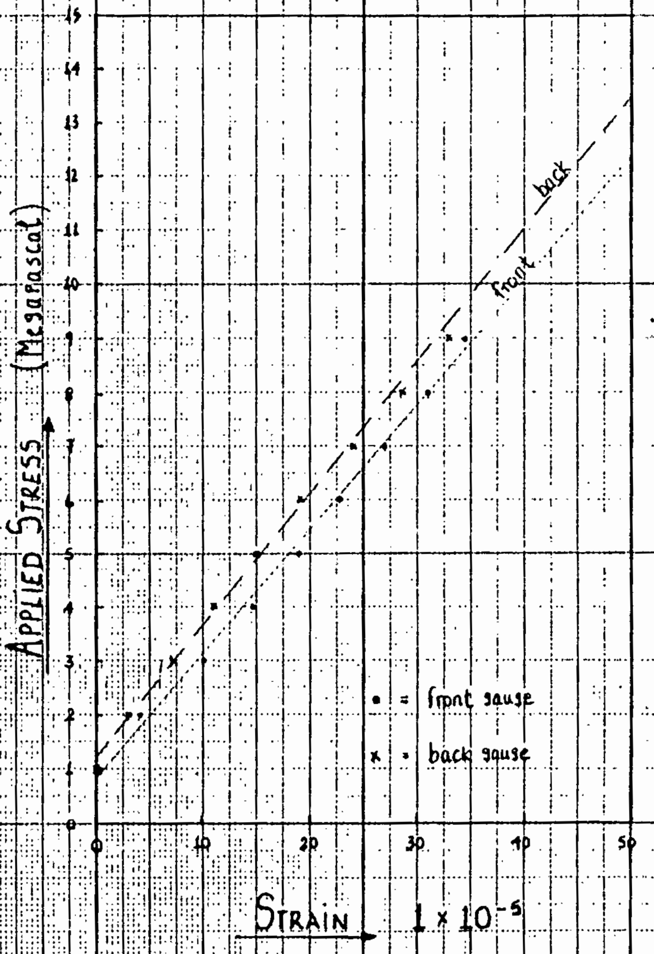
mean slope $\bar{E}$ = 24.946 GPa

diffirence front to back = 0.365 GPa

% diffirence from the mean = 1.46% ∴ accept values

MODULUS OF ELASTICITY.

Mix 1 : cylinder 1.2 @ 28 days



lines fitted by regression analysis E_{front} = 22.971 GPa

E_{back} = 23.872 GPa

mean slope $\bar{E}$ = 23.422 GPa

diffirence front to back = 0.901 GPa

% diffirence from the mean = 3.85% ∴ accept values

ELASTIC MODULUS OF RECYCLED CONCRETE.

Specimens tested : MIX 2 concrete age : 7 days

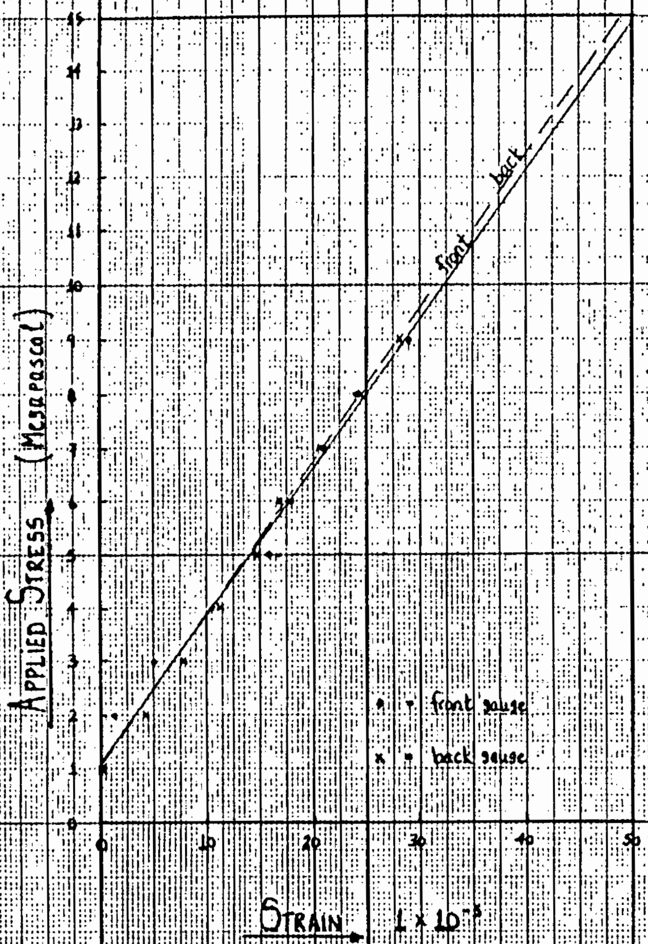
Gauge factor = $1.02 \times 10^{-5} \times 8/6 = 1.36 \times 10^{-5}$

Specimens cast on : 25.11.86 tested on : 2.12.86

		cylinder 2.1						cylinder 2					
Stress	Force	Front Gauge : 2·1			Back Gauge 2·1			Front Gauge 2·2			Back Gauge : 2·2		
(MPa)	(kN)	Reading	Strain	Corrected Strain $\times 10^{-5}$	Reading	Strain	Corrected Strain $\times 10^{-5}$	Reading	Strain	Corrected Strain $\times 10^{-5}$	Reading	Strain	Corrected Strain $\times 10^{-5}$
1.0	8.5	984.7	0.0	0.00	990.3	0.0	0.00	980.8	0.0	0.00	987.6	0.0	0.00
2.0	17.0	983.7	1.0	1.36	987.0	3.3	4.49	978.5	2.3	3.13	985.6	2.0	2.72
3.0	25.5	981.0	3.7	5.03	984.5	5.8	7.89	977.5	3.3	4.49	983.0	4.6	6.26
4.0	34.0	977.0	7.7	10.47	982.1	8.2	11.15	975.0	5.8	7.89	979.6	8.0	10.88
5.0	42.5	973.1	11.6	15.78	979.5	10.8	14.69	971.7	9.1	12.38	978.0	9.6	13.06
6.0	51.0	971.8	12.9	17.54	978.0	12.3	16.73	970.8	10.0	13.60	975.9	11.7	15.91
7.0	59.5	969.2	15.5	21.08	975.0	15.3	20.81	966.6	14.2	19.31	973.4	14.2	19.31
8.0	68.0	967.1	17.6	23.94	972.4	17.9	24.34	963.1	17.7	24.07	969.1	18.5	25.16
9.0	76.5	963.4	21.3	28.97	969.7	20.6	28.02	960.6	20.2	27.47	966.4	21.2	28.33
10.0	85.0	—	—	—	—	—	—	—	—	—	—	—	—
11.0	93.5												
12.0	102.0												
13.0	110.5												
14.0	119.0												

MODULUS OF ELASTICITY

Mix 2 cylinder 2.1 @ 7 days



lines fitted by linear regression analysis : E_{front} = 26.616 GPa

E_{back} = 29.463 GPa

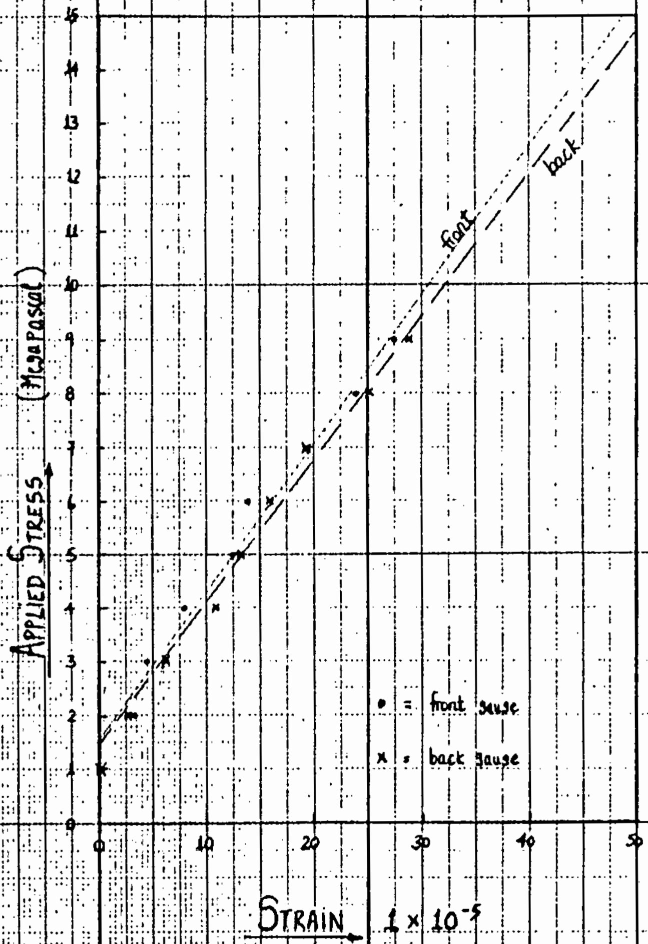
mean slope $\overline{E}$ = 28.040 GPa

diffirence front to back = 2.847 GPa

% diffirence from mean = 10.15% < 15% ∴ accept mean value

MODULUS OF ELASTICITY

Mix 2 : cylinder 2.2 @ 7 days



lines fitted by linear regression analysis : E_{front} = 28.305 GPa

E_{back} = 27.819 GPa

mean slope $\overline{E}$ = 28.062 GPa

diffirence front to back = 0.486 GPa

% diffirence from mean = 1.73% < 15% ∴ accept values.

ELASTIC MODULUS OF RECYCLED CONCRETE

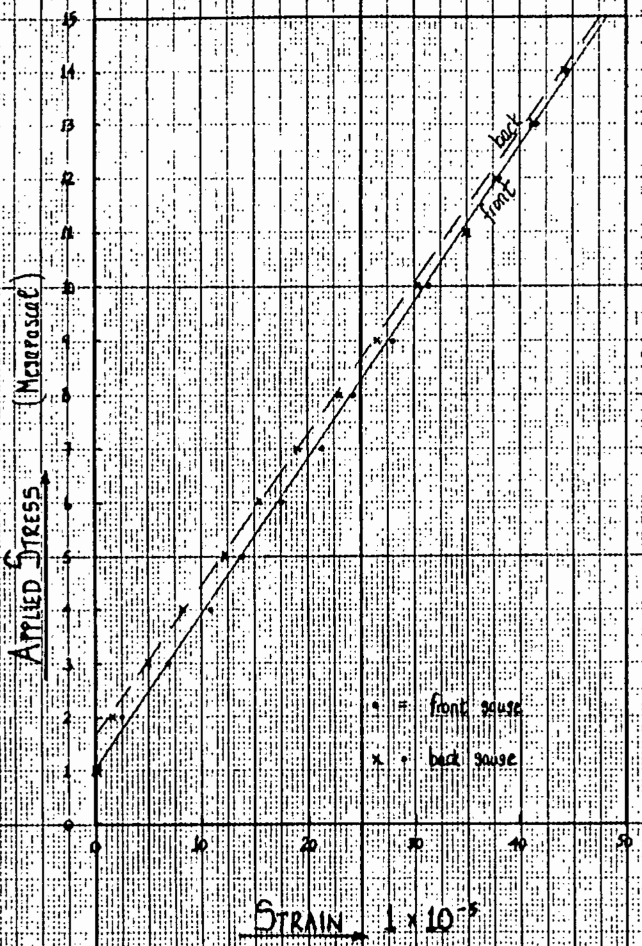
Specimens tested : MIX 2 concrete age : 28days

gauge factor = $1.02 \times 10^{-5} \times 8/6 = 1.36 \times 10^{-5}$ Specimens cast on : 25.11.86 tested on : 23.12.86

		cylinder 1						cylinder 2					
Stress	Force	Front Gauge : 2.1			Back Gauge 2.1			Front Gauge 2.2			Back Gauge : 2.2		
(MPa)	(kN)	Reading	Strain	Corrected Strain $\times 10^{-5}$	Reading	Strain	Corrected Strain $\times 10^{-5}$	Reading	Strain	Corrected Strain $\times 10^{-5}$	Reading	Strain	Corrected Strain $\times 10^{-5}$
1.0	8.5	973.0	0.0	0.00	983.0	0.0	0.00	970.4	0.0	0.00	978.2	0.0	0.00
2.0	17.0	971.2	1.8	2.45	981.8	1.2	1.63	969.1	1.3	1.77	975.9	2.3	3.13
3.0	25.5	968.0	5.0	6.80	979.4	3.6	4.90	967.4	3.0	4.08	972.4	5.8	7.89
4.0	34.0	965.0	8.0	10.88	977.0	6.0	8.16	964.3	6.1	8.30	970.0	8.2	11.15
5.0	42.5	962.9	10.1	13.74	974.0	9.0	12.24	962.0	8.4	11.42	967.7	10.5	14.28
6.0	51.0	960.0	13.0	17.68	971.7	11.3	15.37	959.4	11.0	14.96	965.0	13.2	17.95
7.0	59.5	957.4	15.6	21.22	969.0	14.0	19.04	956.9	13.5	18.36	962.8	15.4	20.94
8.0	68.0	955.1	17.9	24.34	966.2	16.8	22.85	954.1	16.3	22.17	960.2	18.0	24.48
9.0	76.5	952.4	20.6	28.02	963.4	19.6	26.66	951.1	19.3	26.25	957.9	20.3	27.61
10.0	85.0	950.0	23.0	31.28	960.6	22.4	30.46	948.7	21.7	29.51	955.6	22.6	30.74
11.0	93.5	947.2	25.8	35.09	957.2	25.8	35.09	946.0	24.4	33.18	953.2	25.0	34.00
12.0	102.0	945.0	28.0	38.08	955.1	27.9	37.94	943.2	27.2	36.99	951.0	27.2	36.99
13.0	110.5	942.4	30.6	41.62	952.6	30.4	41.34	941.0	29.4	39.98	948.9	29.3	39.85
14.0	119.0	940.3	32.7	44.47	950.6	32.4	44.06	938.1	32.3	43.93	946.6	31.6	42.98

MODULUS OF ELASTICITY.

Mix 2 : cylinder 2.1 @ 28 days



Lines fitted by linear regression analysis : E_{front} = 28.742 GPa

E_{back} = 27.945 GPa

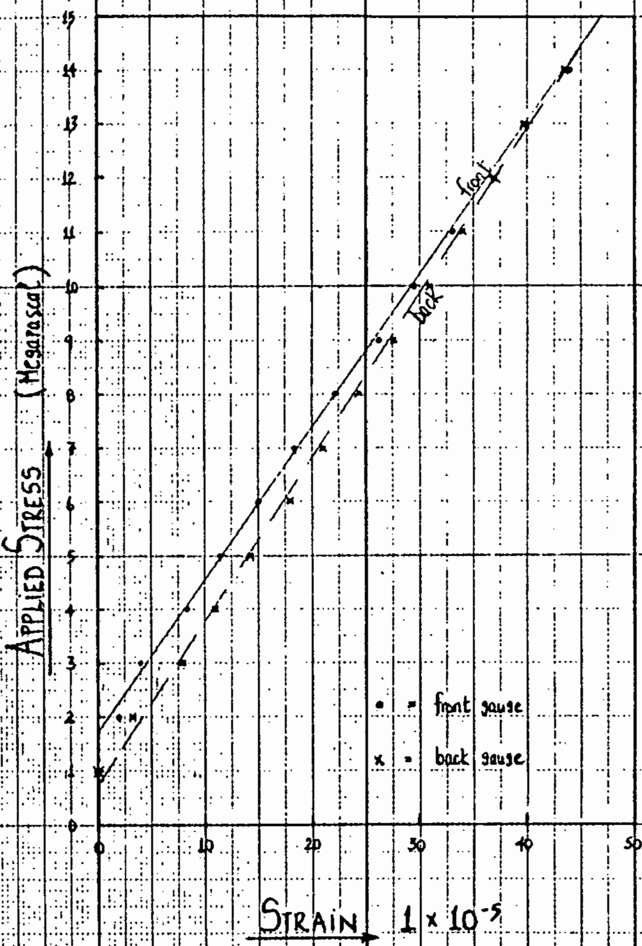
mean slope $\bar{E}$ = 28.344 GPa

difference front to back = 0.797 GPa

% difference from mean = 2.81% < 15% ∴ accept values

MODULUS OF ELASTICITY.

Mix 2 : cylinder 2.2 @ 28 days



Lines fitted by linear regression analysis : E_{front} = 28.551 GPa

E_{back} = 30.297 GPa

mean slope $\bar{E}$ = 29.424 GPa

difference front to back = 1.746 GPa

% difference from mean = 5.93% < 15% ∴ accept values

APPENDIX A8

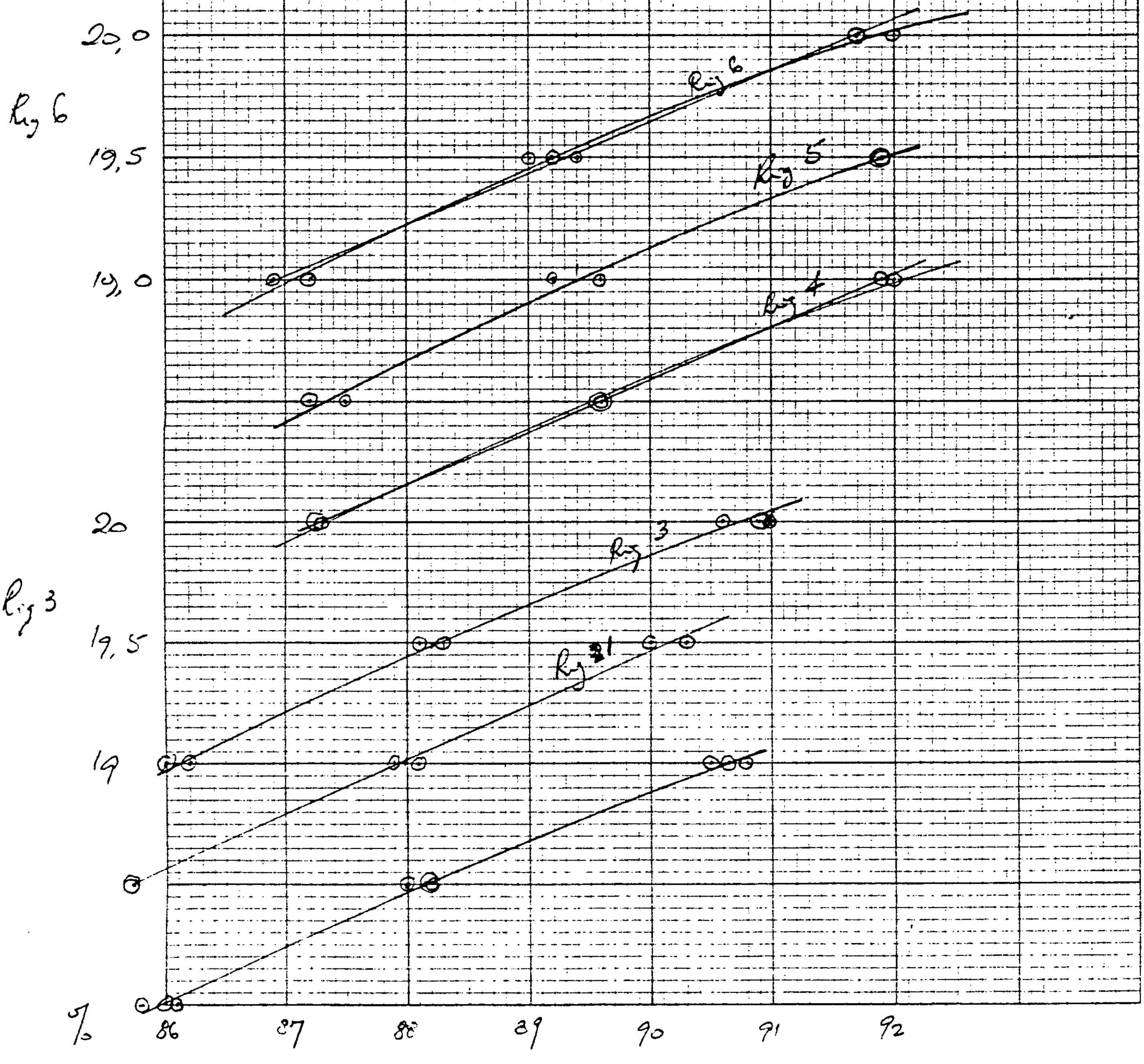
1. Calibration Charts for the U.C.T. Creep Rig (prepared by De Kock and Mallows)

2. Readings taken and the Processing of data for the Shrinkage and Creep of Recycled Concretes

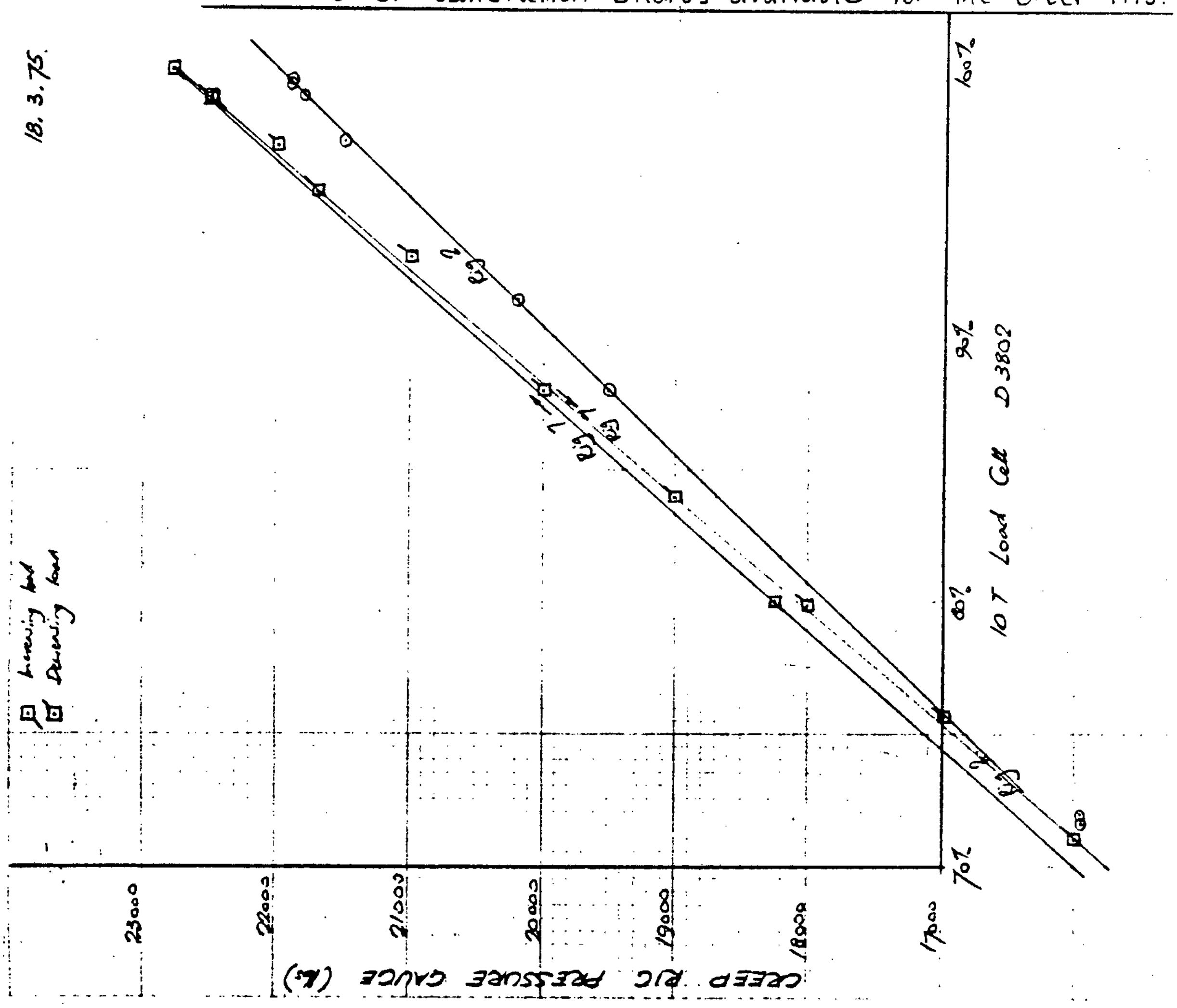
Creep Rigs

Calibrations for Andre Uys
Nov-Dec. 1981

Rig	Figure of 19500 %	Corrected Load in kN. $\frac{\text{Load Cell}}{1,0048}$
1	88,0	87,6
2	88,15	87,7
3	88,2	87,8
4	89,6	89,2
5	89,4	89,0
6	89,2	88,8

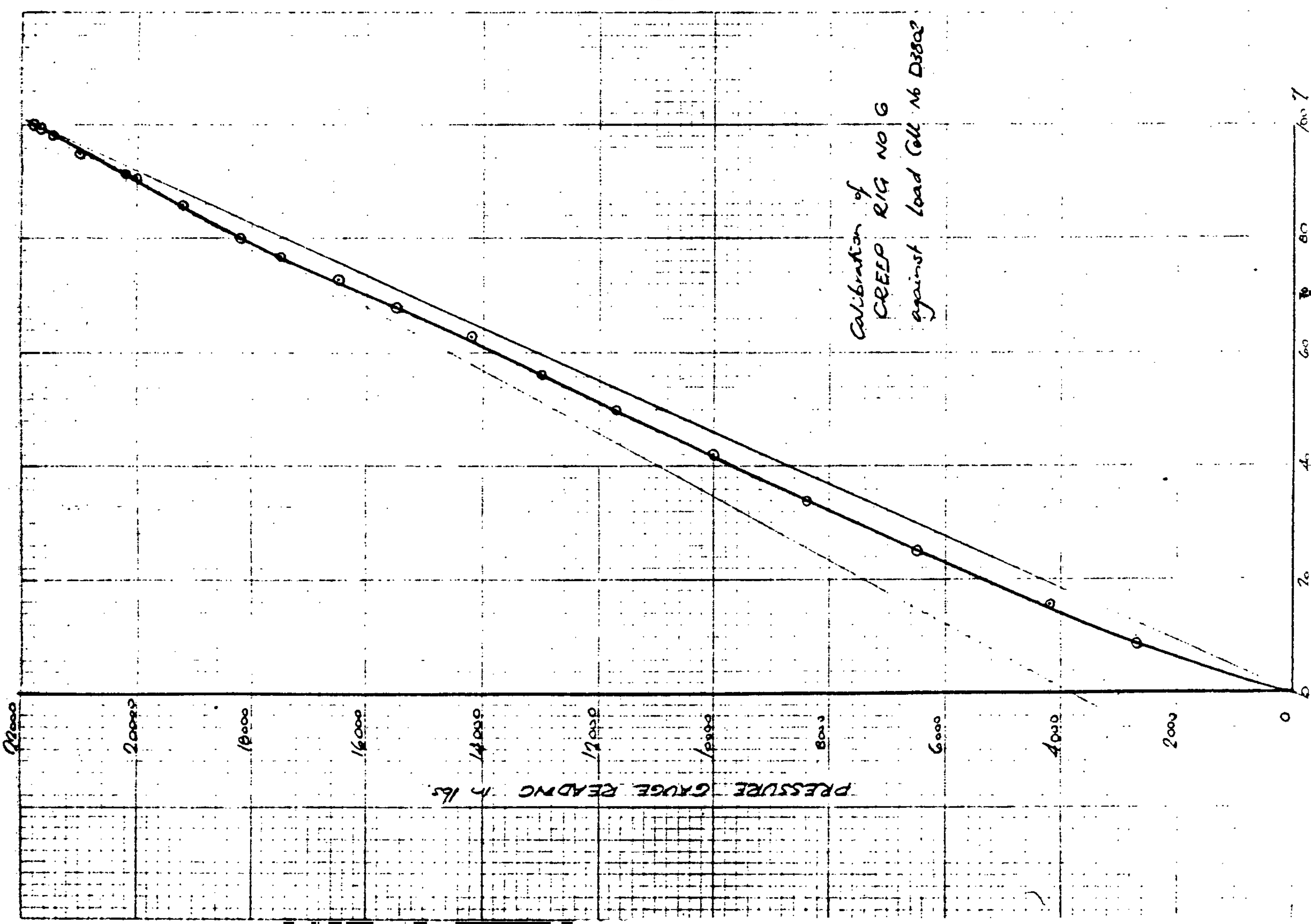


Examples of Calibration Charts available for the Creep Rig.


18. 3. 75.

☐ Increasing load
☐ Decreasing load

10 T Load Cell D 3802


Calibration of CREEP RIG No 6 against Load Cell No D3802

CREEP SPECIMENS FROM MIX 1 LOADED BY RIG # 1.

Date of Reading	Time Under Load	CYLINDER : C.1.1.						CYLINDER : C.1.2.						Mean total incremental strain (both)	Mean total cumulative shrinkage + creep.
		Front Gauge			Rear Gauge			Front Gauge			Rear Gauge				
		Reading	Δ gauge strain	Corrected Δ strain	Reading	Δ gauge strain	Corrected Δ strain	Reading	Δ gauge strain	Corrected Δ strain	Reading	Δ gauge Strain	Corrected Δ strain.		
	(Days)			($\times 10^{-5}$)			($\times 10^{-5}$)			($\times 10^{-5}$)			($\times 10^{-5}$)	($\times 10^{-5}$)	($\times 10^{-5}$)
24·11·86	0	cylinders were cast													
4·12·86	0	cylinders were placed in the creep rigs.													
unloaded	0	989.0	0	0	994.0	0	0	988·0	0	0	994.5	0	0	0	0
loaded	0	965.2	23·8	32·4	967·2	26·8	36·4	951·8	36.2	49.2	966.8	27.7	37.7	38·9	0
+ 30 mins	0·02	963·2	2·6	2.7	963.2	4.0	5.4	950.8	1.0	1.4	966.4	0.4	0.5	2.5	2.5
+ 75 mins	0·05	960.5	2.7	3.7	961.2	2.0	2.7	945.8	5.0	6.8	964.7	1.7	2.3	3.9	6.4
+ 3hrs	0·13	960.2	0.3	0.4	960.2	1.0	1.4	942.0	3.8	5.2	961.0	3.7	5.0	3.0	9·4
5·12·86	1	955·6	4·6	6.3	958.2	2.0	2.7	938.2	3.8	5.2	957.2	3.8	5.2	4.9	14·3
9·12·86	5	947·2	8.4	11.4	950.0	8.2	11.2	929.0	9.2	12.5	948.6	8.6	11.7	11.7	26.0
12·12·86	8	943.0	4.2	5.7	946.0	4.0	5.4	924.0	5.0	6.8	944.0	4.6	6.3	6.1	32.1
17·12·86	13	934.0	9.0	12.2	937.6	8.4	11.4	914.3	9.7	13.2	937.0	7.0	9.5	11.6	43.7
22·12·86	18	927.2	6.8	9.2	931·4	6.2	8.4	908.0	6.3	8.6	930.8	6.2	8.4	8.7	52.4
24·12·86	20	924.0	3.2	4.4	928.7	2.7	3.7	904.5	3.5	4.8	928.6	2.2	3.0	4.0	56.4
06·01·87	33	907.2	16.8	22.8	916.0	12.7	17.3	890.8	13.7	18.6	915.4	13.2	18.0	19.2	75.6
13·01·87	40	904.0	3.2	4.4	909.4	6.6	9.0	884.0	6.8	9.2	908.0	7.4	10.1	8.2	83.8
20·01·87	47	900.0	4.0	5.4	904.1	5.3	7.2	878.3	5.7	7.8	904.0	4.0	5.4	6.5	90.3
02·02·87	60	891.0	9.0	12.2	895.5	8.6	11.7	869.0	9.3	12.6	896.5	7.5	10.2	11.7	102.0
			Σ:	133.4		Σ:	133.9		Σ:	161.9		Σ:	133.3	140.9	
			δ_{c+s} :	101.0		δ_{c+s} :	97.5		δ_{c+s} :	112.7		δ_{c+s} :	95.6		

CREEP SPECIMENS FROM MIX 1 LOADED BY RIG # 4

Date of Reading	Time Under Load	CYLINDER : C.1.3						CYLINDER : C.1.4						Mean total incremental strain (both)	Mean total cumulative shrinkage + creep.
		Front Gauge			Rear Gauge			Front Gauge			Rear Gauge				
		Reading	Δ gauge strain	Corrected Δ strain	Reading	Δ gauge strain	Corrected Δ strain	Reading	Δ gauge strain	Corrected Δ strain	Reading	Δ gauge Strain	Corrected Δ strain.		
	(Days)			($\times 10^{-5}$)			($\times 10^{-5}$)			($\times 10^{-5}$)			($\times 10^{-5}$)	($\times 10^{-5}$)	($\times 10^{-5}$)
24·11·86	0	cylinders were cast													
4·12·86	0	cylinders were placed in the creep rigs.													
unloaded	0	992·6	0	0	998.0	0	0	998.7	0	0	994.3	0	0	0	0
loaded	0	968.0	24.6	33.5	968.7	29.3	39.8	967.7	31.0	42.2	964.3	30.0	40.8	39.1	0
+ 30 mins	0·02	967.8	0.2	0.3	968.4	0.3	0.4	967.4	0.3	0.4	960.8	3.5	4.8	1.5	1.5
+ 75 mins	0·05	964.0	3.8	5.2	965.9	2.5	3.4	963.3	4.1	5.6	956.2	4.6	6.3	5.1	6.6
+ 3hrs	0·13	962.0	2.0	2.7	963.4	2.5	3.4	960.4	2.9	3.9	952.2	4.0	5.4	3.9	10.5
5·12·86	1	959.5	2.5	3.4	960.4	3.0	4.1	956.0	4.4	6.0	948.2	4.0	5.4	4.7	15.2
9·12·86	5	950.7	8.8	12.0	951.0	9.4	12.8	945.0	11.0	15.0	939.5	8.7	11.8	12.9	28.1
12·12·86	8	947.0	3.7	5.0	944.5	6.5	8.8	940.0	5.0	6.8	935.0	4.5	6.1	6.7	34.8
17·12·86	13	938.3	8.7	11.8	937.0	7.5	10.2	929.7	10.3	14.0	925.0	10.0	13.6	12.4	47.2
22·12·86	18	932.0	6.3	8.6	929.4	7.6	10.3	921.0	8.7	11.8	918.0	7.0	9.5	10.1	57.3
24·12·86	20	928.0	4.0	5.4	927.7	1.7	2.3	918.7	2.3	3.1	914.1	3.9	5.3	4.0	61.3
06·01·87	33	918.0	10.0	13.6	913.8	13.9	18.9	905.0	13.7	18.6	901.0	13.1	17.8	17.2	78.5
13·01·87	40	911.0	7.0	9.5	905.7	8.1	11.0	897.0	8.0	10.9	894.8	6.2	8.4	10.0	88.5
20·01·87	47	907.0	4.0	5.4	901.0	4.7	6.4	891.5	5.5	7.5	889.0	5.8	7.9	6.8	95.3
02·02·87	60	897.0	10.0	13.6	891.9	9.1	12.4	881.5	10.0	13.6	879.6	9.4	12.8	13.1	108.4
			Σ:	130.0		Σ:	144.2		Σ:	159.4		Σ:	155.9	147.5	
			δ_{c+s}:	96.5		δ_{c+s}:	104.4		δ_{c+s}:	117.2		δ_{c+s}:	115.1		

UNLOADED SHRINKAGE SPECIMENS OF MIX 1.

Date of Reading	Time Under Load	CYLINDER : S.1.1.						CYLINDER : S.1.2.						Mean total incremental strain (both)	Mean total cumulative shrinkage + creep.
		Front Gauge			Rear Gauge			Front Gauge			Rear Gauge				
		Reading	Δ gauge strain	Corrected Δ strain	Reading	Δ gauge strain	Corrected Δ strain	Reading	Δ gauge strain	Corrected Δ strain	Reading	Δ gauge Strain	Corrected Δ strain.		
	(Days)			(x10⁻⁵)			(x10⁻⁵)			(x10⁻⁵)			(x10⁻⁵)	(x10⁻⁵)	(x10⁻⁵)
24·11·86	0	cylinders were cast													
4·12·86	0	cylinders were placed in the creep rigs.													
unloaded	0	1003.0	0	0	997.9	0	0	996.2	0	0	984.4	0	0	0	0
	0														
+ 30 mins	0·02														
+ 75 mins	0·05	1001.0	-2.0	-2.7	997.9	0	0	996.2	0	0	984.0	-0.4	-0.5	-0.8	-0.8
+ 3hrs	0·13														
5·12·86	1	1000.5	-0.5	-0.7	999.0	+1.1	+1.5	996.0	-0.2	-0.3	985.0	+1.0	+1.4	+0.5	-0.3
9·12·86	5	1000.0	-0.5	-0.7	997.2	-1.8	-2.4	995.4	-0.6	-0.8	984.5	-0.5	-0.7	-1.2	-1.5
12·12·86	8														
17·12·86	13	996.2	-3.8	-5.2	992.0	-5.2	-7.1	991.0	-4.4	-6.0	981.5	-3.0	-4.1	-5.6	-7.1.
22·12·86	18														
24·12·86	20	992.7	-3.5	-4.8	989.5	-2.5	-3.4	988.2	-2.8	-3.8	977.6	-3.9	-5.3	-4.3	-11.4
06·01·87	33	988.0	-4.7	-6.4	985.0	-4.5	-6.1	981.4	-6.8	-9.2	974.0	-3.6	-4.9	-6.7	-18.1
13·01·87	40	984.0	-4.0	-5.4	980.0	-5.0	-6.8	980.2	-1.2	-1.6	971.5	-2.5	-3.4	-4.3	-22.4
20·01·87	47	981.6	-2.4	-3.3	978.7	-1.3	-1.8	978.0	-2.2	-3.0	968.0	-3.5	-4.8	-3.2	-25.6
02·02·87	60	978.0	-3.6	-4.9	976.5	-2.2	-3.0	975.0	-3.0	-4.1	966.2	-1.8	-2.4	-3.6	-29.2
			Σ:	-34.1		Σ:	-29 1		Σ:	-28.8		Σ:	-24.7	-29.2	

CREEP AND SHRINKAGE OF MIX 1

fcu at load = 22 MPa
applied stress = 8.892 MPa
E - modulus (28d) = 22.8 GPa.

DAYS UNDER LOAD	SHRINKAGE MEASURE.		CREEP IN RIG#		CREEP IN RIG#		MEAN TOTAL MEASURE		MEAN CREEP	SPECIFIC CREEP
	Mean Strain.	Mean Cumulative.	Mean Total Strain	Cumulative Total Strain.	Mean Total Strain.	Cumulative Total Strain.	Mean Total Strain	Cumulative Total Strain.	Total less Shrinkage. (Cumulative)	Creep strain / Stress
(units)	X 10^{-5}	X 10^{-5}	X 10^{-5}	X 10^{-5}	X 10^{-5}	X 10^{-5}	X 10^{-5}	X 10^{-5}	X 10^{-5}	X 10^{-5} / MPa
unloaded	0	0	0	0	0	0	0	0	0	0
loaded	0	0	38.9	0	39.1	0	39.0	0	0	0
0·02		(- 0.4)	2.5	2.5	1.5	1.5	2.0	2.0	1.6	1.9
0·05	-0.8	- 0.8	3.9	6.4	5.1	6.6	4.5	6.5	5.7	6.6
0·13		(- 0.5)	3.0	9.4	3.9	10.5	3.5	10.0	9.5	11.0
1	+ 0.5	- 0.3	4.9	14.3	4.7	15.2	4.8	14.8	14.5	16.3
5	- 1.2	- 1.5	11.7	26.0	12.9	28.1	12.3	27.1	25.6	28.8
8		(- 4.3)	6.1	32.1	6.7	34.8	6.4	33.5	29.2	32.8
13	- 5.6	- 7.1	11.6	43.7	12.4	47.2	12.0	45.5	38.4	43.2
18		(-9.2)	8.7	52.4	10.1	57.3	9.4	54.9	45.7	51.4
20	- 4.3	- 11.4	4.0	56.4	4.0	61.3	4.0	58.9	47.5	53.4
33	- 6.7	- 18.1	19.2	75.6	17.2	78.5	18.2	77.1	59.0	66.4
40	- 4.3	- 22.4	8.2	83.8	10.0	88.5	9.1	86.2	63.8	71.7
47	- 3.2	- 25.6	6.5	90.3	6.8	95.3	6.6	92.8	67.2	75.6
60	- 3.6	- 29.2	11.7	102.0	13.1	108.4	12.4	105.2	76.0	85.5

CREEP SPECIMENS FROM MIX 2 LOADED IN RIG # 5

Date of Reading	Time Under Load	CYLINDER : C.2.1.						CYLINDER : C.2.2.						Mean total incremental strain (both)	Mean total cumulative shrinkage + creep.
		Front Gauge			Rear Gauge			Front Gauge			Rear Gauge				
		Reading	Δ gauge strain	Corrected Δ strain	Reading	Δ gauge strain	Corrected Δ strain	Reading	Δ gauge strain	Corrected Δ strain	Reading	Δ gauge strain	Corrected Δ strain.		
	(Days)			($\times 10^{-5}$)			($\times 10^{-5}$)			($\times 10^{-5}$)			($\times 10^{-5}$)	($\times 10^{-5}$)	($\times 10^{-5}$)
25·11·86	0	cylinders were cast													
4·12·86	0	cylinders were placed in the creep rigs.													
unloaded	0	997·2	0	0	978·0	0	0	990·8	0	0	1005.2	0	0	0	0
loaded	0	973.4	23.8	32.4	956.7	21.3	29.0	969.0	21.8	29.6	980.5	24.7	33.6	31.2	0
+ 30 mins	0·02	973.0	0.4	0.5	955.7	1.0	1.4	968.0	1.0	1.4	980.3	0.2	0.3	0.9	0.9
+ 75 mins	0·05	971.0	2.0	2.7	955.2	0.5	0.7	967.0	1.0	1.4	979.7	0.6	0.8	1.4	2.3
+ 3hrs	0·13	970.4	0.6	0.8	953.6	1.6	2.2	965.2	1.8	2.4	978.0	1.7	2.3	1.9	4.2
5·12·86	1	969.0	1.4	1.9	951.2	2.4	3.3	963.0	2.2	3.0	974.5	3.5	4.8	3.3	7.5
9·12·86	5	959.0	10.0	13.6	940.0	11.2	15.2	954.0	9.0	12.2	961.8	12.7	17.3	14.6	22.1
12·12·86	8	955.6	3.4	4.6	938.8	1.2	1.6	948.4	5.6	7.6	960.4	1.4	1.9	3.9	26.0
17·12·86	13	949.2	6.4	8.7	932.0	6.8	9.2	944.0	4.4	6.0	953.0	7.4	10.1	8.5	34.5
22·12·86	18	943.0	6.2	8.4	925.0	7.0	9.5	939.0	5.0	6.8	945.0	8.0	10.9	8.9	43.4
24·12·86	20	942.4	0.6	0.8	923.0	2.0	2.7	936.8	2.2	3.0	944.6	0.4	0.5	1.8	45.2
06·01·87	33	932.0	10.4	14.1	912.3	10.7	14.6	927.0	9.8	13.3	933.0	11.6	15.8	14.5	59.7
13·01·87	40	927.0	5.0	6.8	907.4	4.9	6.7	922.0	5.0	6.8	929.0	4.0	5.4	6.4	66.1
20·01·87	47	923.3	3.7	5.0	903.5	3.9	5.3	918.0	4.0	5.4	924.5	4.5	6.1	5.5	71.6
02·02·87	60	916.4	6.9	9.4	896.3	7.2	9.8	912.0	6.0	8.2	917.0	7.5	10.2	9.4	81.0
			Σ:	108.7		Σ:	111.2		Σ:	107.1		Σ:	120.0	112.2	
			δ_{c+s}:	76.3		δ_{c+s}:	82.2		δ_{c+s}:	77.5		δ_{c+s}:	86.4		

CREEP SPECIMENS FROM MIX 2 LOADED BY RIG # 6

Date of Reading	Time Under Load	CYLINDER : C.2.3.						CYLINDER : C.2.4.						Mean total incremental Strain (both)	Mean total cumulative shrinkage + creep.
		Front Gauge			Rear Gauge			Front Gauge			Rear Gauge				
		Reading	Δ gauge strain	Corrected Δ strain	Reading	Δ gauge strain	Corrected Δ strain	Reading	Δ gauge strain	Corrected Δ strain	Reading	Δ gauge strain	Corrected Δ strain.		
	(Days)			($\times 10^{-5}$)			($\times 10^{-5}$)			($\times 10^{-5}$)			($\times 10^{-5}$)	($\times 10^{-5}$)	($\times 10^{-5}$)
25·11·86	0	cylinders were cast													
4·12·86	0	cylinders were placed in the creep rigs.													
unloaded	0	990·0	0	0	994·1	0	0	996.7	0	0	999·0	0	0	0	0
loaded	0	968.3	21.7	29.5	973.2	20.9	28.4	973.8	22.9	31.1	980.6	18.4	25.0	28.5	0
+ 30 mins	0·02	967.9	0.4	0.5	972.5	0.7	1.0	972.7	1.1	1.5	979.2	1.4	1.9	1.2	1.2
+ 75 mins	0·05	966.0	1.9	2.6	972.3	0.2	0.3	971.0	1.7	2.3	977.0	2.2	3.0	2.1	3.3
+ 3hrs	0·13	965.0	1.0	1.4	968.0	4.3	5.8	969.7	1.3	1.8	976.0	1.0	1.4	2.6	5.9
5·12·86	1	961·8	3·2	4.4	965.6	2.4	3.3	965.2	4.5	6.1	975.0	1.0	1.4	3.8	9.7
9·12·86	5	952.0	9.8	13.3	957.0	8.6	11.7	955.1	10.1	13.7	965.4	9.6	13.1	13.0	22.7
12·12·86	8	949.0	3.0	4.1	954.0	3.0	4.1	951.6	3.5	4.8	962.0	3.4	4.6	4.4	27.1
17·12·86	13	941.7	7.3	9.9	946.8	7.2	9.8	944.4	7.2	9.8	957.5	4.5	6.1	8.9	36.0
22·12·86	18	935.4	6.3	8.6	941.2	5.6	7.6	938.4	6.0	8.2	952.0	5.5	7.5	8.0	44.0
24·12·86	20	934.4	1.0	1.4	941.0	0.2	0.3	937.2	1.2	1.6	950.7	1.3	1.8	1.3	45.3
06·01·87	33	925.2	9.2	12.5	931.5	9.5	12.9	927.4	9.8	13.3	942.0	8.7	11.8	12.6	57.9
13·01·87	40	919.5	5.7	7.8	925.4	6.1	8.3	922.0	5.4	7.3	938.0	4.0	5.4	7.2	65.1
20·01·87	47	916.0	3.5	4.8	923.0	2.4	3.3	918.5	3.5	4.8	933.2	4.8	6.5	4.9	70.0
02·02·87	60	909.6	6.4	8.7	916.8	6.2	8.4	912.3	6.2	8.4	927.5	5.7	7.8	8.3	78.3
			Σ:	109.5		Σ:	105.2		Σ:	114.7		Σ:	97.3	106.8	
			δ_{c+s}:	71.9		δ_{c+s}:	76.8		δ_{c+s}:	83.6		δ_{c+s}:	72.3		

UNLOADED SHRINKAGE SPECIMENS OF MIX 2.

Date of Reading	Time Under Load	CYLINDER : S.2.1.						CYLINDER : S.2.2.						Mean total incremental strain (both)	Mean total cumulative shrinkage + creep.
		Front Gauge			Rear Gauge			Front Gauge			Rear Gauge				
		Reading	Δ gauge strain	Corrected Δ strain	Reading	Δ gauge strain	Corrected Δ strain	Reading	Δ gauge strain	Corrected Δ strain	Reading	Δ gauge Strain	Corrected Δ strain.		
	(Days)			(x10^{-5})			(x10^{-5})			(x10^{-5})			(x10^{-5})	(x10^{-5})	(x10^{-5})
	0	cylinders were cast													
4·12·86	0	cylinders were placed in the creep rigs.													
unloaded	0	997.6	0	0	993.0	0	0	997.2	0	0	995.6	0	0	0	0
	0														
+ 30 mins	0·02														
+ 75 mins	0·05	998.0	+0.4	+0.5	993.0	0	0	997.2	0	0	995.4	-0.2	-0.3	+0.1	+0.1
+ 3hrs	0·13														
5·12·86	1														
9·12·86	5	996.3	-1.7	-2.3	992.4	-0.6	-0.8	996.7	-0.5	-0.7	994.0	-1.4	-1.9	-1.4	-1.3
12·12·86	8														
17·12·86	13	992.3	-4.0	-5.4	986.0	-6.4	-8.7	991.4	-5.3	-7.2	988.3	-5.7	-7.8	-7.3	-8.6
22·12·86	18														
24·12·86	20	990.0	-2.3	-3.1	984.2	-1.8	-2.4	987.0	-4.4	-6.0	986.0	-2.3	-3.1	-3.7	-12.3
06·01·87	33	985.2	-4.8	-6.5	981.0	-3.2	-4.4.	984.0	-3.0	-4.1	981.7	-4.3	-5.8	-5.2	-17.5
13·01·87	40	983.0	-2.2	-3.0	978.0	-3.0	-4.1	980.2	-3.8	-5.2	978.4	-3.3	-4.5	-4.2	-21.7
20·01·87	47	980.0	-3.0	-4.1	974.5	-3.5	-4.8	978.0	-2.2	-3.0	976.1	-2.3	-3.1	-3.8	-25.5
02·02·87	60	978.0	-2.0	-2.7	973.0	-1.5	-2.0	975.2	-2.8	-3.8	973.4	-2.7	-3.7	-3.1	-28.6
			Σ:	-26.6		Σ:	-27.2		Σ:	-30.0		Σ:	-30.2	-28.6	

CREEP AND SHRINKAGE OF MIX 2

fcu at load = 33 MPa
applied stress = 8.359 MPa
E-modulus (28 das) = 28.05 GPa

DAYS	SHRINKAGE MEASURE.		CREEP IN RIG#		CREEP IN RIG#		MEAN TOTAL MEASURE		MEAN CREEP	SPECIFIC CREEP
UNDER LOAD	Mean Strain.	Mean Cumulative.	Mean Total Strain	Cumulative Total Strain.	Mean Total Strain.	Cumulative Total Strain.	Mean Total Strain	Cumulative Total Strain.	Total less Shrinkage. (Cumulative)	$\frac{\text{Creep strain}}{\text{Stress}}$
(units)	$\times 10^{-5}$	$\times 10^{-5}$	$\times 10^{-5}$	$\times 10^{-5}$	$\times 10^{-5}$	$\times 10^{-5}$	$\times 10^{-5}$	$\times 10^{-5}$	$\times 10^{-5}$	$\times 10^{-5}$ / MPa
unloaded	0	0	0	0	0	0	0	0	0	0
loaded	0	0	31.2	0	28.5	0	29.8	0	0	0
0.02	0	0	0.9	0.9	1.2	1.2	1.1	1.1	1.1	1.3
0.05	+0.1	+0.1	1.4	2.3	2.1	3.3	1.7	2.8	2.9	3.5
0.13		(-0.4)	1.9	4.2	2.6	5.9	2.3	5.1	4.7	5.6
1		(-0.8)	3.3	7.5	3.8	9.7	3.5	8.6	7.8	9.3
5	-1.4	-1.3	14.6	22.1	13.0	22.7	13.8	22.4	21.1	25.2
8		(-4.0)	3.9	26.0	4.4	27.1	4.2	26.6	22.6	27.0
13	-7.3	-8.6	8.5	34.5	8.9	36.0	8.7	35.3	26.7	31.9
18		(-11.0)	8.9	43.4	8.0	44.0	8.4	43.7	32.7	39.1
20	-3.7	-12.3	1.8	45.2	1.3	45.3	1.6	45.3	33.0	39.5
33	-5.2	-17.5	14.5	59.7	12.6	57.9	13.5	58.8	41.3	49.4
40	-4.2	-21.7	6.4	66.1	7.2	65.1	6.8	65.6	43.9	52.5
47	-3.8	-25.5	5.5	71.6	4.9	70.0	5.2	70.8	45.3	54.2
60	-3.1	-28.6	9.4	81.0	8.3	78.3	8.9	79.7	51.1	61.1

APPENDIX A9

The CEB Methods of 1970 (*58) for the Estimation of the Creep and Skrinkage of a Concrete

Appendix A9: CEB 1970 Code Recommendations.

R 12.22 Determining the elastic modulus
(See Supplement C 12.22)

R 12.221 DEFORMATIONS UNDER INSTANTANEOUS OR RAPIDLY CHANGING LOADS

In the presence of instantaneous or rapidly changing loads, the elastic modulus tangential to the origin, E_{bj}, of the concrete at an age of j days may be evaluated using the following formulae.

(a) Normal aggregate concretes:

$E_{bj}=66\,000\sqrt{R'_{bj}}$ where E_{bj} and R'_{bj} are expressed in N/cm^2 $= 6600\sqrt{R'_{bj}}$ ..... in MPa

valid as long as the stresses under working conditions do not exceed four-tenths of the compressive strength at j days. In this expression, R'_j is the average compressive strength of the concrete at j days, measured on cylinders.

(b) Lightweight aggregate concretes:

$E_{bj} \simeq 18\,000\sqrt{\gamma^3 R'_{bj}}$ (E_{bj} and R'_{bj} in N/cm^2)

where γ is the volumetric weight of the concrete.

For structural lightweight aggregate concretes, the values of E$_b$ *are subject to a large scatter; the above formula is thus only a guide. It is advisable to deduce* E$_b$ *from tests on cylindrical specimens (see R 12.11).*

R 12.222 DEFORMATIONS UNDER PROLONGED LOADS (CF. R 44.12 AND R 44.13)

For normal aggregate concretes and lightweight aggregate concretes, use may be made of the secant modulus,(in areas with working stresses)equal to the tangent modulus defined above, less 10%.

For the determination of internal forces produced by creep (R 12.31), the elastic modulus is the secant modulus E_{b28} defined for an age $j=28$ days.

R 12.3 DEFERRED DEFORMATIONS OF THE CONCRETE (SHRINKAGE AND CREEP)

The coefficients given in R 12.31 (creep) and R 12.32 (shrinkage) form a working basis and are valid *only* for Portland cement concretes of normal quality, hardening under normal conditions and subject to working stresses at the most equal to 40% of their rupture stress. (See Supplement C 12.3.)

This refers to the average rupture stress on cylinders at the particular time.

R 12.31 Creep

(1) In order to evaluate the order of magnitude of deferred deformations due to creep under working conditions, use may be made of the theory of linear creep. For a constant stress σ_b, this theory leads to a calculation of the final creep deformation from the formula:

$$\varepsilon_f=\frac{\sigma'_b}{E_{b28}}\phi_t$$

In this formula, E_{b28} is the value of the secant modulus of the concrete at an age of 28 days (R 12.222) which gives an indication of the quality of the concrete and ϕ_t is a coefficient covering the particular working conditions envisaged. This coefficient is equal to the product of five partial coefficients

$$\phi_t=k_e\,k_d\,k_b\,k_e\,k_t$$

where:

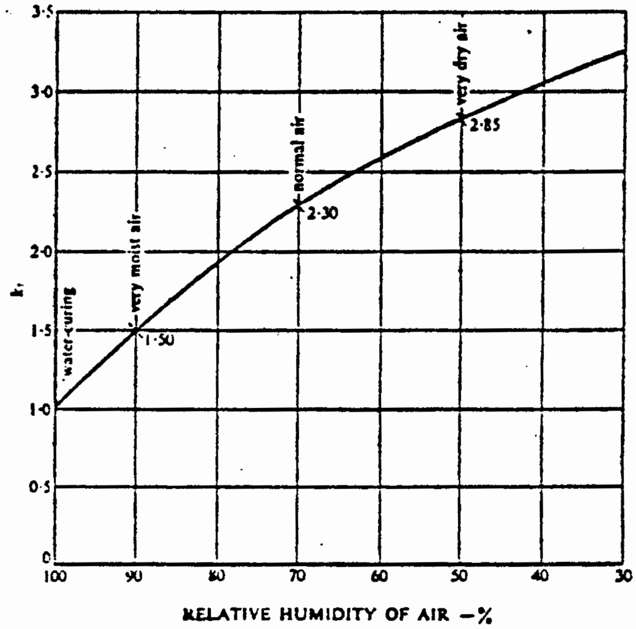
- k_e depends on the environmental conditions,
- k_d depends on the hardening of the concrete at the age of loading,
- k_b depends on the composition of the concrete,
- k_e depends on the theoretical thickness of the member,
- k_t covers the development of the deferred deformation with time.

The value of ϕ_t calculated with the values given below of these different coefficients is an average value. When creep has a large influence on the limit state under consideration, an increase or a reduction of the order of 15% should be considered, so as to cover the most unfavourable case.

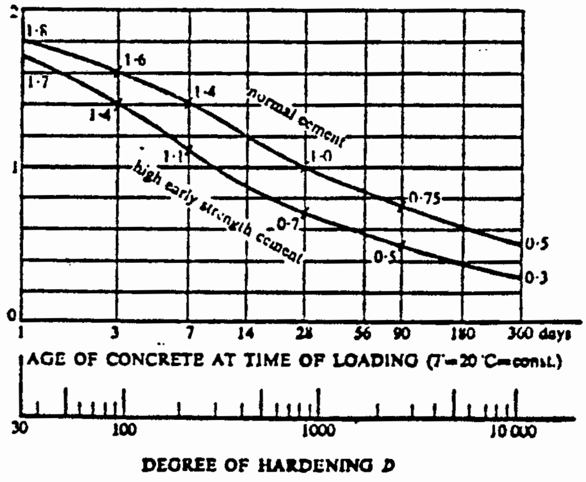
If the stresses producing creep are themselves influenced by creep or if they vary in a continuous manner, it is necessary to use iterative methods or to revert to appropriate analytical methods.

Where creep has a very large effect on the stresses, it may be advantageous to produce curves giving k$_d$ *and* k$_t$ *from equations.*

(2) Coefficient k_e (environmental conditions).



(3) Coefficient k_d (hardening at the age of loading).



The degree of hardening of the concrete at the age of loading exerts an influence at least as big as the climatic conditions.

The values in the diagram above refer to Portland cement, hardened under normal conditions, i.e. at an average concrete temperature of 20°C and with protection against excessive losses of moisture.

If the concrete hardens at a temperature other than 20°C, the age at loading is replaced by the corresponding degree of hardening:

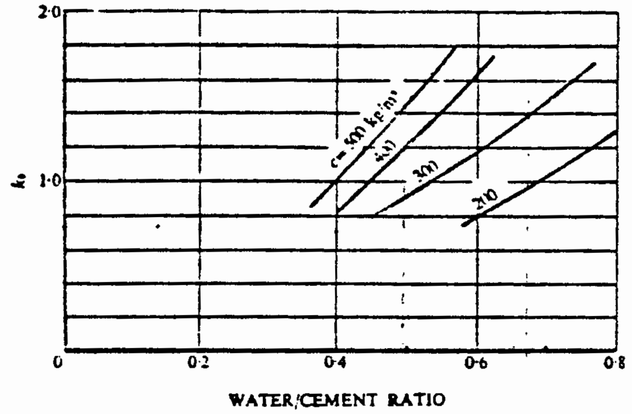
$$D = \Sigma\Delta t\ (T + 10°)$$

in which:

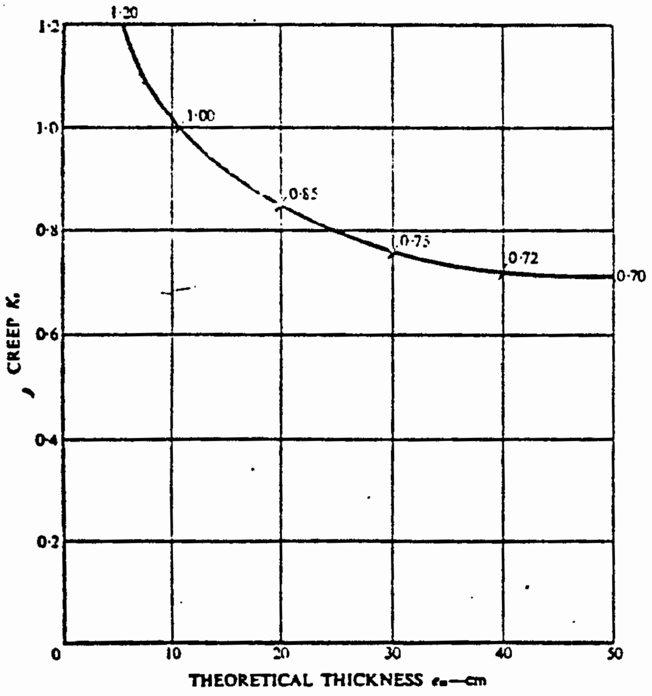
D *represents the degree of hardening at the moment of loading.*

Δt *represents the number of days during which hardening has taken place at* T°C.

(4) Coefficient k_b (composition of the concrete).



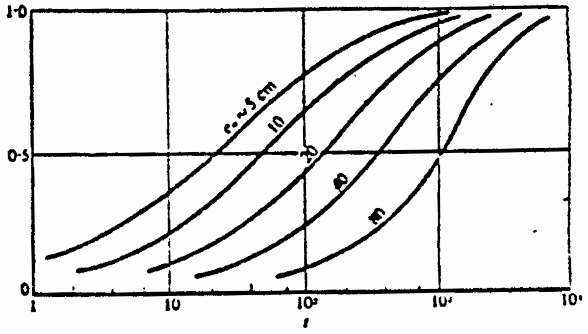
(5) Coefficient k_e (theoretical thickness).



The theoretical thickness e_m *is the quotient of the area of the section* B *divided by the semi-perimeter p/2 in contact with the atmosphere. If one of the dimensions of the section under consideration is very large with respect to the other, the theoretical thickness corresponds almost to the actual thickness.*

If the dimensions are not constant along the member, an average theoretical thickness can be defined by paying particular attention to those sections in which the stresses are maximum.

(6) Coefficient k_t (variation as a function of time)



(t represents the number of days after the application of loads).

(7) In general, the final creep deformation ε_f for light-weight aggregate concretes is greater than that for normal aggregate concretes. This difference is a little less for high-strength concretes than for low-strength concretes. The final creep deformation should be deduced from tests carried out in accordance with the methods laid down by RILEM. Alternatively, it may be calculated by giving E_{b28} the value corresponding to normal aggregate concretes and in multiplying the result obtained by 1·6, or

$$\varepsilon_f = 1{\cdot}6\frac{\sigma_b'}{E_{b28}}$$

(8) At a given moment z, after application of the loads, the influence of a stress σ'_{bj}, applied at the instant j and subject at any moment i to variation in intensity σ'_{bi}, may be expressed as:

$$\varepsilon_{fz} = \frac{1}{E_{b28}}\left[\sigma'_{bj}\varphi_{(z-j)} + \Sigma\sigma'_{bi}\varphi_{(z-i)}\right] \text{ or}$$

$$\varepsilon_{fz} = \frac{k_c\, k_b\, k_e}{E_{b28}}\left[\sigma'_{bj}\, k_{dj}\, k_{t(z-j)} + \Sigma\sigma_{bi}\, k_{di}\, k_{t(z-i)}\right]$$

As shown in the equation, superposition of loads should always be done on the assumption that the stress applied at the beginning operates until the end of the period under consideration. The same method may be applied for all later stress changes; in effect, the values of k_d *have been determined in these hypotheses.*

R 12.32 Shrinkage

(1) The shrinkage deformation ε_r at any instant may be determined by the product of five partial coefficients:

$$\varepsilon_r = \varepsilon_c\, k_b\, k_e\, k_p\, k_t$$

where

ε_c depends on the environment;

k_b depends on the composition of the concrete;

k_e depends on the theoretical thickness of the member (see R 12.315);

k_p depends on the geometric percentage $p = 100A/B$

of longitudinal reinforcement of area A with respect to the cross-sectional area of the member B:

$$k_p = \frac{100}{100+np}$$

where $n = 20$ with regard to the effects of creep;

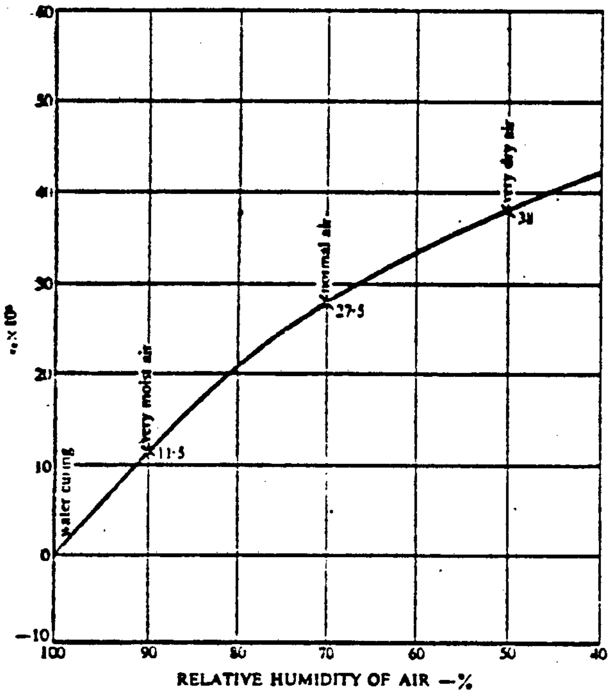
k_t defines the development of shrinkage as a function of time.

As a general rule, ε_r as a function of k_p gives the reduction in length of the fibre at the centre of gravity of the tendon p under consideration.

The average values of the coefficients ε_c, k_b, k_e and k_t, as functions of the parameters which define them, may be taken from the following diagrams which are valid only for concretes which have been protected from excessive losses of moisture in their early days.

(2) Coefficient ε_e (environment).

For unreinforced concrete, the average values of ε_e can be taken from the following diagram:



For underfloor heating, ovens, etc., values of the coefficient ε_c should be taken from experience.

(3) Coefficient k_b (composition of the concrete).

The same coefficients may be used as for creep, see diagram in R 12.314.

(4) Coefficient k_e (theoretical thickness).

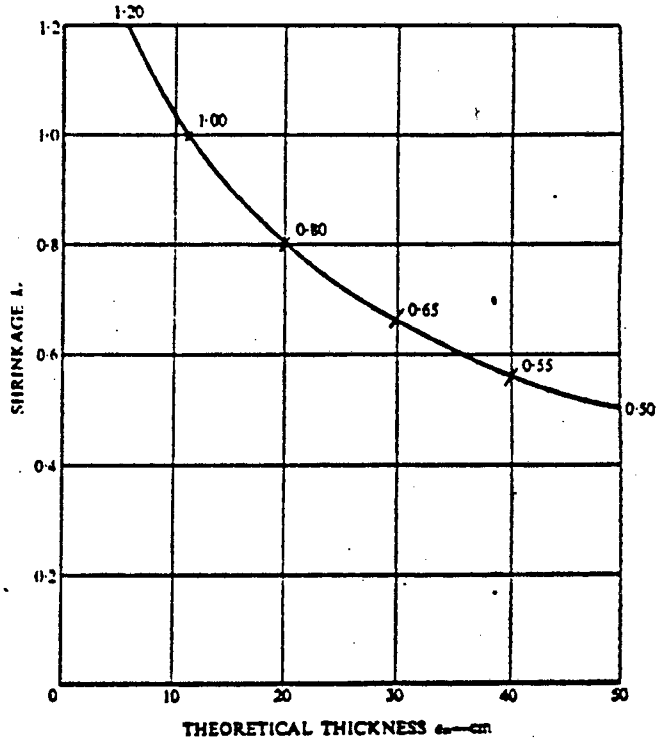
(5) Coefficient k_t (variation as a function of time).

The same coefficient may be used as for creep, see diagram in R 12.315.

Where climatic conditions are constant, that part of the deformation due to shrinkage in an interval of time $(z-t)$ is equal to:

$$\Delta\varepsilon_{r(z-t)} = \varepsilon_c\, k_b\, k_e\, k_p\, (k_{tz} - k_{tt})$$

At early ages, the shrinkage of a protected concrete is lower than that of an unprotected concrete (this is important when trying to avoid cracking in concrete which is young and therefore of low strength), the difference decreasing with time and finally vanishing. This feature is less noticeable for massive members.



(6) It has been shown experimentally that shrinkage of structural lightweight concretes lies between one and two times that of normal aggregate concretes with the same compressive strength.

APPENDIX A10

Details of the 20 credits of Course Work
Completed towards the M.Sc. degree

Year	Course			Credits
1985	CE5B17	Finite Element Analysis	*	4
1985	CE5G1	The Properties of Concrete	□	5
1985	CE5B11	Structural Loading	∅	3
1986	CIV502F	Prestressed Concrete	∅	5
1986	CIV535S	Finite Element Modelling of Structures	□	4

* = exam only
∅ = exam and project
□ = project only

UNIVERSITY OF CAPE TOWN

DEPARTMENT OF CIVIL ENGINEERING

FINAL EXAM. MONDAY, 24 JUNE 1985

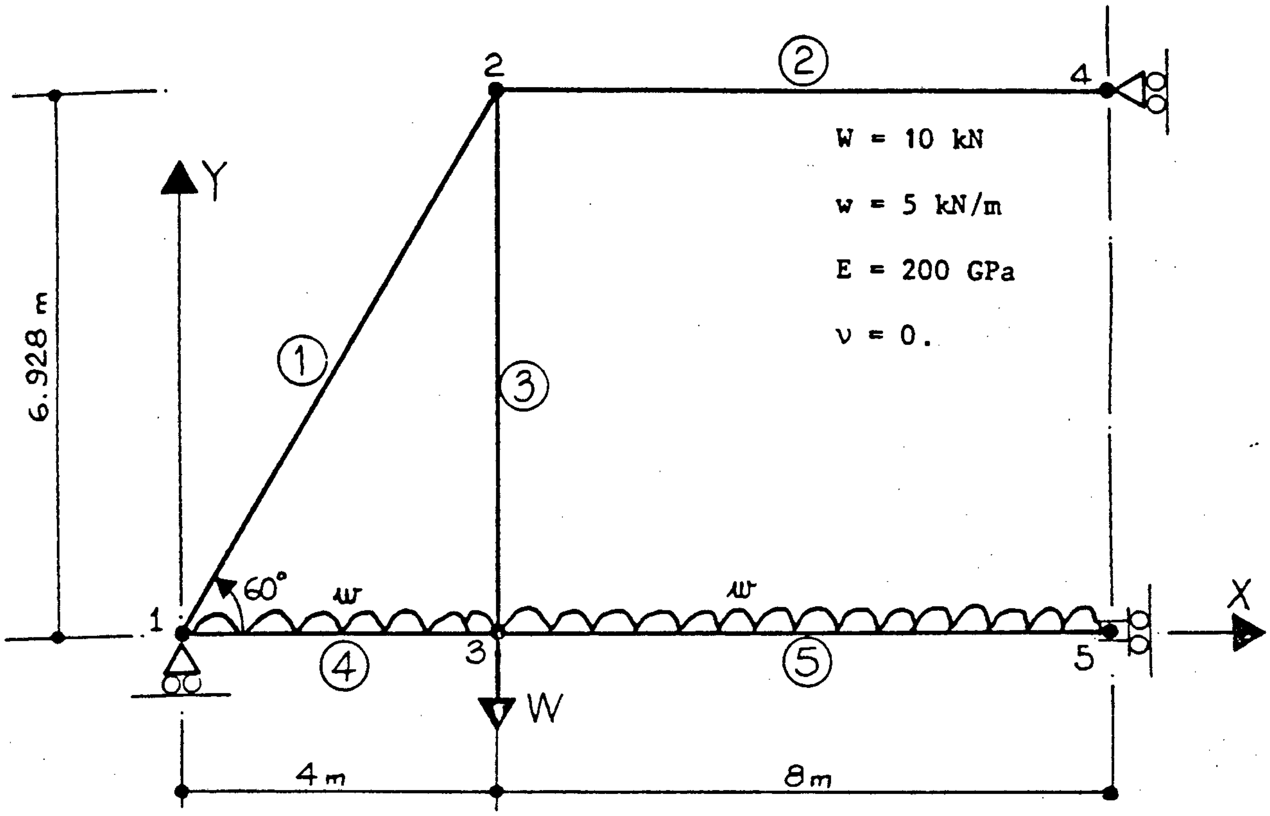
CE 5B17 : FINITE ELEMENT ANALYSIS

TIME : 3 hours

Note:

The student may refer to class notes and assignments.

1. The diagram shows half a plane symmetric frame structure, which is to be modelled using 5 elements.



Element 1,2 : linear bar ; $A = 5000 \text{ mm}^2$

3 : Bernoulli-Euler beam ; $A = 30000 \text{ mm}^2$

$I = 50 \times 10^6 \text{ mm}^4$

4,5 : linear Timoshenko beam ; $A = 125000 \text{ mm}^2$

$I = 2600 \times 10^6 \text{ mm}^4$

$\alpha = 1.2$

(i) Compute the <u>global</u> element stiffness matrices for elements 1, 3 and 4 .

(20)

(ii) Comment <u>briefly</u> on the relative stiffnesses contained in these element matrices.

(3)

(iii) Assemble elements 1 and 4 <u>only</u> into the global system stiffness matrix; show only what is necessary, i.e. nodes 1, 2 and 3 .

(5)

(iv) Compute the global system load vector.

(5)

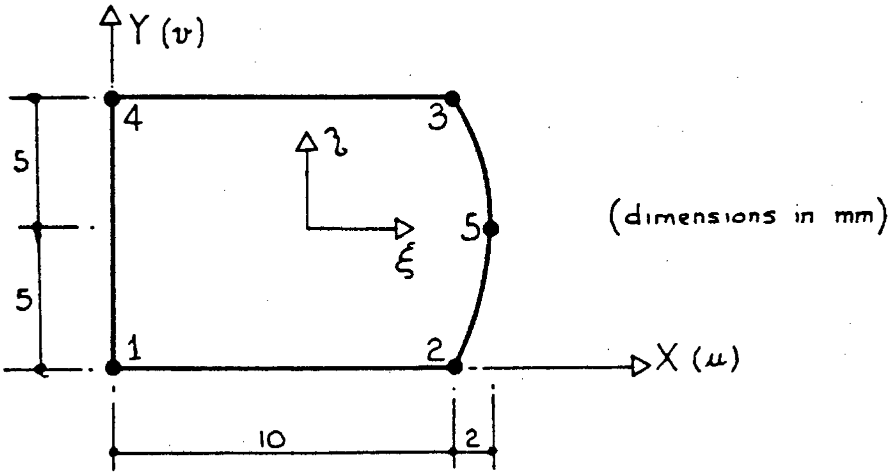
(v) Assume the following displacement solution (mm and rads) :

Node	u	v	θ
1	0.010	0.	-1.0×10^{-6}
3	0.012	-0.001	-0.5×10^{-6}

Using this solution compute the shear force and bending diagrams for element 4 .

(12)

2. A 5-noded quadrilateral plane stress element is shown below. Side 2-5-3 is curved.



(i) Show that the Jacobian matrix for this element is :

$$J_{11} = 6 - \eta^2 \qquad J_{12} = 0$$

$$J_{21} = -2\eta(1 + \xi) \qquad J_{22} = 5$$

(10)

(ii) For a thickness $t = 1$ mm , compute the volume of the element using exact numerical integration.

(5)

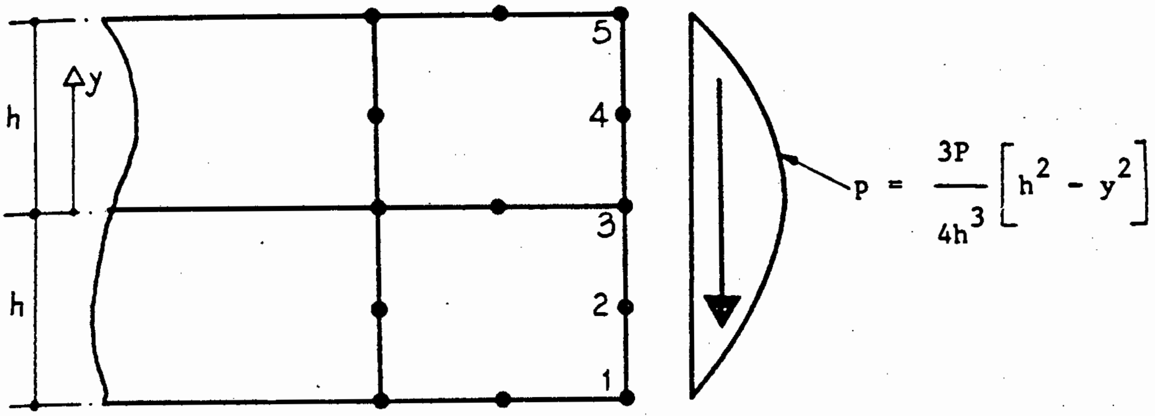
(iii) Show that the normal strain along the side 3-4 is a constant with magnitude

$$\varepsilon_{xx} = 0.1 (u_3 - u_4)$$

(10)

Note: You may request the element shape functions if you do not have them in your notes.

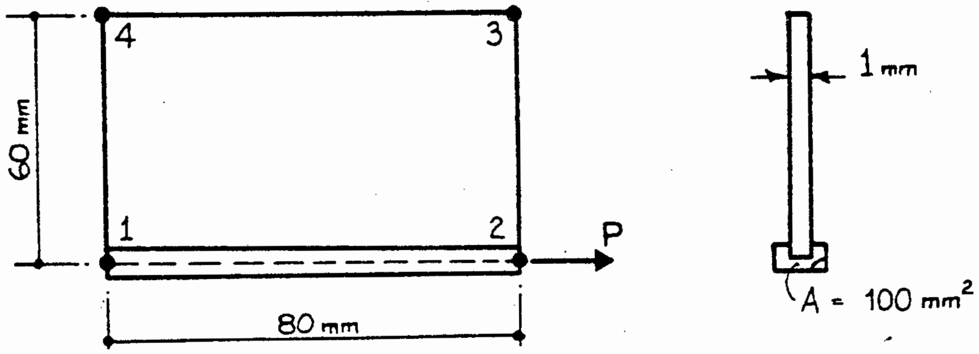
3. A parabolic shear load is applied across the edges of two 8-node quadrilateral elements as shown in the diagram.



Show that the equivalent nodal load at node 3 is (11/40)P .

(15)

4. A 4-node quadrilateral element and a 2-node bar element together support a point load $P = 6000N$. Nodes 1, 3 and 4 are fully restrained, and node 2 can only move horizontally.



The following additional information is given :

$$\frac{\partial N_2}{\partial x} = \frac{1}{16}(1-\eta) \quad ; \quad \frac{\partial N_2}{\partial y} = -\frac{1}{12}(1+\xi)$$

$$\underset{\sim}{J} = \begin{bmatrix} 4 & 0 \\ 0 & 3 \end{bmatrix} \quad ; \quad E = 300 \text{ GPa} \; ; \quad \nu = 0.3$$

Compute the horizontal displacement at node 2.

(15)

SYNOPSIS. CE 5G1 : PROPERTIES OF CONCRETE.

This project was performed to fulfill the requirements of the course CE 5G1: "The Properties of Concrete". Suitable reference were obtained from the UCT Library from where the information was taken and assembled for this report.

Four categories of Lightweight Concrete exist: (1) No-fines concrete, (2) Partially compacted lightweight concrete, (3) Structural lightweight concrete, (4) Aerated concrete.

No-fines concrete and aerated concrete are lightweight concretes in which there are very little variations in aggregate – in fact, no-fines concrete usually has no fine aggregate at all, and aerated concretes generally have no coarse aggregate. The physical and mechanical properties of these two lightweight concrete types can therefore be discussed directly with reference to their mix proportions, cement and water content, mixing, placing and curing techniques.

Partially compacted- and structural lightweight concretes may employ a wide variety of different lightweight aggregates – the major ones being foamed blast-furnace slag, sintered pulverised fuel ash and expanded clays because they have the least amount of deleterious effect on the cement and concrete. The physical and mechanical properties of these two lightweight concrete categories must therefore be inspected with direct reference to the aggregate used and its specific physical and mechanical properties.

Lightweight concretes are finding increasing use worldwide as an economic alternative to normal dense concrete. The economy in lightweight concrete lies mainly in its ability to drastically reduce dead loads in structures and it usually allows for more rapid constuction if pre-cast members are used. However, lightweight concretes are still mainly used for its good thermal insulation, fire protection and acoustic properties. In these types of applications the strength of the concrete becomes of lesser importance.

UNIVERSITY OF CAPE TOWN

DEPARTMENT OF CIVIL ENGINEERING

OPEN BOOK EXAMINATION

CE 5B11 - STRUCTURAL LOADING

Time allowed: 3 hours Date: 2 November 1985

Answers must be concise

1. Explain how the loading data differs for the three levels of limit state design.

2. State which probability distribution fits each type of loading best, and explain why the tail of a typical distribution curve is so significant in reliability theory.

3. Discuss the meanings and applications of "global loads" and "local loads" on buildings and bridges.

4. List all the possible categories of bridge loading and explain their meanings.

5. Define the term "loaded length" for highway bridges and discuss its effect on traffic load intensity.

6. Sketch typical power spectra for wind and earthquakes, and relate these to the responses of different types of structures.

7. Discuss the factors affecting restraint actions caused by structural deformation and outline an analysis procedure.

8. Describe one method of obtaining a design spectrum for seismic effects on structures.

9. Discuss the reasoning behind the different forms of load combination rules.

10. Explain how each relevant factor influences formwork pressures for a high battered reinforced concrete retaining wall.

11. Discuss the pressures experienced by a sheet pile harbour quay wall, driven into a clayey seabed. It is backfilled with sand and paved with a concrete slab on one side; and the seabed is dredged on the other side.

12. Give a method of determining berthing forces on fenders in harbours.

(Equal marks for all questions)

UNIVERSITY OF CAPE TOWN
DEPARTMENT OF CIVIL ENGINEERING

UNIVERSITY EXAMINATION CIV502F (1986)

OPEN BOOK EXAMINATION - 3 HOURS

1. Discuss briefly all the desirable properties of
   - (a) the steel used for prestressing, and
   - (b) the concrete used for prestressed concrete. (9)

2. Sketch and discuss the concrete stress distributions behind different arrangements and sizes of tendon anchorages. (7)

3. Discuss the advantages of full prestressing vs. partial prestressing vs. reinforcing only, of concrete beams. (9)

4. Give the advantages of pretensioning vs. post-tensioning of concrete members. (10)

5. (a) For the prestressed concrete beam section shown overleaf, find the stresses in the extreme fibres, in the reinforcement and in the tendons at the SLS using an uncracked section analysis. (17)
   - (b) What is the degree of prestress κ ? (4)
   - (c) Estimate the maximum crack widths on the beam soffit at the SLS by any Code; without doing a cracked section analysis. (9)

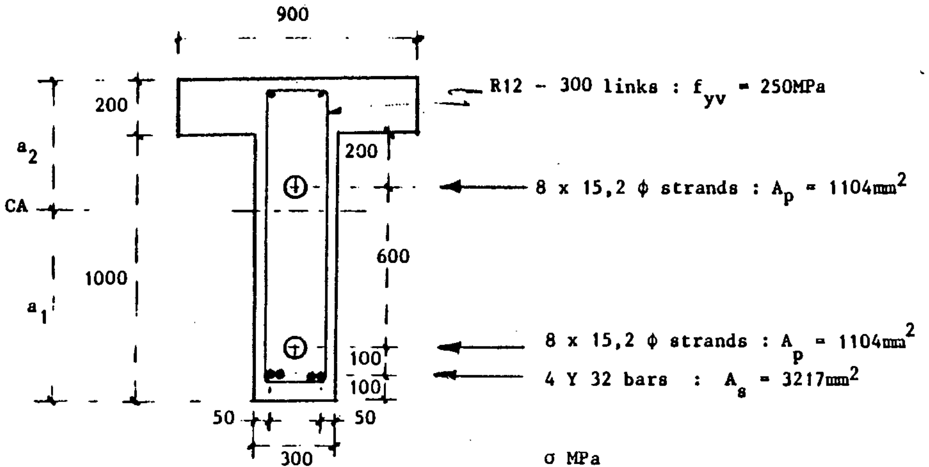
6. For the same prestressed concrete beam shown overleaf, find
   - (a) the sagging flexural capacity M_u in kNm , by analysing the section, and (20)
   - (b) the shear capacity V_u in kN ; (15)

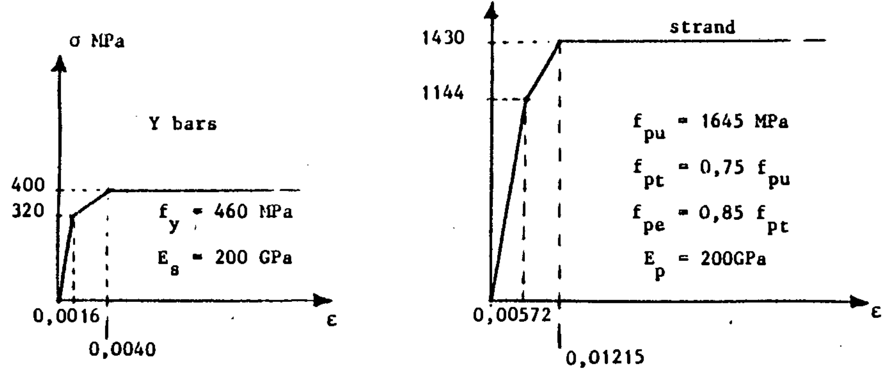
- both by SABS0100 for the ULS. (MARKS)

The strands are conventional, horizontal and grouted.

Page 2./ .....

BEAM SECTION : $A = 0{,}480m^2$, $I = 0{,}0661m^4$,
$Z_1 = 0{,}09117m^3$, $Z_2 = 0{,}13916m^3$,
$a_1 = 725$, $a_2 = 475$





ULS DESIGN STRESS-STRAIN GRAPHS

Concrete grade f_{cu} = 50 MPa : E_c = 34 GPa

flexural tensile strength = 2,6 MPa by BS8110

S.L.S. values $\begin{cases} M_d = 900 \text{ kNm} \\ M_{imax} = 1100 \text{ kNm} \\ M_{imin} = 0 \end{cases}$

U.L.S. values $\left\{ \begin{array}{l} M = 3000 \text{ kNm} \\ V = 500 \text{ kN} \end{array} \right\}$ occurring simultaneously at the same section

Civ 502 F : PRESTRESSED CONCRETE : 1986.

"PRESTRESSED LIGHTWEIGHT CONCRETE" by Clayton Frick.

SYNOPSIS :

This project was written from a literary research in the topic. It serves to introduce students and others involved in the field of concrete to the concepts of prestressing lightweight concrete.

After a brief introductory chapter, this project then covers the ways in which prestressed lightweight concrete (PLWC) may be used in construction and also in marine applications. The benefits of using PLWC in these fields are discussed. The types of lightweight aggregate suitable for use in PLWC are also covered - there are many diffirent lightweight aggregates, but expanded clays, shales and slate, as well as sintered pfa predominate in this respect. Recommendations are given on the manufacture of PLWC and several mix design charts are included too.

A discussion on the properties of lightweight concrete specifically related to prestressed concrete design follows in Section 5. It is found that sufficiently high compressive strengths are attainable, but the tensile and flexural strengths are slightly lower than in normal concrete. The modulus of elasticity is often substantially lower, but the substitution of fine sand for some of the lightweight fines will alleviate this problem. The shrinkage and creep strains in LWC are usually greater than in normal concrete - and with the fact that elastic modulus is lower, the prestress losses are therefore greater, but special curing techniques will remedy the problem.

Finally, a table summarising numerous case studies on PLWC is presented from which a fair amount may be learnt about the technology of prestressing LWC.

UNIVERSITY OF CAPE TOWN

CIV 535 S

Finite Element Modelling

PROJECT 1986

"The Structural Analysis of an Incrementally Constructed Arch Bridge using the ADINA Package."

SYNOPSIS

The purpose of this project is to demonstrate the use of the birth and death options on elements and the time-functions on loads that the ADINA analysis package has. A realistic structure was chosen for this demonstration, namely a 50 m span cable-stayed incrementally constructed concrete arch bridge. The output from the three processors of ADINA is shown and demonstrates how the time-functions and birth / death options operate, and also how such a structure may succesfully be analysed.

Clayton Frick, M.Sc. Student, November 1986

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22 JUN 1987