

CIV5000Z: DISSERTATION FOR THE DEGREE OF MASTERS OF SCIENCE IN
ENGINEERING

**Relating concrete cube, core and cylinder
compressive strengths that are cast, cured, prepared
and tested in laboratory conditions**



**National
Research
Foundation**



The financial assistance of the National Research Foundation (NRF) towards this research is hereby acknowledged. Opinions expressed and conclusions arrived at, are those of the author and are not necessarily to be attributed to the NRF.

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Dissertation submitted in fulfilment of the requirements for the degree of
Masters of Science in Engineering

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Acknowledgements

I would like to take this opportunity to give thanks and appreciation to a number of individuals and companies that provided me with assistance and support during my research. Without your help my investigation would not have been a success.

- My supervisor, Prof Hans Beushausen, for his tremendous amount of mentorship and guidance for the duration of the research.
- Concrete Materials and Structural Integrity Research Unit (CoMSIRU) for the funding and sponsorship for the duration of my research.
- The National Research Fund (NRF) for the funding and sponsorship for the duration of my research.
- Mr Nooredien Hassen and Tahir Mukaddam for their assistance and time during the laboratory work of the research.
- The University of Cape Town laboratory staff for their assistance during the laboratory investigation.
- Mr Haris Sohawon for his assistance, guidance and time in editing my dissertation.
- Mr Matthew Holmes for his assistance, guidance and time in editing my dissertation.
- Mr Alastair Rhorer for his assistance, guidance and time in editing my dissertation.
- Afrimat for providing the quartzitic sandstone aggregate for the investigation.
- University of Cape Town and staff for accommodating myself during the laboratory work.

Abstract

In practice, concrete is initially tested for compressive strength by casting a cube/cylinder, which is left to cure in favourable conditions until the date of testing. The results obtained from such tests can give a consultant guidance on the material's properties such as estimated porosity, density and compressive strength. These tests are known as control and conformity tests. Supplementary tests may be needed if the control test fails or further investigation must be done to the concrete. These tests are done by drilling core specimens out of the in-situ concrete and applying the necessary tests. These results are used to verify conformity with specifications set out by the engineer. The outcome of such a test is extremely important as it is often used as the basis to decide the integrity of the structure. Although important, in-situ compressive strength remains as one of the least understood concrete properties due to the difficulty in relating and interpreting the results. Furthermore, there is no reliable universal relationship between compressive strength of cores and; moulded cubes and cylinders. A comprehensive literature and experimental study was attempted to relate standard cube and core compressive strength, as well as, cylinder and core strengths to identify the factors that may affect the analysis and interpretation of results.

An experimental program was set out to relate the compressive strength of cubes, cores and cylinders, with a length/diameter ratio of 1.0. All specimens were cast, cured, prepared and tested in the University of Cape Town, New Engineering Building (NEB) laboratory according to *South African National Standards*. Twelve concrete mixes were designed using two concrete strengths (30 and 50 MPa), three maximum aggregate sizes (9.2, 19.2 and 26.5 mm) and two aggregate types, namely greywacke and quartzitic sandstone. An additional two mixes of high strength concrete were created (60 and 75 MPa) using 19.2mm greywacke aggregate. The compressive tests involved a 100 mm cube, three diameter cylinders (70, 100 and 150 mm) and four core diameter sizes (50, 70, 100 and 150 mm). All core specimens were drilled from beams that were cast. A total of 520 specimens were tested during this study. An analysis of variance (ANOVA) was applied to all the results to identify if the compressive strengths were statistically significantly different.

The compressive strength and statistical results indicate that 100 mm cubes and 100 mm diameter cores have statistically similar compressive strengths. The diameter of the core and cylinder influenced the compressive strength. It was found, as the diameter size decreased the strength increased for core specimens and the opposite was found for the cylinder. Both findings were inconsistent with literature. However, as the core and cylinder diameters increased to a size larger than 100 mm, the compressive strengths were statistically similar. With respect to the maximum aggregate size, the strength was influenced in correspondence with the diameter size. As the core diameter decreased and the maximum aggregate size increased, the compressive strength increased. Whereas, the opposite was found with the cylinders. The strength level further determined the influence that the coarse aggregate type had on the compressive strength. At the 30 MPa strength level, the aggregate types produced statistically similar strength. At the 50 MPa strength level, the sandstone produced a statistically higher compressive strength compared to

the greywacke aggregate. Finally, as the strength level increased over 50 MPa there was no significant difference between the mean compressive strength of cubes and cores.

It was concluded, owing to the controlled environment that the all specimens were cast, cured, prepared and tested; as well as the similarity in the geometric size, statistically comparable compressive strengths were obtained for cubes and cores.

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Acronyms and abbreviations

HAC	High Alumina Cement
HCP	Hardened Cement Paste
HSC	High strength Concrete
ITZ	Interfacial Transition Zone
MSB	Mean sum of squares between groups
MSW	Mean sum of squares within groups
SANS	South African National Standards
SSB	Sum of squares between groups
SST	Total sum of squares
SSW	Sum of squares within groups

Symbols

A	Area (m ²)
b	Breath
d_c	Diameter of core or cylinder
F	Statistical F value from F-chart
f_c	Concrete compressive strength
h	Height
k	Number of samples
l	Length
l/d	Length/diameter ratio
n_i	Number of values
p	Probability value
P	Load (N)
s_i	Variance
w/c	Water/cement ratio
\bar{x}	Mean
$\bar{\bar{x}}$	Total mean of all the values between groups

1. Introduction

1.1 Background and context

The most important concrete property in structural design is compressive strength. In case of doubt that concrete in an existing structure has sufficient strength, a quality inspection of the concrete's structural integrity and compressive strength must be carried out (Ozyildirim & Carino, 2006). In practice, concrete is initially tested for compressive strength by casting cubes/cylinders from a batch of concrete that was used in the structure. These test samples are left to cure in favourable conditions until date of testing. The results obtained from such tests can give a consultant, educated in concrete, guidance on the material's properties such estimated porosity, density, compressive strength, etc. but a common practitioner only the latter. These standard tests are known as control and conformity tests. If the strength of the standard tests fail, supplementary tests must be performed on the hardened concrete to confirm the in-situ concrete strength. The most common and reliable method to assess in-situ concrete is by testing concrete cores that are removed from the structure. The compressive strength of hardened concrete is tested in South Africa by methods described in *South African National Standards (SANS) 5865:2006 Concrete tests- the drilling, preparation, and testing for compressive strength of concrete cores taken from hardened concrete*. The core testing of hardened concrete plays an important role in establishing the structural integrity and compressive strength of the concrete in existing structures.

To ensure that concrete in an existing structure has sufficient strength for which it has been designed a great deal of time and effort should be put into the testing of concrete core specimens to establish whether the structural integrity is satisfactory (Bungey *et al.*, 2006). The outcome of such tests is often used as the basis to decide on the quality of the concrete, as insufficient core strength may result in partial or full demolition of the structure or its members. Therefore, it is authoritative that the core specimen removal and testing for compressive strength follows set standards and rules so that the results are non-ambiguous and reliable.

1.2 Research motivation

Testing of both standard and in-situ compressive strengths are important to verify conformity with specifications set out by the engineer. Furthermore, in-situ compressive strength tests (core testing) allows practitioners to assess whether an existing concrete structure has sufficient strength for its future performance. Therefore, knowledge and experience should be used during the testing and interpretation of the results. In addition, sufficient care and time should be spent on the preparation of the cores ensuring that the specimens are prepared and tested correctly, according to required standards, to acquire the most accurate results.

When testing cores due to the lack of conformity with specifications, the results are compared to the failed 28-day standard strength test. This is to see if the standard test gives the correct representation of the compressive strength. The testing of core specimens is not

complicated; however, the interpretation of the results may be difficult. The difficulty in interpretation is due to the number of factors that affect concrete core strength. These factors include: aspect ratio, diameter of the sample, aggregate type, maximum aggregate size, presence of reinforcement, curing history and degree of compaction. Bungey, *et al.* (2006) states, inappropriate or misleading test results are often obtained due to a genuine lack of knowledge or understanding of the procedures involved. Incorrect or misleading compressive strength can lead to serious economic and legal implications between numerous parties due to extra costs of unnecessarily strengthening structural member (Bugai *et al.*, 2012). In cases where core testing was performed to assess the in-situ strength of the concrete structures, analysis and interpretation of results were found to be difficult and uncertain.

In response to in-situ compressive strength remaining as one of the less understood concrete properties, that is used on an everyday basis, this study investigated the relationship of concrete cubes', cores' and cylinders' compressive strengths in controlled conditions. During this study, the aspect ratio of all the specimens were approximately 1.0. This investigation will aid in making the analysis and interpretation of concrete core test results more clear.

1.3 Objectives of investigations

Compressive strength is the most important and frequently used concrete design parameter for concrete structures. For the most reliable core compressive strength results, the sample must be prepared, tested and the results interpreted strictly according to guidelines stipulated in national standards. SANS 5865:1994 provides reliable guidance for the preparation and testing of concrete cores. However, sufficient guidance for the interpretation and comparison of core strength to standard cube strength is not available. Therefore, this study investigated the relationship between concrete cube, core and cylinder compressive strengths. The aims of this study are to:

- Investigate the procedures in which cores are obtained from hardened concrete;
- Investigate the factors that affect the compressive strength of cubes, cores and cylinders;
- Establish the influence of core and cylinder diameter size on the concrete compressive strength;
- Establish the influence of aggregate type and the maximum size of the aggregate in coherence with diameter size and concrete strengths;
- Investigate the influence of concrete strength on the crack pattern produced at failure;
- Analyse the test results using appropriate statistical methods;
- Compare the results obtained by the cubes, cores and cylinders; and find a relationship between the three sample types;
- Critique current design standards and conformity rules given in codes; and
- Provide guideline for the interpretation of concrete core test results.

1.4 Scope and limitations

The scope of this study was to investigate the relationship between concrete cube and core, as well as, core and cylinder compressive strength. During the investigation, all the specimens contained an aspect ratio of 1.0. The primary emphasis of this dissertation was to compare the compressive strength of cubes and cores from the same batch of concrete, to identify if similar compressive strengths would be obtained. Further work was done to investigate how the moulded cylinder wall would influence the compressive strength compared to the exposed aggregate wall of a core. The experimental investigation included several parameters that could have had an influence on the compressive strength such as aggregate size and type, specimen diameter size, strength of the concrete mix and the manner in which the sample fails.

Part of the scope was to use common concrete strengths. The four strengths that were used were 30, 50, 60 and 75 MPa. All the material used was locally sourced from the Western Cape. Two aggregate types were investigated, greywacke and quartzitic sandstone. All specimens that were cast were cured in a saturated condition. Cylinders and cores were drilled and prepared at 21 days. All specimens were tested at 28-day strength.

Previous research has shown that the aspect ratio can significantly alter the compressive strength due to the slenderness of the test specimen. The literature study below reviewed the aspect ratio from previous investigations and briefly discussed this parameter in the literature review. However, for geometric and size consistency only a length/diameter (l/d) ratio of 1.0 was used.

This dissertation focused on the compressive strength of concrete cubes, cores and cylinders. It does not cover the interpretation of other correction factors such as reinforcement factors and excess voids that are found in SANS 5865:1994, these factors have been considered to fall outside the scope of this investigation.

1.5 Dissertation structure

Chapter 1 introduces testing of concrete compressive strength. It stresses the importance of the testing procedures and interpretation of standard and supplementary concrete compressive strengths. It describes how the testing of concrete specimens is straight forward; but the interpretation of results is often misleading due to the number of parameter that can affect the strength. The motivation for the investigation was then described, emphasizing the need for a clearer understanding of the factors affecting supplementary concrete compressive strength testing. The clarity would aid in better interpretation and analysis of results. The investigation objectives were then stated, emphasizing the final comparison between cubes', cores' and cylinders' compressive strengths.

Chapter 2 further describes concrete compressive strength and the different methods in which it may be tested. It reviews the mechanisms in which concrete fails and the factors that may affect concrete compressive strength. An in-depth review on the mechanisms of concrete cube, core

and cylinder strengths was completed to analyse how each of these samples may be related to each other.

Chapter 3 states the method in which the extensive laboratory investigation was completed. It discusses the concrete mixes that were used, including the multiple water/cement (w/c) ratios and the different aggregate types and sizes. It further discusses SANS 5863:1994 and 5865:2006, the standards that were used for the testing of cubes and cylinders and the preparation and testing of core specimens respectively. This section finally discusses the method in which the data was analysed with regard to the statistical analysis that was completed.

Chapter 4 illustrates the mean compressive strength results and standard deviations that were obtained during experimental investigation.

Chapter 5 discusses the results that were found during the investigation and the factors that influenced the compressive strength of the different concrete specimens. An in-depth statistical analysis was done on all the results that were collected to identify the relationship between concrete cube, core and cylinder compressive strength.

Chapter 6 provides possible conclusions that can be derived from the experimental and statistical results. Additionally, it suggests further recommendations for future investigations on the relationship of standard cube, cylinder and in-situ core compressive strength, for the goal of accurate interpretation of compressive strength test results.

2. Literature review

2.1 Introduction

Circumstances may arise where the compressive strength results of the standard 28-day strength indicates nonconformity with specifications. This will lead to a sense of doubt about the reliability and quality of concrete that has been used in the structure (Neville, 2001; Ozyildirim & Carino, 2006). In this case, an in-situ test of the concrete structure will be carried out to identify whether the concrete supplied does comply with the specifications and whether the structure has sufficient strength to carry the load that it has been designed for (Bungey *et al.*, 2006). One of the in-situ tests that can be carried out to identify the compressive strength of an existing structure, is a method whereby core specimens are drilled and removed from the hardened concrete and sent to a laboratory for compressive strength testing. The drilling, preparation and testing of concrete cores taken from in-situ concrete should be done by experts in this field as the testing and interpretation of results may require a great deal of time and expense (Bungey *et al.*, 2006).

The outcome of such tests is often used as a basis to decide whether the existing concrete conforms with specification, additionally can be used to identify which party is at fault. It can also determine if the structural integrity of the concrete is sufficient and if not, will determine whether the structure will need to be partially or fully demolished, depending on the core locations. Therefore, it is imperative that the preparation and testing of the concrete cores follow set standards so that the results are non-ambiguous and reliable (Smith, 2014).

Although it is essential that these tests should be performed and interpreted by experienced specialists, many difficulties arise during both the planning and interpretation stages due to a lack of common knowledge (Bungey *et al.*, 2006). Less qualified workers who are instructed to prepare and test the concrete cores may produce misleading results due to their lack of knowledge in preparing, testing and interpreting the core samples (Bungey *et al.*, 2006).

2.2 Nature of hardened concrete strength

Compressive strength is considered to be the most valuable property of concrete as it usually gives an overall depiction of the quality of the concrete. Compressive strength of the concrete can be directly related to the hardened cement paste (Neville, 1975). Concrete in compression is the most cost-effective material compared to any other construction material. Without adequate strength the concrete is impractical and if a high strength concrete is supplied unnecessarily, for a low strength application, this would deem the element not cost-effective (Owens, 2012). Therefore, to use concrete effectively, strength testing must be specified and monitored so that the correct strength is supplied for the best efficiency (Addis, 1998).

Concrete is considered a brittle material even though it provides a small amount of plastic deformation (Neville, 1975). Neville (1975) explains, that the nature of concrete strength mainly arises from the cement paste; however, the paste is known to have several discontinuities

including pores, fissures and voids. Due to these discontinuities, the mechanism through which the strength is affected is difficult to determine. He further mentions that in well compacted concrete, these discontinuities are distributed in a random fashion. Owing to the random distributions of discontinuities in the cement paste, the mechanisms of rupture rather form through the weaker bond strength between the paste and aggregate. The manner in which the concrete fails in compression will be further discussed in Section 2.2.3.

2.2.1 Forms of concrete strength

The forms of concrete strength consist of compressive strength, tensile, indirect tensile, torsion and shear strength. Each of these strength types will be briefly discussed below.

2.2.1.1 Compressive strength

Concrete's most important physical property is compressive strength. The maximum compressive strength of concrete is defined as the maximum stress a concrete sample can withstand, even when no external signs of failure are visible. The maximum compressive strength can be derived as the calculated ratio of maximum possible uniaxial load that is applied at a specific rate, sustained by the concrete over a constant cross-sectional area (Addis, 1998).

$$f_c = \frac{P}{A} \quad \text{Eq. 2-1}$$

f_c	=	Compressive strength, MPa
P	=	Load at failure, N (Newton)
A	=	Cross sectional area, mm ²

2.2.1.2 Tensile strength

The tensile strength of any material is the resistance to longitudinal stress by measuring the maximum amount of stress applied before rupture. The nature of concrete strength is good in compression; however, weak in tension. Due to the difficulty in applying a direct concentric tensile load to a concrete sample, it is generally difficult to measure the direct tensile strength. Therefore, the tensile strength of concrete is often impractical to test; however, there are indirect methods in which it can be tested.

Indirect tensile concrete strength can be measured by the split-cylinder test and the flexural test. The split-cylinder test is done by apply a compressive load along two diametrically opposed lines. According the Perrie (2009), the principal tensile stress joining the two diametrically opposed lines causes splitting in the plane. This occurs due to the high compressive vertical stress directly beneath loading points, which causes a uniform tensile stress to act horizontally, as seen in Figure 2-1. The tensile strength is calculate using elastic theory. The flexural test consists of loading a beam, either by two loads at third points or a single load at midspan, as seen in Figure 2-1. During loading, the beam will be subjected to pure bending; thus, inducing an indirect

tensile stress to the beam, in which the tensile stress can be calculated. The maximum tensile stress that is reached is called “Modulus of rupture”.

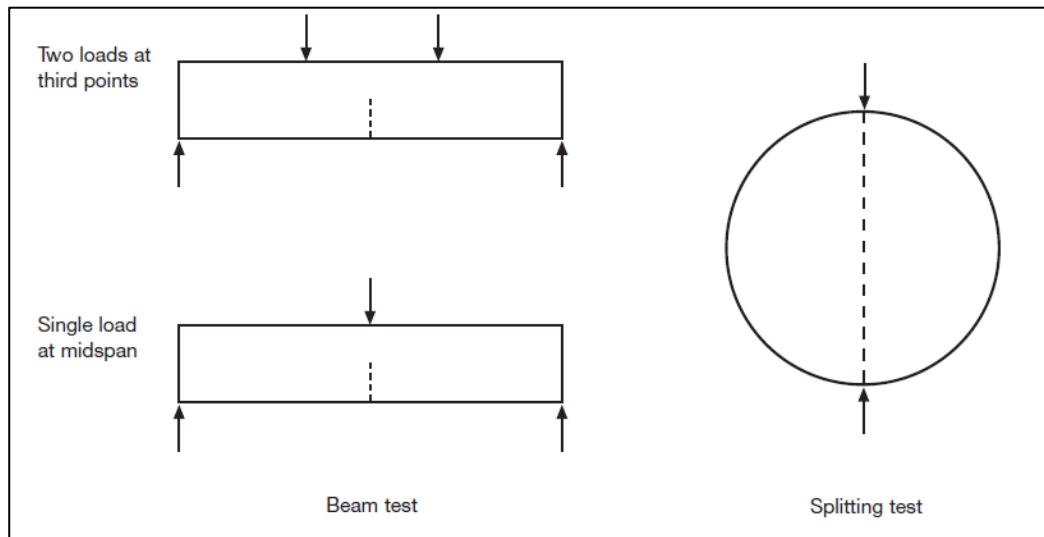


Figure 2-1 – Configuration of the splitting and flexural tests for indirect tensile strength tests (Perrie, 2009)

2.2.1.3 Shear strength

Shear strength is the stress that resists forces that act perpendicular to the longitudinal axis in a structural element. Like the tensile strength of concrete, the shear strength is weak as the forces land up creating tensile stresses in the structural element. Owing to the weak shear strength, reinforcing shear bars are normally placed in the structural element, such as the beam or slab, to take the shear load.

2.2.1.4 Torsion strength

Torsional strength is the stress that resists forces that subject a structural element to twisting about its longitudinal axis. Torsional stress leads to shear stress which create diagonal tension stress as seen in Figure 2-2. Due to the torsional stress finally leading to tension stress, reinforcing must be allocated to the member as concrete is weak in tension. If the structural element is not adequate reinforced for torsion, a brittle failure can occur.

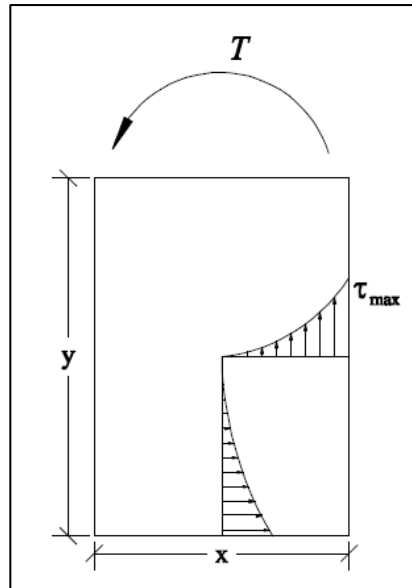


Figure 2-2 – Torsional stress leading to shear stress in a rectangular element

2.2.2 Measuring concrete strength

The most common hardened concrete property measured is compressive strength (Ozyildirim & Carino, 2006). Ozyildirim and Carino (2006) demonstrate that there are three main reasons for this and they are:

- i) Compressive strength of concrete gives a direct indication of its capacity to resist loads in structural applications;
- ii) Compressive strength tests are relatively easy to conduct; and
- iii) A correlation can be developed relating concrete compressive strength to other concrete properties, that are difficult to measure.

Ozyildirim and Carino (2006) further demonstrate that strength testing of concrete specimens is used for three main purposes:

- i) Quality control and quality assurance (Conformity with specifications set out by engineer);
- ii) Determining in-place concrete strengths (Supplementary tests to confirm conformity with specifications or indicate compressive strength for future use of the structure); and
- iii) Research

2.2.2.1 Compressive strength

The compressive strength of concrete can be measured by means of the standard cube and cylinder test (Addis, 1998). The measured compressive strength of concrete depends on the intrinsic and extrinsic factors. As stated by Owens (2012), “In South Africa, the compressive strength of concrete, as determined in accordance with SANS 5860, 5861-2, 5861-3 and 5863 for cube compressive strength and 5865 for core strength, is used as a criterion of concrete quality and as an index of the strength of concrete in the structure”.

The test methods used for determining the compressive strength of concrete are briefly described below.

Cube

A concrete compliance/conformity compressive strength test should be conducted to ensure that the concrete used in construction meets the design specifications set out by the engineer. This test is done in accordance to SANS 5863:2006; whereby, cube specimens (100 or 150 mm) are cast and tested at 28-day strength. These compressive strength results are taken as the basis of the structural performance and the estimated potential strength of the concrete in the structure. In research a 100 mm cube is often used in the laboratory and in practice a 150 mm cube is used on site.

Core

The compressive strength of in-situ concrete is tested in accordance with SANS 5865:1994. This is done by removing concrete core specimens from a structure and testing them in a laboratory. This test is commonly required if the standard test strength that is measured does not meet the required specifications or if the strength of an existing structure is unknown. Extracting cores from a structure is the best way to test the actual concrete strength, in the structure.

Tests used in other countries

Similar to testing the compressive strength of cubes many countries such as USA, Australia, France and Canada use cylinders (100 mm diameter and 200 length) to test compressive strength. The important factor about testing the compressive strength of a cylinder is the length/diameter (l/d) ratio of 2.0. Due to this aspect ratio, the cube strength is higher than the cylinder strength and will be discussed in greater detail in Section 2.3.3.2.

2.2.3 How concrete fails in compression

Concrete contains a number of elements that have different physical properties. Due to concrete being a multiphase material it has a very complex microstructure. The varying internal structures and stresses result in intricate failure modes (Perrie, 2009).

The cement paste technically acts as a brittle material; although, it exhibits a small amount of plastic deformation. Hence, concrete fails in a brittle way and fractures occur in response to tensile stresses as plastic deformations occurs. These fractures form and propagate through the cross-section of the specimen and form perpendicular to the applied stress (Perrie, 2009).

As discussed above, the manner in which concrete is tested for compressive strength is by placing either a cube or a cylinder between two platens and applying a compressive load until the specimen fails. Although desirable, true uniaxial stress throughout the specimen is not possible. As explained by Elwell & Fu (2005), frictional effects between the specimen ends and the machine platen produce lateral stresses in the specimen as load is applied. Due to the lateral stresses, subsequent plastic deformations are experienced, as illustrated in Figure 2-3. Figure 2-3 a) illustrates the exaggerated deformation of the cube under increased load and b) illustrates as the cube is loaded (vertical arrows), the specimen is placed in a multiaxial state of stress (clear hourglass shape), causing the specimen to deform outwards (horizontal arrows). The lateral

stresses affect the specimen stress state in a triangular like manner; thus, creating a failure surface at approximately 20° to 30° from the direction of load. For this reason, the cube is affected by a multiaxial state of stress throughout its height and a cylinder is affected for only a portion of its height, where the centre region is unaffected, as seen in Figure 2-4. Therefore, cubes obtain higher strengths compared cylinders. The influences of l/d ratio will be further discussed in Section 2.3.3.3.

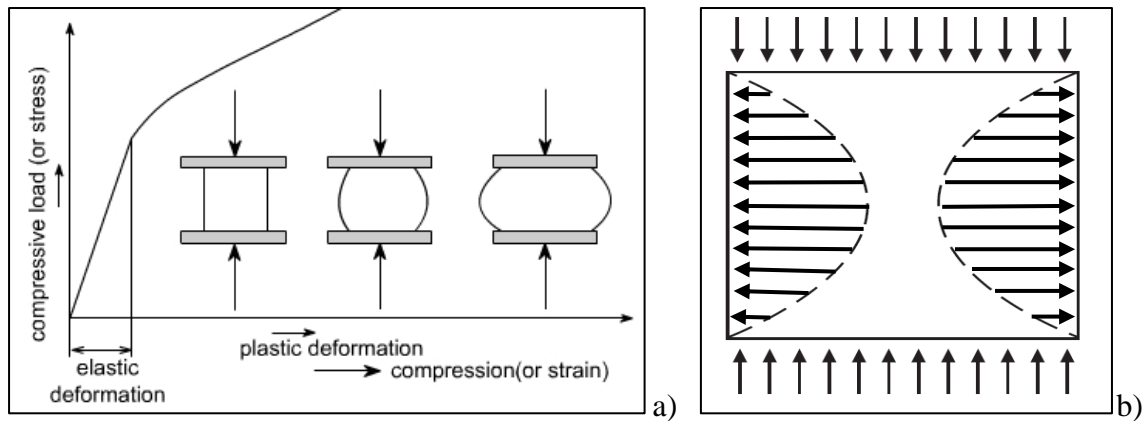


Figure 2-3 – a) Deformation of a cube under compressive load (NPTEL, 2016) b) Multiaxial state of stress due to compressive stress

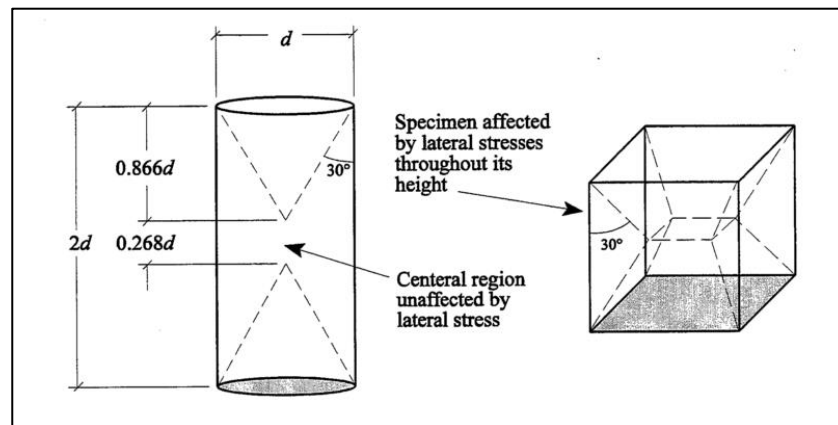


Figure 2-4 – Approximate effects of multiaxial stresses in cylinder and cube specimens (Elwell & Fu, 1995)

Although the cement paste captures most of the strength in normal concrete, it encloses several discontinuities including: voids, pores and fissures. During loading, the specimen is placed in a state of stress. As the load is increased, stresses induce micro-cracks in the internal concrete matrix. Due to the lateral strains induced by Poisson's ratio, during loading, cracks develop as illustrated in Figure 2-3. Failure of the concrete occurs due to the development of a network of micro-cracks that progress between these discontinuities as the load is increased. Neville (1975) describes how the micro-cracks develop using Griffith's hypothesis. It is understood that the discontinuities are regarded as flaws in the concrete and under load the flaws contain high stress concentrations. As illustrated in Figure 2-5, very high stresses are reached in a very small volume, which results in micro-fractures in the position of the flaw, even though the stress in the whole

specimen is still relatively low. There are also very fine cracks that are present between cement paste and aggregate; thus, creating a zone of weakness. This zone is referred to as the interfacial transition zone (ITZ). It is generally accepted that the stress and crack patterns, during loading, follows the path of least resistance; thus, will generate through the points of weakness. Therefore, as the loading increases, micro-cracks generally form in the location of the ITZ and propagate into the concrete matrix. As illustrated in Figure 2-6, with the increase in stress there is an increase in micro fractures which join through the cement paste and ITZ. These micro-cracks combine and create macro-cracks that form at ultimate failure. Therefore, the strength of a specimen is governed by the weakest element in the specimen, which creates a chain of weakness. Although the principle stress may be compressive, the specimen fails in tension as the compressive stress that is created on the edge of the flaw induces a tensile stress at multiple points, which causes fractures (Neville, 1975).

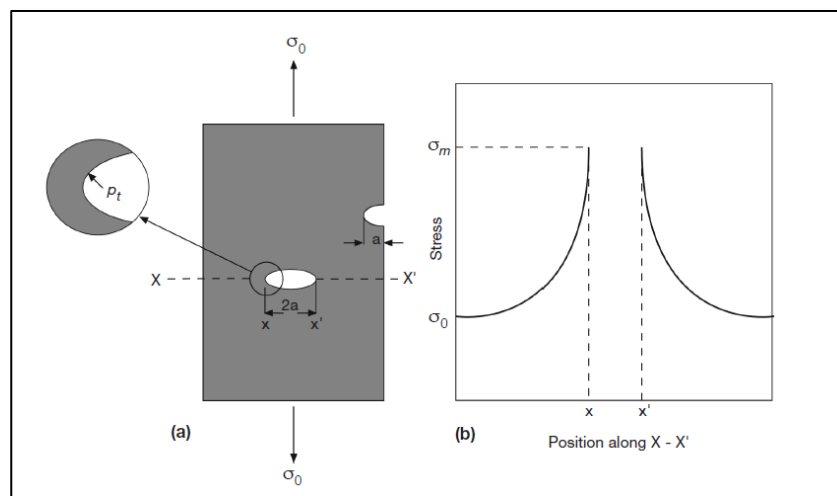


Figure 2-5 – (a) The geometry of surface and internal cracks. (b) Schematic stress profile along line X-X' in (a), demonstrating stress amplification at flaw position (Perrie, 2009)

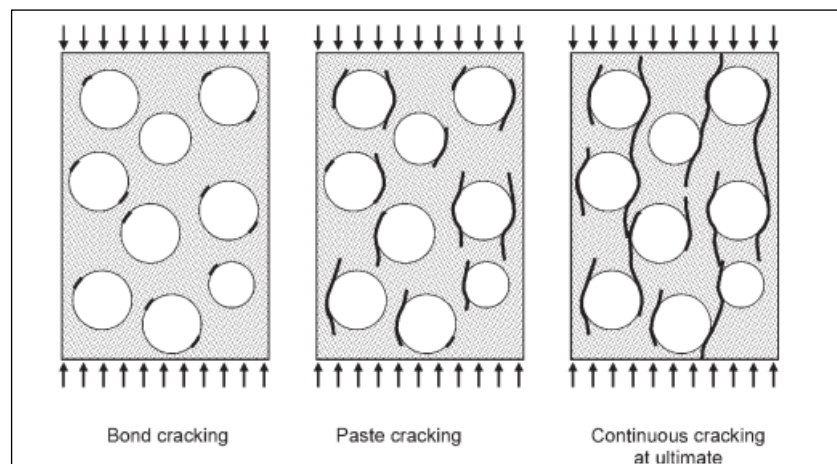


Figure 2-6 – Crack formations with increased load (Ozyildirim & Carino, 2006)

Although the HCP provides most of the strength in concrete, other materials can attribute to the strength and manner in which the specimen fails. The main reason for the addition of coarse

aggregate is to dilute the cement paste in order to make it more dimensionally stable. Even though HCP provides most of the strength in normal concrete, coarse aggregate is the strongest material in the concrete matrix. Owing to the coarse aggregate's physical properties, such as elastic modulus, it plays a role in the concrete's compressive strength and effect localised mechanisms involved with concrete failure. As discussed above, the crack pattern generally follows the path of least resistance; therefore, the crack formation commonly forms around the coarse aggregate due to the increased porosity of the ITZ. In low and medium strength concrete the aggregate will have little contribution to the compressive strength as the stress will propagate through the ITZ, due to the large differences in elastic modulus of the aggregate and the HCP. However, as the strength level of the concrete increases, the aggregate will have an increased contribution. This is because the aggregate and HCP begin to act in uniform. In this case, cracking will begin to pass through the aggregate; thus, aggregate properties may be present in the strength. The role of aggregates will be further discussed in Section 2.3.2.2. A number of other factors that affect the compressive strength of concrete are also discussed in the next section.

2.3 Factors that influence concrete strength

2.3.1 Mix design

2.3.1.1 Water/cement ratio

Controlling the water/cement (w/c) ratio plays an important role in the production of concrete as it influences the hardened concrete strength. In general, concrete strength is inversely proportional to the w/c ratio. The volume of water in the concrete mix also effects the workability of the concrete; however, with modern concrete technology, the workability of the concrete can be manipulated using admixtures, such as superplasticizers. Nonetheless, it is still imperative to determine the optimum w/c ratio to produce economical concrete.

The manner in which the w/c ratio influences the strength of the concrete is by the degree of porosity, which is dependent on the extent of hydration. As the w/c ratio increases, there are less cement particles to create the pore filling hydration products. Hence, the porosity of the concrete matrix increases, resulting in lower compressive strengths. Figure 2-7 indicates the schematic relationship of concrete strength and w/c ratios.

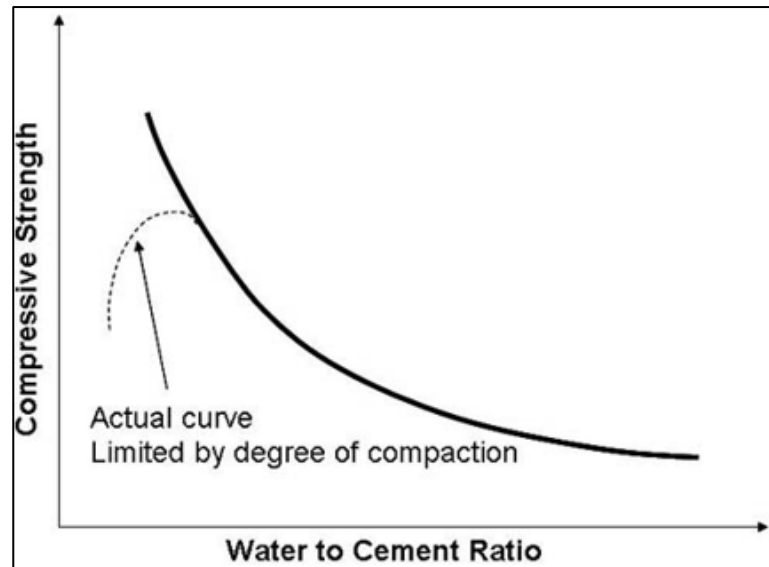


Figure 2-7 – Relationship between strength and w/c ratio (Portal, 2017)

2.3.2 Intrinsic factors

2.3.2.1 Hardened cement paste

The strength of hardened cement paste (HCP) significantly influences the strength of concrete. There are several factors listed below that influences the strength of HCP.

Heterogeneity

Concrete consists of multiple elements which include large and small aggregate and hardened cement paste. Each of these elements have different physical properties and vary in size in the hardened concrete. Owing to the different elements in concrete, the material is heterogeneous.

Perrie (2009) indicated, the significance of the heterogeneity is witnessed in concrete when the material is loaded. During compressive loading, locations of high stress and strains form between the interface of different elements in the concrete matrix. This can be observed at the interfacial transition zone (ITZ), which is the boundary between the HCP and coarse aggregate. Compressive loading results in increased stresses that initially form in the ITZ and effectively weaken the concrete matrix.

Porosity

Strength of concrete is generally dependent on the physical structure of the hydration product, created by the cement particles. The primary factor that influences the strength of concrete is the porosity. Porosity is linked to the relative volume of pores or voids in the cement paste which creates a source of weakness.

The porosity of concrete is created by water in the fresh concrete paste. The excess water that is not used for the hydration of the cement particle creates pores in the concrete. However, if a concrete mix was created that ensured all the cement particles are to be fully hydrated and

no excess water is to remain, the concrete would still contain approximately 18.5% residual space, made of pores and capillaries (Neville & Brooks, 2010).

As discussed, above the capillary porosity is a function of the w/c ratio and the reactivity of the cement. The higher the w/c ratio, the higher the porosity due to the increase in water volume; thus, making the w/c ratio an important factor to consider for an economical concrete. The reactivity of the cement will also have an influence on the porosity. If the cement is not substantially reactive, the porosity will increase as there will be less hydration product to fill the pores and an increase in unhydrated cement.

Furthermore, fresh concrete contains entrained air that can be trapped during the casting of the concrete. This air is normally expelled during compaction of the fresh concrete to achieve maximum density, strength and impermeability. However, if the fresh concrete is not compacted effectively and excess voids remain, the strength will be reduced. As illustrated in Figure 2-8, the method and degree of compaction of the fresh concrete can significantly affect the strength of concrete if not done correctly. Therefore, the degree of compaction plays an important role in concrete strength and durability. Addis & Goodman (2009) claim that 1.0% excess air voids may reduce the strength of concrete up to 6.0%.

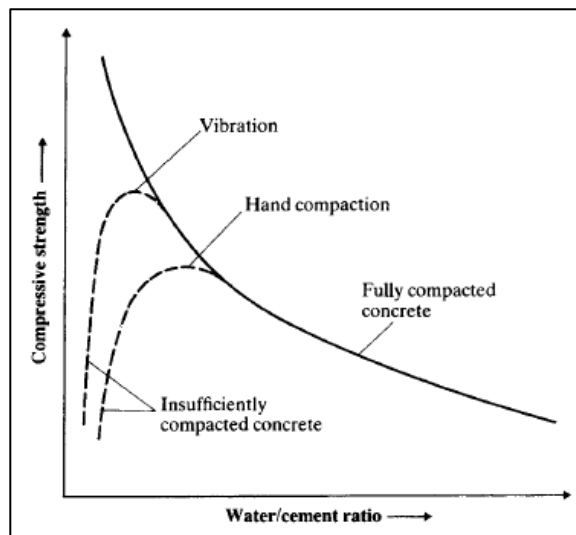


Figure 2-8 – Relation between strength and w/c ratio of concrete (Neville & Brooks, 2010)

Microstructure

As discussed above, the porosity is an important parameter to analyse when looking at the strength of concrete; however, there are other aspects in the HCP microstructure that may have additional influences on the strength. The aspects that influence the concrete strength are discussed below:

- Pore size – The size of the pore has an inverse relationship with the compressive strength of concrete. Perrie (2009) explains how the large pores are formed by the uneven distribution of cement particles in the fresh concrete. Additionally, large pores can be created by poor compaction.

- Crystalline solids – During the hydration process of the cement particles, two major crystals are formed namely calcium silica hydrate (contains most the strength) and calcium hydroxide (does not significantly contribute to strength). However, the strength of the HCP can be increased with the use of pozzolanic cement extenders which react with the calcium hydroxides to form the strengthening gel, calcium silica hydrates.
- Unhydrated cement – It is often found that during the mixing of concrete, not all the cement particles are fully hydrated, leaving some un-hydrated cement particles in the HCP. The un-hydrated cement particles that remain are commonly coarse particles that cannot fully hydrate. Fortunately, the clinker material is hard and potentially acts as a fine filler. Un-hydrated cement can contribute to a small proportion of the strength and plays an important role in the microstructure of concrete.

2.3.2.2 Aggregate

Coarse aggregate is used in concrete to dilute the cement paste and add dimensional stability. Additionally, aggregates are less expensive compared to cement paste; thus, reducing the cost of the concrete. It was previously believed that all the strength in concrete was taken up by the HCP and the aggregate remained as an inert filler. However, it has been found that the properties of the aggregate do have an influence on the compressive strength of concrete.

In normal strength concrete, coarse aggregate is the strongest material within the heterogeneous structure, but as the strength of the concrete increases, to high strength concrete (HSC), the aggregate strength properties may be weaker than that of the cement paste. Therefore, the degree at which aggregate influences the concrete is dependent on the strength of the concrete. The higher the strength of concrete, the increased influence that the aggregate properties may have on the compressive strength. However, the strength properties of the aggregate may also determine the strength properties of the concrete, as the strength of the aggregate increases so does the concrete (Beushausen & Dittmer, 2015).

Other properties of coarse aggregate, such as the elastic modulus, also have an influence on the extent at which the aggregate plays a role in the compressive strength. As illustrated in Figure 2-9, the elastic modulus of the aggregate in normal strength concrete is significantly higher than that of the cement paste. There are several sources where coarse aggregate may be extracted; thus, there are many different aggregate types. Each aggregate type has its own unique properties in strength and elastic modulus. Alexander & Mindess (2005) claim that the elastic modulus of concrete is directly proportional to the stiffness of the concrete paste, aggregate and ITZ. An investigation completed by Beushausen & Dittmer (2015), on the influence of aggregate type on the strength and elastic modulus of high strength concrete, confirmed the findings by Alexander & Mindess (2005), as they found that the stiffness of the aggregate had a direct impact on the stiffness of the concrete. It was found that aggregate with a high stiffness significantly increases the elastic modulus of the concrete. However, the opposite was found when comparing the stiffness of the aggregate to the strength of the concrete.

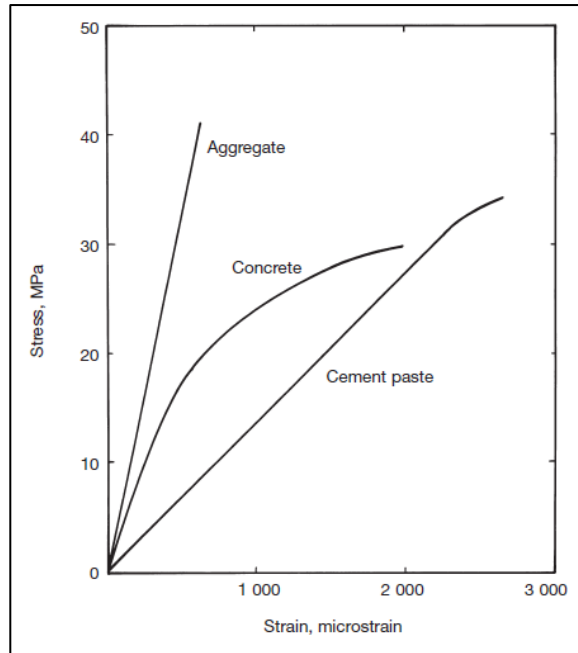


Figure 2-9 – Stress-strain relations for cement paste, aggregate and concrete (Grieve, 2007)

Following on from the investigation by Beushausen & Dittmer (2015), it was found that for the higher strength and stiffer aggregate, a lower concrete compressive strength was recorded compared to the aggregate with a lower stiffness. Although, contradictory to the general views of increased aggregate strength leading to increased concrete strength, the findings were similar to what is found in literature. An explanation for this occurrence, by Beushausen & Dittmer (2015), was the stiffer aggregate results in higher stress concentrations at the cement-aggregate interface; thus, resulting in earlier failure. Therefore, the lower elastic modulus aggregate obtained an ITZ that produced minimised stress concentrations to such a degree that a stronger concrete compressive strength was reached. Owing to these findings, the elastic modulus of the aggregate and strength level of the concrete has a significant effect to the amount of influence that the aggregate may have on the compressive strength.

Neville (2011) mentioned that the stress at which cracks are caused in concrete is influenced by the shape and texture of the coarse aggregate. It was found that aggregates with a smooth surface tend to crack at a lower stress compared to aggregates with an irregular rough surface. This was due to the irregular surface having more angular edges to which the cement gel could bond. The interfacial zone is further discussed in the next section.

The size of the aggregate also plays an important role in the compressive strength of concrete. The maximum aggregate size may influence a number of aspects in concrete that contribute to concrete strength. A number of these aspects include; porosity, internal bleeding and ITZ size. The aggregate size has an influence on the degree of the porosity of the concrete. As seen in Table 2-1, with the increase in size of coarse aggregate, there is a decrease in entrapped air content in the concrete; thus, leading to an increase in strength (Neville & Brooks, 2010). However, the opposite is found with the effects of internal bleeding and size of the ITZ. As the size of the aggregate increases, there is a decrease in compressive strength due to increased water

capture and ponding under large pieces of individual aggregate. This will result in a large porous ITZ under each piece of coarse aggregate, which will lead to an uneven distribution of weaknesses. An investigation, completed by Elsharief *et al.* (2003) and discussed by Alexander & Sidney (2005), found that the smaller aggregate sizes produced a reduced porosity and an increase content of unhydrated cement at the ITZ; thus, increasing the strength of the concrete as the ITZ was similar to the HCP. Whereas, larger aggregate will have an increased porosity in the surrounding ITZ which will lead to a point of weakness. It was also found that the influence was greater in lower w/c ratio mixes (Elsharief *et al.*, 2003).

Therefore, as found in literature coarse aggregate type and size has a plays a significant role in the compressive strength of concrete.

Table 2-1 – Approximate entrapped air content for different sizes of aggregate, according to ACI 211.1-91 (Neville & Brooks, 2010)

Nominal Maximum size of aggregate	Entrapped air content
mm	%
10.0	3.0
12.5	2.5
20.0	2.0
25.0	1.5
40.0	1.0
50.0	0.5
70.0	0.0
150.0	0.2

2.3.2.3 Aggregate paste interface

During the testing of concrete, it is often found that micro-cracking is initiated between the hardened cement paste (HCP) and the coarse aggregate as briefly discussed in section 2.3.2.1. This zone is commonly known as the interfacial transition zone (ITZ).

The ITZ contains a unique microstructure that differs in properties compared to the HCP and coarse aggregate. In a normal strength concrete, the ITZ contains a strength lower than that of the hardened cement paste. The primary reason for this is the movement of water and cement particles during mixing and compaction of the fresh concrete. Neville (2011) describes how cement particles are unable to become closely packed to the coarse aggregate during mixing; thus, reducing the amount of hydration product around the coarse aggregate. Additionally, due to the different material densities, the elements tend to displace. During compaction of the fresh concrete, the water has a lesser density than the other elements, which causes the water to migrate upwards. The water is then trapped beneath the aggregate. Due to the reduced cement particles and increased water present beneath the coarse aggregate, there is an increase in w/c ratio in this zone. Therefore, the ITZ contains a higher porosity near the cement paste-aggregate interface and reduced porosity further away from the aggregate. This is illustrated in Figure 2-10, as it

shows an increased porosity in the vicinity of the ITZ and as the distance increase away from the aggregate the porosity is significantly reduced.

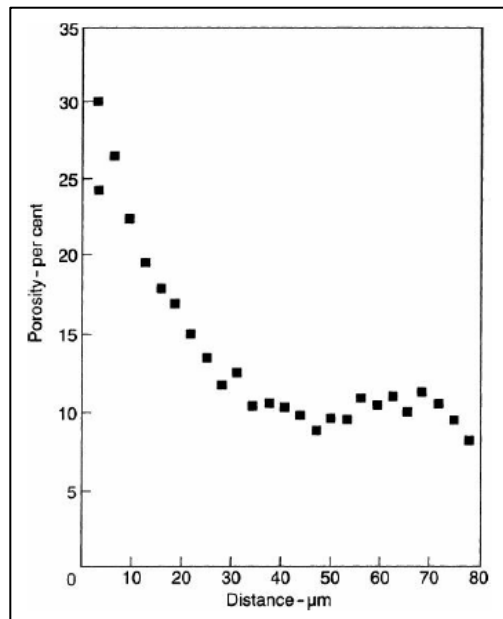


Figure 2-10 – Variation in porosity of hydrated cement paste with distance from the surface of an aggregate particle (A. M. Neville, 2011)

However, Perrie (2009) indicated that the strength of the ITZ may be influenced by several factors and are described below:

- **Water/cement (w/c) ratio** – It has been found that with a decrease in w/c ratio there is an increase in strength of the ITZ. This is due to the increase in cement particles that can interlock with the coarse aggregate during mixing. In addition, there is less water that may be trapped beneath the aggregate during compaction; thus, keeping the w/c ratio of the ITZ and HCP similar.
- **Amount of bleeding of the fresh concrete** – As the bleeding of the concrete reduces, the ITZ strength is improved. This is due to the reduced amount of water displaced to the top of the concrete. Thus, less water is captured under the aggregate which would otherwise cause an increase in porosity. Ultra-fines in the fine aggregate can aid in reducing bleeding of the concrete and can also act as a fine filler, which will reduce the porosity of the ITZ. This can assist in strengthening the ITZ. Reducing the aggregate size may reduce the effect of bleeding.
- **Type of cementitious material** – Other cementitious materials may contain finer particles that interlock with the coarse aggregate better than the cement particles (Neville, 2011). These materials are known cement extenders, such as silica fume. These fine particles act as fillers; thus, reducing the porosity of the ITZ over time.

Chiaia *et al.* (1998) investigated the crack growth mechanism in different concrete and found that for normal strength concrete, it is commonly accepted that the bond between the aggregate

and the concrete matrix is the weakest zone in the material structure. Additionally, it was found that the strength, stress combination of the ITZ plays a dominant role in crack initiation. It was described that at the interface between the concrete matrix and aggregate, two different materials meet, but still retain their considerably different identities in elastic modulus. Owing to the different elastic moduli, as the specimen is loaded stress concentrations form in this zone. As a result, the micro-crack initiation begins in the ITZ as it is the point with the highest stress relative to its strength (Chiaia *et al.*, 1998). As described above, these micro-cracks propagate into the concrete matrix to join other cracks and flaws that lead to macro-cracks at failure.

Overall, there are several intrinsic factors that may affect the compressive strength of concrete in various ways.

2.3.3 Extrinsic factors

The compressive strength of concrete is influenced by a number of factors. These factors relate to the manner in which the concrete specimen is cured, prepared and tested. A number of these factors are described below:

2.3.3.1 Curing

The term curing of concrete stands for “procedures devoted to promote cement hydration, consisting of control of time, temperature, and humidity conditions immediately after the placement of concrete into formwork” (Metha & Monteiro, 1993).

The objective of curing is to keep the concrete specimen in a controlled hydrated condition for a specific amount of time, so that the original water filled spaces react with the cement compound to create the hydration product. Therefore, the reason for saturating the specimen is to attempt to eliminate evaporation of the water in capillaries before the hydration process has taken place (Neville, 1975).

Consequently, curing is very important and has a large influence on the properties of hardened concrete. Curing of concrete improves strength, durability, impermeability, etc. Concrete strength increases rapidly in its early ages and continues more slowly thereafter, for an indefinite time (Kosmatka *et al.*, 2003). Figure 2-11 illustrates the strength gain of concrete with different periods of moist curing. SANS 5863:2006 recommends that standard cubes cure in a saturated environment for 28 days before testing. The reason for this is to keep all tests constant.

Curing of specimens in controlled conditions, such as a laboratory, can be done simply by placing the specimen in a saturated condition for 28 days. However, the curing of freshly placed concrete on a construction site is not as simple. Large volumes and surface areas of concrete need to be protected from extreme temperature and rapid drying out, to ensure minimal moisture loss and maximum water retention. There are a few practical methods in which this is done, for example, by covering or wrapping of structural element, such as columns, or by fogging or sprinkling slabs. Although, these are the most efficient methods of curing on a construction site they are not as effective as submerged curing. Owing to the less effective method of curing, reduced hydration may be present in the concrete cast on site; thus, increasing the degree of

porosity and decreasing the strength. Therefore, it is commonly found that strength of in-situ concrete is lower than that of the standard cube strength. The curing of concrete on site is of great importance to obtain the concrete's integrity it was initially designed for.

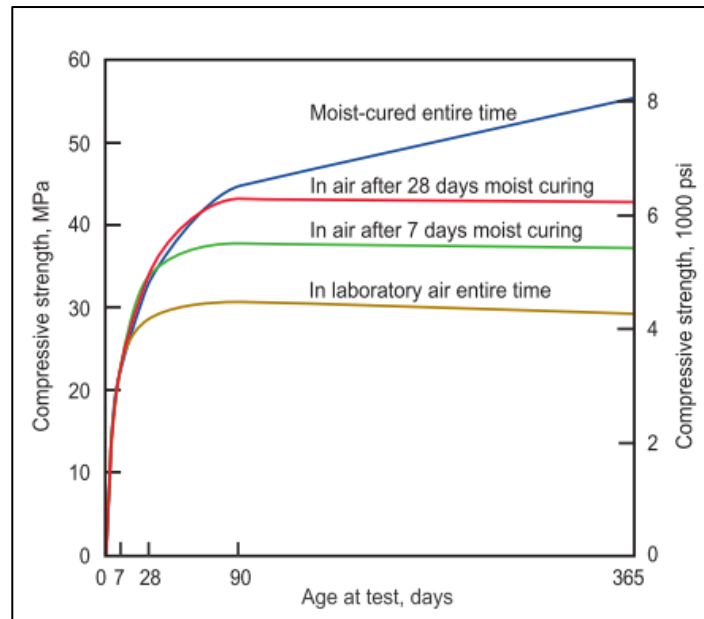


Figure 2-11 – Effects of moist curing on strength gain of concrete (Kosmatka *et al.*, 2003).

2.3.3.2 Geometry of specimen

The shape of a standard concrete test specimen varies from one country to another. The main two shapes that are used are cubes and cylinders. Common sizes of the cubes and cylinders that are used in construction are 150 x 150 x 150 mm and 100 x 200 mm respectively. Standard test specimens that are used in research may differ in size. The cylinder has an aspect ratio double that of the cube. As a result of the aspect ratio, it has been found in vast amounts of research and standards, that the cube compressive strength is approximately 1.2 times stronger than the cylinder strength (Elwell & Fu, 1995; Tokyay & Özdemir, 1997; Yi *et al.*, 2006).

As discussed and illustrated in Section 2.2.3, frictional effects between the specimen ends and the machine platen produce lateral stresses in the specimen as load is applied. Lateral stresses are experienced in the centre of the specimen subsequent to plastic deformation. This effect creates a state of multiaxial stress in the test specimen (Chung *et al.*, 2013). The lateral stresses affect the specimen stress state in a triangular like manner creating a failure surface at approximately 20° to 30° from the direction of load. For this reason, the cube is in a multiaxial state of stress throughout its height and a cylinder is affected for only a portion, where 0.268d in the centre region is unaffected by lateral stress, as seen Figure 2-12. The state of stress in a cylinder is more clearly shown in Figure 2-13. This figure illustrates how the frictional effects caused a multiaxial state of stress near the cylinder ends and this diminishes to a uniaxial stress in the centre. This is caused by the lateral deformation of the specimen during testing; consequently, causing the cylinder to have a weaker compressive strength. Recent studies have

shown that the effect of aspect ratio is more prominent in lower strength concrete and as the strength rises this effect diminishes (Tokyay & Özdemir, 1997; Ince & Arici, 2004).

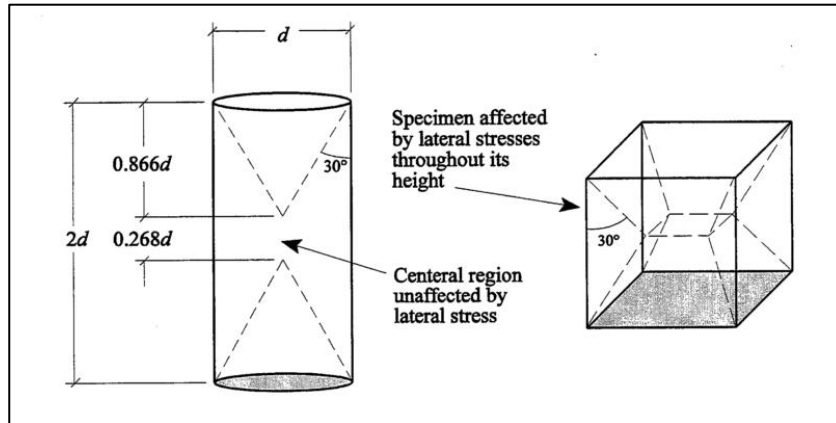


Figure 2-12 – Variation of stress distributions in multiple geometric shaped specimens (Elwell & Fu, 1995)

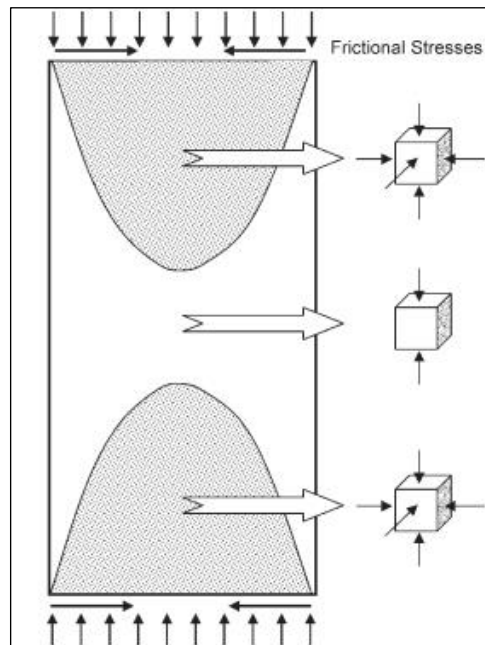


Figure 2-13 – Friction restraint at the ends of the cylinder results in a state of tri-axial compression shown as shaded region (Ozyildirim & Carino, 2006)

As illustrated in Figure 2-14, the correction factors for cylinders with a l/d less than 2.0 indicates that as the ratio decreases, the measured strength will increase due to the effect of specimen's aspect ratio (Ozyildirim & Carino, 2006; Chung *et al.*, 2013). However, it is also illustrated in these figures that as the l/d ratio decrease from 2.0 to 1.75, the difference in compressive strength is not significant (Tokyay & Özdemir, 1997); however, as the l/d ratio decrease past 1.75, there is an increased rate at which the strength increases. This is due to the total height of the cylinder being placed in a multiaxial state of stress. The variations in strength increases as the aspect ratio decreases.

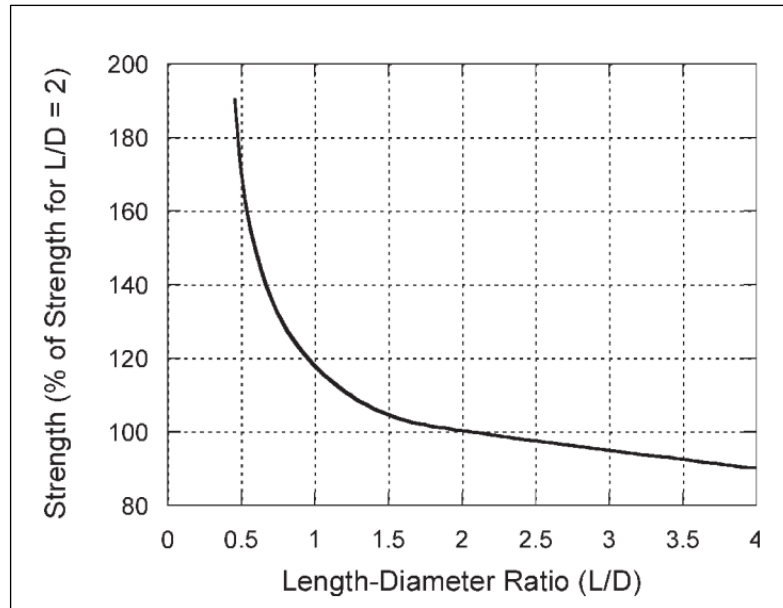


Figure 2-14 – Relationship between measured compressive strength and length/diameter ratio (Ozyildirim & Carino, 2006)

Further investigation on the l/d ratio correction factors in coherence with concrete strength, found that as the strength of concrete increases, the difference in strength decreases. An investigation by Chung *et al.* (2013), on the compressive strength of cylinders with various l/d ratios, found compressive ratios of 0.882 and 0.926 for 25 and 40 MPa concrete respectively when comparing cylinder l/d ratios of 1.0 and 2.0. Tokyay & Özdemir (1997) further concluded, in an investigation on specimen shape and size effects on compressive strength of higher strength concretes, that the effect of l/d ratio on the compressive strength of cylinders is not significant in higher strength concretes. Furthermore, this also stands true for the comparison between a cylinder and a cube. For normal strength concrete, the cylinder/cube factor was approximately 0.8; however, as the strength of the concrete got higher the factor gradually increased and was almost 1.0 when concrete reached 100 MPa (Elwell & Fu, 1995; Tokyay & Özdemir, 1997; Yi *et al.*, 2006; Neville, 2011). Yi *et al.* (2006) mentioned that as the strength increases, the size of the failure zone decreases and similar failure process zones begin to form in the cube and cylinder. The cylinder/cube factor may increase as the strength increases, due to the deformation and increased elastic modulus of the concrete. Owing to this, as the strength increases, the elastic modulus increase and the strain decreases; therefore, HSC will obtain a reduced deformation compared to normal strength concretes (Beushausen & Dehn, 2009). As a result, there will be less lateral strain in the centre of the cylinder, which causes the cylinder to bulge and fail. Due to a cube having a l/d ratio of 1.0, the lateral strains are not significantly reduced. Therefore, as the strength increases, the lateral strains in a cylinder decrease at a quicker rate than the cube, resulting in a similar strength.

The geometric shape of the specimen's cross-section is said to have no influence on the compressive strength if the aspect ratio is kept constant. Studies have indicated that cylinders and prisms with the same width/diameter-to-height ratio obtain similar strength results. Thus,

concluding that there is no significant difference in compressive strength when using different geometrical shape, such as, a prism and cylinder (Elwell & Fu, 1995). This was further emphasized by Neville (2001), as it was stated that a cylinder with an l/d ratio of 1.0 has approximately the same strength as a cube whose edges are equal to the diameter of the cylinder.

Although the l/d ratio has been extensively researched with respects to cylinders, there is a gap in research comparing cubes and cylinders with a l/d of 1.0. It may be assumed that they will produce similar strength due to their similar geometric size and shape, but there may be a number of other factors that may influence the strength comparison.

2.3.3.3 Size of specimen

The size of the specimen has shown to have an influence on concrete compressive strength. It has been found in many studies that the compressive strength and variability of results decreases with an increase in physical size of the element (Tokyay & Özdemir, 1997; Perrie, 2009). As discussed in Section 2.2.3, concrete contains a large amount of flaws in its matrix and concrete strength is governed by the weakest part in the matrix (Ozyildirim & Carino, 2006). When the concrete is stressed, these flaws create micro-cracks and finally propagate to macro-cracks at which the concrete fails (Ozyildirim & Carino, 2006). Therefore, the bigger the size of the specimen, the greater the probability that the specimen will contain a flaw that will induce failure at a given stress (Perrie, 2009). Figure 2-15 illustrates an investigation by Neville (1959) and discussed by Perrie (2009) in which it was concluded that the smaller size specimens have a higher strength (it is shown in Figure 2-15 a) with the use of the gradient of the trend line). It was found during this investigation that a 100 mm cube obtained a strength approximately 8% higher than that of a 200 mm cube. However, C&CI followed up with a minor investigation, testing the strengths of 100 mm and 150 mm cubes, and it was found after 28 days the results were nearly identical (Perrie, 2009). Further investigation found that specimens with a size lesser than 100 mm were more affected by the size factor; however, specimens with a size greater than that of 100 mm were not effected as significantly, agreeing with the results found by the C&CI.

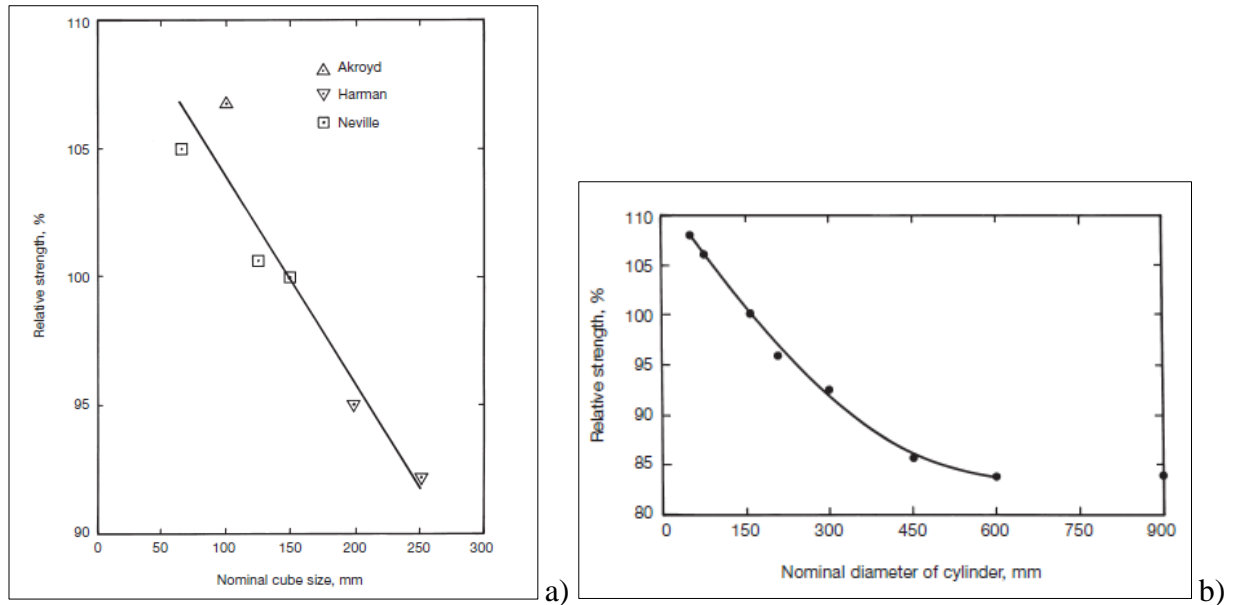


Figure 2-15 – a) Strength of cubes of different sizes b) Strength of cylinders of different sizes (Perrie, 2009)

During research by Tokyay & Özdemir (1997), contradictory results were found to what was stated above. It was found that the 150 mm cylinders contained higher strengths compared to the 75 and 100 mm specimens. However, it was proposed that the lesser strength was due to the “wall effect”. The “wall effect” is “the quantity of mortar required to fill the space between the particles of coarse aggregate as well as the wall of the mould” (Tokyay & Özdemir, 1997). This affects the compactability of the specimens that have a large lateral surface-area-to-volume ratio. It was found that at 60 and 75 MPa strength levels, the 100 mm diameter cylinder produced results that were approximately 6% higher than that of the 75 mm specimens. It was also noticed that these results were more significant in the higher strength concretes. Further research by Tokyay & Özdemir (1997) confirmed their assumption, as they added additional mortar to the mix to eliminate the wall effect. During the later research similar results were produced to the C&CI as stated above.

Maximum coarse aggregate size may also have an influence on the strength of smaller specimens. Large particles of coarse aggregate in small specimens (26 mm aggregate in 70 mm cylinders) may provide varying results, depending on the type and surface of the aggregate. Large natural aggregates commonly have a smooth surface. The smooth surface does not provide a good area which the cement particle can interlock; thus, producing a weaker ITZ. Therefore, during loading of the small specimen, with large natural aggregate, the failure path will move around the weaker ITZ, producing a lower strength. However, large aggregate with an angular surface, which the cement particles can sufficiently interlock, may have a failure pattern that flows through the aggregate and not the ITZ. Due to the aggregate commonly being the strongest element in normal concrete, the small test specimen with large coarse aggregate will produce a higher compressive strength.

The opposite is generally found in the testing of core specimens. It is commonly found, as the specimen's diameter decreases, the strength of the core decreases. This trend is more significant in cores that have a diameter size less than 100 mm. Drilling damages are generally the main influence that reduces the strength of the cores. More factors that influence core strength will be discussed further in Section 2.7.

2.3.3.4 Direction of loading compared to casting

The direction of loading compared to casting is different for cubes and cylinders. Cubes are loaded perpendicular to the direction in which they are cast; whereas, cylinders are loaded parallel. This is said to have an influence on the compressive strength of the specimen due to two factors: i) aggregate segregation and ii) platen fixity (Elwell & Fu, 1995).

Segregation of the concrete is important to consider due to the variations of strength and elasticity between the particles (Elwell & Fu, 1995). The difference in measured compressive strength may be due to the water that accumulated under the aggregate during compaction or bleeding. This causes a weak paste-aggregate interface aligned perpendicular to the casting direction, as shown in Figure 2-16 (Ozyildirim & Carino, 2006). Thus, the concrete tends to act like a horizontally-layered material with horizontal planes of weakness (Perrie, 2009). Elwell & Fu (1995) further explains, when cubes are flipped, the load acts perpendicular to the direction of cast and parallel to the horizontal planes of weakness, resulting in lower strength. Owing to concrete truly failing in tension, during a compressive strength test, concrete will be stronger when the planes of weakness are perpendicular to the load direction and weaker when they are parallel.

Perrie (2009) explains that the variations in strengths are specific to the concrete and there is no general relationship with regard to loading direction compared to casting. However, a relationship has been noticed with concrete cores and will be further discussed in Section 2.7.2.1.

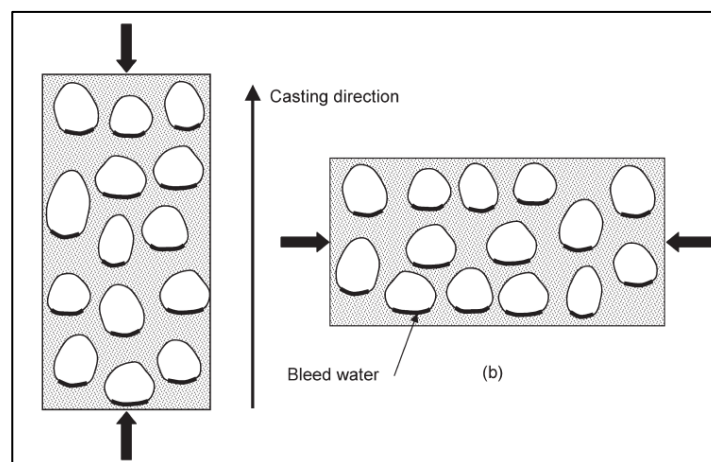


Figure 2-16 – Planes of weakness due to bleeding: (a) Axis of specimen vertical and (b) axis of specimen horizontal (Ozyildirim & Carino, 2006)

2.3.3.5 Moisture

Moisture content in concrete has an influence on the strength. Dry concrete has a higher compressive strength compared to saturated concrete. This influence is due to pore water pressure. When stress is applied to a saturated concrete specimen, the water that remains in the pores exerts a positive pressure on the pore walls due to the water attempting to escape. This creates a weakening effect on the pore walls, which finally generates micro-cracks in the concrete. If there were to be no water in the pores, there would be no water pressure to exert additional stress (Perrie, 2009); thus, the pores would be able to absorb more stress before weakening.

Although saturated specimens have a reduced compressive strength, SANS 5863:2006 requires the specimens to be saturated. This is to standardise the test as there would be more complications/variations when testing dry specimens. All specimens are to be tested at saturated conditions and may not dry before testing.

2.3.3.6 Rate of loading

As the rate of loading increases, the output strength is increased. The dependence of ultimate strength on loading rate was associated with creep and micro-cracking (Ozyildirim & Carino, 2006). In standardised compressive tests the specimens are normally loaded at a short-term static loading rate of between 0.07-7 MPa/second. SANS 5863/5865:1994 stipulate that the specimen must be loaded at a rate of 0.3 ± 0.1 MPa/second.

Perrie (2009) mentioned, a specimen may be loaded to at least 50% of its ultimate load at any rate without affecting its ultimate strength. However, if the loading rate is slower than normal and passes 50% of its ultimate strength, it can cause failure at stresses 75 to 80% of that under more rapid loading due to limiting rate of crack propagation.

2.4 Aims of compressive strength testing

There are three basic categories of concrete testing as mentioned by Bungey, *et al.* (2006):

- i) Control testing – Testing carried out by the contractor or concrete producers to indicate adjustments necessary to ensure an acceptable and economical concrete, as indicated in certain specifications.
- ii) Compliance/Conformity testing – Testing performed by, or for, the engineer according to an agreed plan, to judge compliance with the specifications.
- iii) Supplementary testing – Testing carried out on hardened concrete in, or extracted from, the structure. This may be required in situations where there is doubt about the reliability of control and compliance results. These tests may also be done when the results are unavailable or inappropriate as tests may be done on old, damaged or deteriorating structures. All testing which is not planned before construction will be in this category, although longer monitoring is also included.

Studies in these three categories show that the control and compliance tests have traditionally been performed on ‘standard’ hardened specimens made from a sample of the same concrete that has been used in a structure i.e. the standard cube or cylinder test. The methods of testing used in control and compliance tests are non-destructive; however, the compressive strength that is produced is an estimate strength of the concrete in the actual structure (Neville, 2011). There is an increasing awareness amongst engineers that standard specimen testing, although theoretically the same material, may misinterpret the true quality of the concrete in the structure as the curing, compaction or general work of the standard specimens would vary from the in-situ concrete and could affect the future durability (Bungey *et al.*, 2006). Bungey *et al.* (2006) further explains that the in-situ testing of structures is becoming more common as a form of in-situ conformity testing and it is beginning to play major roles in large construction projects. Another advantage of in-situ testing is early warning of any deficiencies in the concrete. This aids in planning a sufficient maintenance program for the structure to reach its design life.

The principle usage of in-situ tests falls into the category of supplementary testing. Supplementary testing, as mentioned above, is where tests are carried out on the hardened concrete (Bungey *et al.*, 2006). There are two main reasons why supplementary testing is done namely: conformity with specifications and assessment of in-situ quality and integrity. Conformity with specifications is when the concrete of an existing structure is tested to confirm that the specifications set out by the engineer are met. Assessment of in-situ quality and integrity is when an existing structure is tested for primary concerns with the structure’s current adequacy and its future performance. It is important to distinguish between the need to assess the properties of the material and the performance of a structural member as a whole (Bungey *et al.*, 2006).

Although all three categories are extremely important in the construction industry, little research has been complete to relate standardised compressive strength with core strength. Some research has been done relating control and compliance testing of cubes and cylinders; however, there is very little information on the relationship between cubes and cylinders with a l/d ratio of one, as tested in South Africa. Furthermore, there is little research on the relationship comparing cubes, cores and cylinders; and the factors that may influence their strengths.

2.5 Compressive strength test method available

Studies show that there are three main categories of test methods, as follows:

- i) *Standard methods* – The standard test methods of testing concrete compressive strength is performed using the cube or cylinder strength test. These are the most common tests and are done frequently during a construction project. These tests are the control and compliance tests and are used to ensure that the concrete supplied conforms with specifications
- ii) *Non-destructive methods* – Non-destructive testing methods can be performed directly on the in-situ concrete without removing a sample from the structure. These methods are generally defined as not impairing the intended performance of the element or member under test, and when applied to concrete it may include methods which cause localised surface zone damage

(Bungey *et al.*, 2006). A few of these tests include; the penetration resistance test, concrete hardness test, ultrasonic pulse velocity methods, maturity concept, breaking off method and pull-out test method. Each of the tests basically measures a particular property of concrete and is influenced by varying degrees by different parameters. Therefore, not all the concrete parameters can be performed in one test. Of the non-destructive methods available, the pull-out tests appears to have the best acceptance as to measure the compressive strength of in place concrete (Yener & Chen, 1984).

iii) *Methods requiring sample extraction* – This is the method where samples are taken, in form of drilled cores, from the existing concrete structure. These samples are taken to a laboratory and can be tested for various strengths and concrete properties including durability. Other analyses may be done on the cores, such as petrographic and chemical analysis.

2.6 Guidance on in-situ compressive strength testing available from ‘standards’ and other documents

In South Africa, the standard used for the testing of regular compressive strength is *South African National Standards (SANS) 5863:2006 Concrete Tests – Compressive strength of hardened concrete*; the standard used for testing core compressive strength is *SANS 5865:1994 Concrete tests- the drilling, preparation, and testing for compressive strength of concrete cores taken from hardened concrete (2006)*. The interpretation and acceptance of the results is done according to *SANS 10100-2:1994 The structural use of concrete Part 2: Materials and execution of work*.

2.6.1 Materials used in preparation of core samples

SANS 5863:2006 and 5865:1994 states that the following materials listed below should be used for the preparation of the cast end of a cylinder and both ends of the core. All the materials needed for the preparation of the core specimens are summarized below.

- High alumina cement
- Sand
- Sulphur
- Carbon Black

These specific materials are used because they have a higher compressive strength compared to the specimen being tested. This eliminates the chance that the capping material will fail before the core specimen. It must be noted for high strength concrete core testing, there is a possibility that the core strength is higher than the capping material, it is suggested that a different method of preparation should be used such as grinding. This should reduce the variability in results.

2.6.2 Apparatus commonly used for extracting and preparing cores

All the apparatus needed for the drilling, preparation and testing of the core specimens are summarized below:

- Concrete core drill
- Concrete core saw
- Grinder
- Capping plates and collar

All concrete laboratories that test the compressive strength of concrete cores should contain all the equipment listed above to prepare the concrete sample correctly. Depending on the method of preparation, as discussed in Section 2.6.4, the apparatus should be able to prepare the core so that the ends of the core plane are within 0.5 mm/m and square to the axis within 0.5°.

2.6.3 Drilling of concrete cores

SANS 10100-2:1994 states that cores should be drilled and tested when the age of the concrete is as close as possible to the age at which the design strength should set. SANS 10100-2:1994 also suggests that at least three cores shall be taken from each member.

2.6.3.1 Core location

Before the drilling of the concrete cores, the core location must be determined. SANS 10100-2:1994 suggests that the locations of the cores should be determined by the engineer. This is to ensure the least impairment to the structure. Neville (2001) further suggests that an experienced structural engineer should determine where the core specimens should be removed from as they will have a better understanding of where the concrete may be questionable and locations where there will be the least destructive harm to the structure. However, Bungey, *et al.* (2006) suggests that the core location will be governed primarily by the basic purpose of the testing, bearing in mind the likely strength distribution within the member related to the expected stress distribution. “*Where serviceability assessment is the principal aim, test should be normally taken at points of likely minimum strengths.*” (Bungey *et al.*, 2006). SANS 10100-2:1994 further suggests that the lesser of the top 300 mm and top 20 % of the depth of the concrete member shall not be used for core testing unless unavoidable (i.e. thin slabs).

2.6.3.2 Specimen Size

For research purposes the preferred size of the cube is 100 x 100 x 100 mm but in practice a 150 x 150 x 150 mm cube is used. With regard to testing cylinders the sizes differs between countries. In America, the preferred size of the cylinder is 100 mm diameter and 200 mm length.

According to SANS 5865:1994 the core size and drilling position should be done in accordance with SANS 10100-2:1994. SANS 5865:1994 further shows the procedures of sizing the cores. The procedures are as follows:

Size of cores – The preferred core diameter is 100 mm, but cores of smaller diameter may be used, provided that the diameter is at least 65 mm or three times the maximum size of the aggregate. However, in the UK and other standards, the preferred dimension of the concrete core specimen is 100 mm in diameter and 200 mm in length, which is the same dimensions as a standard concrete cylinder (Chungs, 1979). The effect of core size is further explained in Section 2.7.5. The preferred 100 mm core diameter is an attempt to reduce the geometric size factor when comparing the standard cube strength to core strength. Therefore, it is always advised in standards to keep the geometric size of standard test specimens and cores constant.

However, it must be understood that the size of the core may be determined by a number of other factors such as; reducing the amount of damage to the structure, structural element size, position of reinforcing and ease of transportation. Owing to these factors the core is often reduced in size.

2.6.3.3 Drilling

Once the location and the size of the cores have been determined, the drilling of the cores can commence. A core specimen is usually cut by means of a rotary cutting tool, as described in SANS 5865:1994. The equipment is heavy and must be firmly supported and braced against the concrete element to prevent relative movement, which will result in a distorted or broken core. Water supply is also required to cool and lubricate the diamond drill piece (Bungey *et al.*, 2006). The drilling of the core specimen includes the orientation in which the core must be drilled. SANS 5865:1994 provides the guidance of the procedures of core orientation, drilling and marking. The effects on the concrete core's compressive strength due to drilling are further discussed in Section 2.7.1. The procedures are as follows:

- *Orientation* – The orientation of the cores will be dictated by the shape, size and position of the member or section. The cores should be taken perpendicular to the outer surface of the concrete with the longitudinal axis of the core horizontal. It must be noted that the core should also be taken where there is less chance of cutting reinforcement.
- *Drilling* – A diamond tipped core drilling machine should be firmly positioned so that damage to the core by movement or vibration is prevented. The core must be drilled to a sufficient depth to ensure that the outer 20% of the cores length may be cut off, so that the remaining length of the core is sufficient for testing, as described in Section 2.6.4. It must be recognised that reinforcing bars present through the core sample will increase the uncertainty of strength testing and should be avoided during the core drilling operation where possible (Bungey *et al.*, 2006).
- *Marking* – Once the core specimen has been extracted, the core should be marked noting the number of cores, position where they were drilled and any defects on the cores or area around drilling location.

2.6.4 Preparation of cores

Preparation of the core sample, before testing, consists of trimming the ends to the correct dimension. After trimming, the preparation of the core ends, by means of grinding or capping, must be completed to meet specification stated in the standards. The preparation of the cast end of a cylinder should also be completed in the same manner. Standards such as SANS 5865:1994 are put in place as a guideline to establish uniformity in the testing environment and to attempt to reduce the variation of test results. All guidance for the preparation of concrete core specimens were taken from SANS 5865:1994 – Section 6 *Preparation of cores*.

- *Dimensions* – SANS 5865:1994 specifies that the tolerance on the longitudinal surface plane parallel to the longitudinal axis of each core should be within 2% of the diameter (d_c). The maximum and minimum lengths of each core must be measured to the nearest 1 mm and any core that does not have a trim length/diameter ratio of at least 0.85 or a ground/diameter ratio of at least 0.9 must be discarded.
- *Trimming* – Trimming of the core is done with the use of a diamond tipped concrete saw. Both ends of the core should be trimmed, ensuring that they are perpendicular to the axis of the core and to obtain a trimmed core that:
 - i) Does not contain any concrete from the top 20% (with a minimum of 50 mm) of the member or section, or any surface laitance. The surface laitance layer must be removed because it does not indicate the true strength of the concrete. The surface laitance layer is formed during compaction when the heavier material tends to move down and the light materials get displaced towards the top; thus, causing a greater water to cement ratio, which will reduce the strength of the concrete at the top (Naik, 1990).
 - ii) In case of cores to be capped, a trimmed length/diameter (l/d) ratio of at least 0.85 to 1.05 and in the case of cores to be ground, a ground a l/d ratio of at least 0.9 to 1.1. The trimmed l/d ratio is stipulated to ensure a final l/d ratio of 1.0 is achieved. The reason for the l/d ratio to be approximately 1.0 is, as described by Neville (2001), so that the core's dimensions are approximately the same as a standard cube; thus, making it easier to compare strengths.
- Preparation of core ends - There are three methods in which the core ends can be prepared:
 - i) *Grinding* – Core ends are ground using a diamond tipped core grinder. The method in which the grinding procedures are stipulated are in SANS 5865:1994 – Section 6.3.1. Specifications for grinding are such that a ground l/d ratio of 0.9 to 1.1 is obtained.
 - ii) *Capping with High Alumina Cement (HAC)* – Core ends are capped using HAC. The method in which the capping with HAC is stipulated in SANS 5865:1994 – Section 6.3.2.
 - iii) *Capping with sulphur mortar* – Core ends are capped using sulphur. The method in which the capping with sulphur mortar is stipulated in SANS 5865:1994 – Section 6.3.3.

The specifications, for all three test methods, are that both ends of the core plane must be prepared so that they are 0.5 mm/m and square to the axis of the core or to within 0.5°. SANS 5865:1994 stipulates these end conditions so that planeness and perpendicularity will achieve a uniform

transfer of load directly through the specimen (Ozyildirim & Carino, 2006). The effects of the preparation of the core ends are further discussed in Section 2.7.3. It must also be noted before testing, the prepared core specimen must be immersed in water at 22°C to 25°C for 48 hours. The effects of the saturating the core specimens are discussed in Section 2.7.7.

2.6.5 Test Procedure

The testing procedures of the core can be referred to in SANS 5865:1994 – Section 7 *Testing procedures*. The rate of loading during testing is 0.3 MPa/s ± 0.1.

2.6.6 Expressing and recording of results

After the specimens have been tested the dial reading is recorded. The readings, normally in kN, are converted to stress and compared to the designed strength of the concrete:

- i) Core cross-sectional area (bearing surface), is the area of the specimen that will be in contact with the compression machine. For a cylinder or core, the diameter and length are measured six and two times respectively before testing. For a cube, the length, breadth and height are measure twice each to the nearest 0.2 mm before testing.

The cross-sectional surface (A) is calculated using the following formula:

$$A = \frac{\pi}{4} d_c^2 \text{ (Cores and cylinders)} \quad (\text{Eq. 2-2})$$

$$A = l \times b \text{ (Cubes)} \quad (\text{Eq. 2-3})$$

A	=	Calculated cross-sectional area (mm ²)
d_c	=	Measure diameter (mm)
l & b	=	Length and breadth (mm)

- ii) Measured core compressive strength

The compressive strengths of the specimens are calculated in mega pascals (MPa). The measured compressive strength of each core will be calculated using Eq. 2-1. It must be noted that according to SANS 5865:1994 the compressive strength must be recorded to the nearest 0.5 MPa. Interpretation of results must be done in accordance to SANS 10100-2:1994 Section 14.4.3.

Although good guidelines are given in standards to interpret the strength of either a control, conformity or supplementary tests; there is little guidance on relating the strengths obtained from these tests. Additionally, as mention by Bungey *et al.* (2006), there is an increase awareness that concrete placed on site may not obtain the same quality as standard specimens due to variability of curing, compaction, possible non-uniform material supplied or general work. Therefore, it is of great importance to relate the strengths of concrete from different tests.

2.7 Factors affecting measured core compressive strength

There are a number of factors that may influence the strength of a core specimen. These influences may occur during extraction, preparation and testing of the core. These factors may reduce the strength of the core which makes the relating of the in-situ concrete strength difficult. Several of the strength influencing factors are discussed below.

2.7.1 Drilling of cores

It is important that the correct equipment is used and maintained properly during the drilling of cores. If the core drill is not maintained correctly, the drill piece is not sharp or the machine is not rigidly fastened, wobbling of the drill bit will occur. Naik (1990) explains how the wobbling of the drill bit tends to create marks on the concrete core. During coring, large shear forces are produced between the drill bit and the concrete that may have an effect on the aggregate (Khoury *et al.*, 2014). This may lead to additional stress concentrations in the concrete core which will lead to a lower compressive strength. It has been found in industry that the wobbling of the core drill creates indentations in the core side, which if prominent, has an effect on the preparation of the core specimen, as it is difficult for the core ends to be prepared perpendicular to the core sides.

The following findings were confirmed during an investigation by Khoury *et al.* (2014), damages that may have occurred to a core during the drilling or cutting is directly related to the concrete strength; furthermore, the aggregate properties also play a role. During coring, coarse aggregate is cut through which is said to damage the ITZ bond due to the different stiffness of the aggregate and vibrations of the core drill. Therefore, the type and size of the aggregate plays a role in how extensive the damage may be. It was found that the use of natural aggregate, containing smooth edges, has a strength reduction of up to 14-20% compared to crushed aggregate, containing rough angular edges. As mentioned above, the concrete strength is the main factor that will influence the potential damage to the core during drilling as the shear forces may damage the cement paste-aggregate bond. Thus, in higher strength concretes, where the cement-aggregate bond is stronger and more rigid, less damage to the core will occur. Khoury *et al.* (2014) derived a correction factor formula for drilling damages that may occur. This formula can be seen in Eq. 2-4. As shown in the equation, there is a constant that is dependent on the aggregate type. During the investigation, the constant was stipulated as 0.06 for crushed pink lime stone; however, no further constants were given.

$$F_{dmg} = 2.4 \times \frac{\left(\frac{l}{d_c}\right)^{0.006}}{[(d_c)^{0.1} \times (f_{core})^\alpha]} \quad (\text{Eq.2-4})$$

F_{dmg}	=	Correction factor due to core drilling damage
f_{core}	=	Measured compressive strength (MPa)
l	=	Core length (mm)
d_c	=	Core diameter (mm)
α	=	Constant depending on the type of aggregate

There is a direct relationship between the diameter size and drilling damages of a core. Research has found that as the size of the core decreases, there is a decrease in compressive strength due to the cut surface area to volume ratio (Ozyildirim & Carino, 2006). The effects of core diameter size are further discussed in detail in Section 2.7.5.

The drilling damage influence on cored specimens makes relating standard cube, cylinder and in-situ core strengths difficult. Due to the number of factors that may influence the damage caused by drilling, many researchers have produced unique correction factors in their research. Therefore, relating standard cube and cylinder strength to in-situ core strength remains unclear.

2.7.2 Location and depth of drilling

During the placing of fresh concrete, it is common that the strength of the concrete may not be uniform over the entire structural element. The location for the removal of cores is a very important aspect to consider. Cores should be taken from positions where the weakest strength can be predicted; however, the removal of the core must never hinder the future performance of the structure. As explained in Section 2.6.3.1, the location of the core is an important factor as the core should be removed from where the designed concrete strength is questionable. Therefore, it is strongly suggested that an experienced engineer identifies the location of coring.

Naik (1990) explains how concrete at the top of a column has a weaker compressive strength to the bottom of the column, due to consolidation of the material. This was further emphasized by an investigation by Khoury *et al.* (2014), where it was found that the relative strength of the cores at the top of the column were 25 and 15% less than the strength at the bottom of the member for 0.6 and 0.4 *w/c* ratios respectively, this was clearly illustrated in Figure 2-17. Figure 2-18 shows the compressive strength reduction with respect to the depth of the slab.

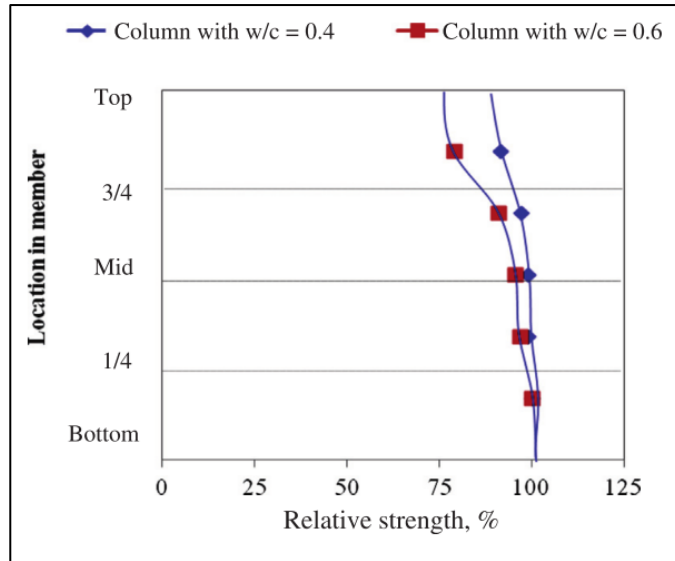


Figure 2-17 – Core compressive strength variation through column height (Khoury *et al.*, 2014)

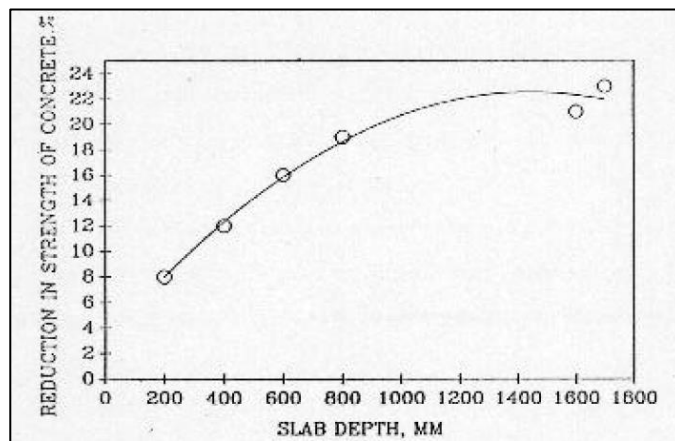


Figure 2-18 – The effect of slab depth on the strength reduction in the concrete (Naik, 1990)

However, it is also important to consider if the cutting of the member may hinder the performance of the element especially with respect to slender members; thus, indicating that the cores should not be removed from critical locations.

In South Africa, a core should be drilled to a depth so that the laitance layer can be completely removed during trimming. According to SANS 5865:1994, the final l/d ratio should be 1.0, making the core easy to size. The American Standards ASTM C39M stipulates, the core should have a l/d 2.0. This makes the sizing of the core difficult and the choice of core diameter will be influenced by the length of the core and size of the member being drilled (Bungey *et al.*, 2006). However, the reduction in core diameter size makes it difficult to interpret the results correctly.

2.7.2.1 Direction of drilling

The direction in which cores are drilled is not a significant factor; but it is rather, the direction of the uniaxial load that is applied compared to casting. This concept was described in Section 2.3.3.4. Naik (1990) explains that wall cores are taken perpendicular to the direction of cast and slab cores are taken in the same direction of cast. As a result of the layering effect, the measured strength of the cores drilled vertically relative to the direction of casting is likely to be greater than that for a horizontally drilled specimen, from the same concrete (Limited, 2013). This is generally attributed to the bleeding of the fresh concrete, creating a higher w/c ratio beneath the coarse aggregate. This leads to a more porous ITZ being perpendicular to the direction of cast.

It has been found in a number of investigations that there is approximately an 8% difference between cores that are tested parallel to the casting plane and cores tested perpendicular to the casting plane, for normal strength concrete (Bungey *et al.*, 2006; Khoury *et al.*, 2014). However, as the concrete strength increases the difference in strength decrease (Ergün & Kürklü, 2012). Another study by Bartlett and MacGregor (1994) mentioned that there was no significant difference in strength.

2.7.3 Effects of core end conditions

As mentioned in Section 2.6.4, SANS 5865:1994 – Section 6 *Preparation of cores* states that the ends of cylindrical samples must not depart from perpendicularity with the sample's axis by more than 0.5° and that the ends must be in plane to within 0.5 mm/m. If the specimen does not meet this requirement it should be prepared by capping or grinding.

The reason for specifying end condition requirements of planeness and perpendicularity is to achieve a uniform transfer of load to the test sample (Ozyildirim & Carino, 2006). Surface irregularities on the original concrete core would lead to local concentrations of stresses, even cores that are capped need to meet the planeness requirements. Ozyildirim and Carino (2006) claim that specimens that do not have the required end conditions prior to testing will cause a degree of strength reduction and variation increase for higher-strength concretes.

The materials used for capping of the cores may also have an effect on the strength of the core. The two materials that SANS 5865:1994 stipulate are namely; hot sulphur mortar and High Alumina Cement (HAC) mortar. If these capping materials are not applied correctly, reductions in strength may occur.

An investigation was compiled by Bugai, *et al.* (2012) and found that the preparation of the end caps with sulphur and HAC mortar are essentially the same. The only difference is that a sheet of flat glass is used for the hot sulphur mortar to form the plane-bearing surfaces; whereas, a metal plate is used for the HAC mortar. It was found that the hot sulphur was not the preferred option for capping due to health and safety reasons including; risks of burns, fire and inhalation of sulphur fumes. Owing to this, a number of laboratories have elected to use the HAC mortar cap. During the investigation by Bugai, *et al.* (2012) it was found that HAC mortar-capped samples often contained capping defects. He confirmed that the end-bearing surfaces were often

out of plane (lumpy) and that there was evidence of rocking when placed on a plane surface. Additionally, the bearing ends formed gaps between the cast ends and the plane surface when tested with a feeler gauge. Figure 2-19 illustrates, the point of contact transfer on to a plane surfaces using fingerprint paint. The sulphur-capped sample, Figure 2-19 a), exhibits an even distribution of contact as shown with the even distribution of colour; whereas, the HAC mortar-capped sample, Figure 2-19 b), prepared with the steel trowel exhibits three pinpoint points of contact. It was found during the investigation, the HAC mortar-capped specimens were on average 46.5% weaker than the average cube strength; compared to the sulphur capped specimens that were only 5.9%. Further investigation confirmed the reason for the departure from the planes and lower strengths were because laboratory workers trowel the end surfaces of the cap instead of casting them against a flat surface (Metal base plate). Thus, not working consistently with the standards.

The test was then repeated and worked strictly according to SANS 5865:1994. It was found that the deviation from the cube strength, for HAC and sulphur capped cores, were 1.6% and 4.7% respectively. Thus, emphasizing the importance of working strictly according to the standards. Bugai, *et al.* (2012) concluded that proper preparation of the core samples will result accurate compressive strength results. “The choice of capping (sulphur or HAC mortar) does not appear to have a significant effect on the results, as long as a standard procedure is followed to ensure that the end-bearing surfaces are plane” (Bugai *et al.*, 2012).

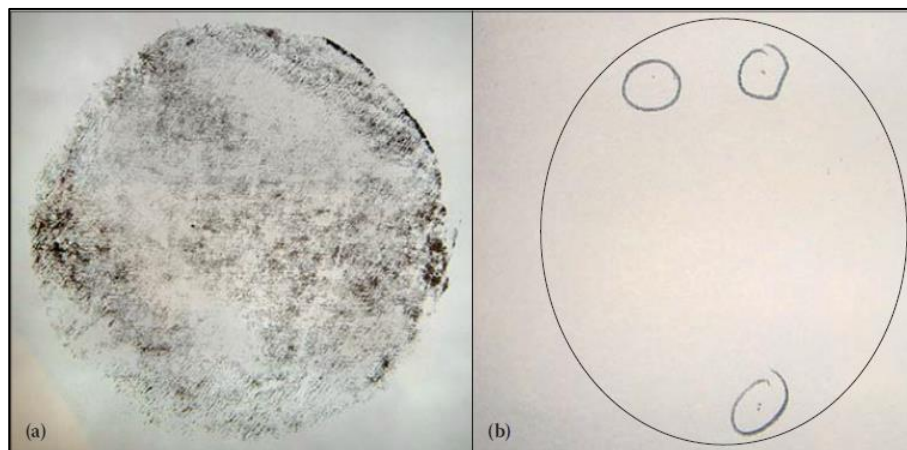


Figure 2-19 – “Footprints” of end-caps transferred with fingerprint paint (a) and carbon paper (b) to record the points of contact onto a plane surface (Bugai *et al.*, 2012)

An investigation was done on the testing of concrete core compressive strength, involving different laboratories in South Africa by Smith (2014). It was found during the investigation that the laboratories qualified to test core compressive strength were not preparing the core ends correctly. This was due to a number of reasons but the main reasons were cost, time and uneducated personnel conducting the preparation and tests. The material required to do the preparations were said to be costly and the laboratories opted to use alternate materials, which failed before the cores failed; thus, producing incorrect results. The laboratories often said that the method of preparation was time consuming and they used alternative methods which were quicker; however, left the core caps broken or debonding from the core. This led to irregularities on the core end surface and a reduced compressive strength.

Therefore, it is authoritative that core ends are prepared strictly according to national standards, to ensure obtained results are non-ambiguous and reliable. Although, this section only discussed cores, cylinders also need their cast end prepared in the same manner. If the cast end is not prepared correctly, similar consequences in reduced strength will be obtained.

2.7.4 Degree of compaction and effect of void ratio

The degree of compaction is one of the most important factors when it comes to the mechanical properties of concrete. The aim of compaction is to expel the excess air voids from the fresh concrete mix. It is said that an increase of 1% in voids can decrease the compressive strength by approximately 6% due to the increase stress concentrations around the void boundaries (Perrie, 2009).

This effect has been compensated for when testing concrete cores by the measurement of excess voidage in SANS 5865:1994 Appendix B.2. Appendix B.2 allows for the adjustment of measured compressive strength for cores with excess voids. By the judgment of the test operator, the degree of excess voids will be estimated as a percentage in the core. The concrete's true compressive strength, if there were no voids present, can be estimated by applying a correction factor to the measured compressive strength. The correction factors can be referred to in SANS 5865:1994 Appendix B.2 Table B.1. The core's adjusted compression strength may be determined using the following formula:

$$F_V = F \times f_V \quad (\text{Eq. 2-5})$$

F = Measured core compressive strength

F_v = Correction factor for excess voids found in SANS 5865:1994 Appendix B.2 Table B.1.

The method in which the void ratio is judged is subjective to the inspector. The manner in which the correction factor is estimated, is by comparing the voids to four images that are found in SANS 5865:1994 Annex B. The images that are supplied are not clear and it is difficult to estimate the correct void factor. Therefore, variations in the void factor estimation may occur between different laboratory testers.

2.7.5 Effect of the core size

2.7.5.1 Diameter

As mentioned in Section 2.6.3, the preferred diameter size of the core specimen, as stated in SANS 5865:1994, is 100 mm. If a smaller core is used, the diameter must be at least three times the size of the maximum aggregate size used. The preferred length of the core specimen correlates to the diameter and the l/d ratio should be at least 0.9.

It was mentioned by Bungey *et al.* (2006) that smaller cores have a considerable advantage over larger cores, smaller cores will save time and cost due to reduced effort of cutting and damage to the structure. An additional advantage is that there is less chance of the core containing

reinforcement. However, the influence in size of the core is opposite to that of cube and cylinder with regard to compressive strength. As mentioned above for standard specimens, as the size increases, the strength decreases due to an increased chance of flaws being present in the sample (Ozyildirim & Carino, 2006). However, the opposite results are found with cores. Tuncan *et al.* (2008); Omer *et al.* (2010) and Khoury *et al.* (2014) found that core strength decreases with the reduction in core diameter. It was concluded in the investigation by Khoury *et al.* (2014) that there was a strength reduction of up to 8% for the cores with a diameter between 50 – 75 mm. It was concluded that this influence was due to the cut surface area to volume ratio increase as diameter decreased, hence the potential influence of drilling damage was increased (Omer *et al.*, 2010; Khoury *et al.*, 2014). It was mentioned by Ozyildirim & Carino (2006) and Khoury *et al.* (2014) that cores with a diameter less than 100 mm may have an increased chance of reduced compressive strength.

It was further found that as the core diameter size was reduced to a diameter less than 100 mm the maximum aggregate size plays an increased role in compressive strength (Tuncan *et al.*, 2008). It was further found during the investigation by Tuncan *et al.* (2008), on assessing concrete strength by means of small core diameters, that the relative strength of a 46 mm diameter core, with respect to a standard cylinder, produced strengths that were 15% and 28% lower when using 10 mm and 30 mm maximum aggregate size respectively.

As Ozyildirim & Carino (2006) explained, the testing of smaller cores is more convenient; however, precision of strength determination should not be sacrificed. SANS 5865:1994 prefers the core diameter to be 100 mm, fortunately the drilling damages to this size core are significantly reduced. However, the reason for the 100 mm core diameter is for convenience in size comparison with the standard 100 mm cube during strength comparison. Although, in practice a 150 mm cube is used, it has been found that the 100 mm and 150 mm cubes produce similar compressive strengths. Although, the desired cube and cores sizes are similar there is still little understanding on how the core and the cube relate in terms of compressive strength.

2.7.6 Length/diameter (l/d) ratio of core

The diameter of the core depends on the size of the drilling tool and the length of the core depends on the thickness of the member, that the core is being drilled from (Wedding & Chung, 1979). The effect of the l/d ratio of a core is similar to that of a cylinder. As discussed in Section 2.3.3.2, as the l/d increases, the strength decreases but the variation in results decrease.

There are other factors that may influence the compressive strength of a core with varying l/d ratios, such as the diameter size and strength level of the concrete. It is found that the influence of l/d ratio, on compressive strength, was more significant in 50 mm cores compared to 100 mm cores (Bartlett & MacGregor, 1994). As illustrated in Figure 2-20, the decrease in strength of the 46 mm core is more prominent than the 69 mm core. During this investigation by Tuncan *et al.* (2008) it was found that this was predominantly due to the increased drilling damages in smaller cores.

The l/d ratio for cores in South Africa is 1.0, with a minimum of 0.9. This is because of the use of the cubes as our standardised compressive test. By keeping the l/d constant, this aids in the comparison between standard and supplementary tests. However, the l/d ratio in other countries that use the cylinder, as their standardised compression test, is more relevant as sometimes it is difficult to obtain a core with a l/d of 2.0. Therefore, much research has been done on the relationship between cylinders and varying diameter size to obtain a correction factor that is reliable. However, there is little understanding in the relationship between cores and cylinders with the same l/d ratio of 1.0. Therefore, further research needs to be done between cores and moulded cylinders with an l/d ratio of 1.0.

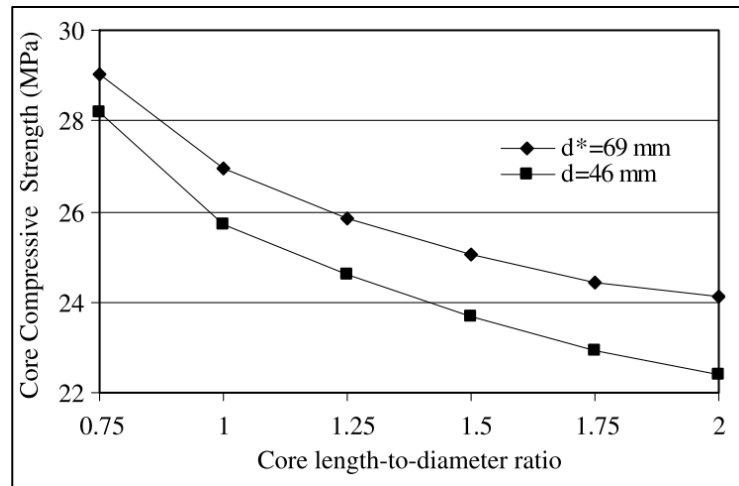


Figure 2-20 – Development of core strengths versus length-to-diameter ratio (Tuncan *et al.*, 2008)

2.7.7 Moisture content

The moisture conditions of concrete cores influence the measured compressive strength. Therefore, it is important that the relative moisture conditions of cores are taken into account while estimating the in-situ concrete strengths.

In practice, it is important that the test is performed under standard conditions; therefore, the moisture content of the concrete is kept constant. To ensure a constant comparison between core strength and standardised cube/cylinder strength, it is imperative that cores are to be tested at saturated conditions. Therefore, cores are generally soaked in a water for 48 hours prior to testing.

Bartlett and MacGregor (1994) concluded during their research that the compressive strength of concrete core specimens decreases if the moisture content is uniformly increased throughout its volume. Thus, a saturated specimen that has been soaked for 48 hours has a compressive strength value of 10% to 15% lower than a comparable dry specimen that has been left to dry in air for 7 days (Bungey *et al.*, 2006). The reason for the difference in compressive strength is explained by Bartlett and MacGregor (1994), “Water absorption into the gel pores of the concrete is believed to cause distension within the test specimen and as the applied load increases, a hydrostatic excess pressure develops since the absorbed water is prevented from being squeezed out of the specimen. This pressure must be resisted by the solid matrix along the

sides of the specimen; thus, causing a transverse bursting effect.” Whereas, the distension in the dried specimen is eliminated (Bartlett & MacGregor, 1994).

If the cores were to be dried, there would be no relationship between in-situ core strength and standard cube or cylinder strength, as the test would be done under completely different boundary conditions. In conclusion to the moisture content of the core specimen and the nature of the topic being based in South Africa, the moisture content procedures were strictly done in accordance to the guidelines stipulated in SANS 5865:1994, to retain the uniformity between multiple tests.

2.7.8 Reinforcement

The presence of reinforcing in in-situ strength testing causes significant variations in the produced results. Bungey, *et al.* (2006) stated, “Published results indicate that the reduction in measure strength due to reinforcement may be less than 10%; however, sometimes due to the variable size, location and bond makes it virtually impossible to allow accuracy for this effect.” Therefore, when drilling a core, reinforcing must be avoided at all costs.

However, if a core is removed and contains reinforcing that is perpendicular to the axis of the core; a correction factor may be applied to measure the core strength; although, sometime the core should be disregarded. There are number variables associated with this aspect and they include:

- i) Effect of diameter of reinforcing bars
- ii) Effect of number of reinforcing bars
- iii) Distance of reinforcing bars from the axis of the core
- iv) Distance of reinforcing to the end plane of the core

The correction factor is as follows:

$$f_{corrected} = f_{measured} \times \left[1.0 + 1.5 \left(\frac{\phi_r}{\phi_c} \times \frac{h}{l} \right) \right] \quad (\text{Eq. 2-5})$$

Where,

ϕ_r	=	Bar Diameter, mm
ϕ_c	=	Core Diameter, mm
h	=	Distance of the bar axis from nearer end of core, mm
l	=	Core length (uncapped), mm
$f_{corrected}$	=	Corrected strength, MPa
$f_{measured}$	=	Measured Strength, MPa

Due to the nature of this investigation no reinforcing steel was placed in the concrete from which the concrete cores were extracted from; thus, eliminating any variation in strength cause by reinforcement.

2.7.9 Effect of testing machine characteristics

The use of incorrect equipment while testing concrete cores can lead to reduced compressive strength results (Ozyildirim & Carino, 2006). Among the requirements of the testing machine's characteristics, is the capacity for smooth and continuous load application; accurate load measurements; and two bearing blocks, one being spherically seated and one being solid, both which must satisfy further requirements of surface planeness, minimum and maximum diameters and other features (Ozyildirim & Carino, 2006).

Ozyildirim & Carino (2006) states that the spherically seated bearing block must be free to rotate to accommodate any small deviation from parallelism of the ends. It was further mentioned that there may be up to a 20% reduction in compressive strength if there is no spherical seatings. Furthermore, if the specimen is placed off centre, with respect to the loading axis, by only 13 mm the strength may be reduced by up to 10%.

2.8 Interpretation of results

Taking into consideration the investigation topic, the interpretation of results was reviewed from *South African National Standards (SANS) 10100-2:1994 The structural use of concrete Part 2: Materials and execution of work*. The section that will be relevant to this topic will be Section 14.4 *Strength tests of concrete in place*. However, in some cases SANS 10100-2:1994 will be compared to other standards and papers.

2.8.1 Acceptance of concrete based on core strength

Once the concrete cores have been tested by a laboratory, the compressive strength results will need to be interpreted. The interpretation of these results will be used to verify whether the concrete used conforms to the specifications set out by the engineer and to assess whether the hardened concrete has sufficient compressive strength for which it has been designed for. Therefore, the core strength that is obtained will be related to the cube strength as well as the specified strength. The outcome of these tests is often used as the basis in which a decision whether the structural integrity, due to insufficient core strength, may result in partial or full demolition of the structure or its members; as well as, which party in the project is to be blame for the reduced compressive strength (Smith, 2014). Therefore, it is imperative that the relationship in strength between a core and a cube is well understood, owing to the fact that there are a number of factors that may influence the strength of a core.

According to SANS 10100-2:1994, Section 14.4.3 *Acceptance of concrete on the basis of core strengths* Section 14.4.3.1 states, if the average core strength is at least 80% of the specified strength, and if no single core strength is less than 70 % of the specified strength, the concrete shall be accepted. The reason a concrete core may have a compressive strength less than the

specified strength or the standard cube strength will be explained in Section 2.9. However, it is unknown where the 80% factor between cube and core strength originates from and why SANS 10100-2:1994 stipulates this factor. Therefore, further research needs to be done to understand the universal relationship between the compressive strength of cores drilled from concrete elements and moulded cubes.

According to Section 14.4.3.2 of SANS 10100-2:1994 if the concrete in a certain area fails to comply with Section 14.4.3.1 because a single core result falls below 70% of the specified strength, a further set of three cores may be taken from the same area, to determine the extent of deficient concrete. If the second set of cores complies with the requirements of Section 14.4.3.1, the area represented by the second set of cores shall be considered acceptable. However, if the second set of three cores fails to meet the requirements in Section 14.4.3.1 further inspection of the member must be performed.

If Section 14.4.3.1 as well as Section 14.4.3.2 of SANS 10100-2:1994 fail, further investigations and considerations must be done and a number of guidelines are stated Section 14.4.3.3:

- i) Strength requirements for the member(s);
- ii) Performance of a full-scale load test;
- iii) Strengthening the deficient part of the structure; or
- iv) Removal and replacement of the deficient part of the structure

As mentioned above, the considerations and alternative solutions in relation to the deficient part of the structure are not economical. This may lead to serious economic and legal implications if the deficient concrete in the structure is not removed or replaced (Bugai *et al.*, 2012). However, there would be far greater legal implications between the contractor and the test laboratory if it was found that the core specimens that were removed were not prepared and tested correctly according to the standards. Furthermore, if it were found that the test operators, specific laboratory conditions as well as laboratory equipment had a negative influences on the test and produced miss leading results, there would be a large dispute. These miss-leading results may result in fully demolishing a sufficiently strengthened concrete member. This unnecessary demolition of a member, due to the negative influences by the test laboratory, would have cost a party in a construction project an unnecessary large expense which will lead to serious legal implications.

Therefore, a great deal of time and effort should be put into the testing of concrete cores. Experts should be sought to conduct these tests correctly according to standards, to ensure that the analysis of the results are non-ambiguous, reliable and repetitive.

2.9 Relating equivalent cube, cylinder and in-situ core strength

Cubes and cores made from the same given concrete and tested in accordance with the appropriate standards will achieve different strength due to various factors (Owens, 2012). Malhortra (1977) mentioned that relating core strength to standard specimen strength often creates more problems than it solves. Consequently, in-situ compressive strength is probably one of the least understood concrete properties. It has been found that there is no universal relationship between the compressive strength of cores, drilled from concrete, and moulded cube (Güneyisi *et al.*, 2015). This is due to a number of factors that may affect mechanical properties of the core. Generally, it was found that the differences in strengths were due to; aspect ratios, diameter sizes, presence of reinforcing, different bearing-end conditions, different degree of compaction, different methods of curing, moisture content, and damages that the core may experience during drilling.

Generally, in attempt to relate the in-situ compressive strength to standard cube/cylinder compressive strength, correction factors are put in place. There are different factors for different standards and some are more complicated than others. However, once these correction factors have been put in place, the concrete must still be assessed to see if the compressive strength may be accepted. As mentioned above, SANS stipulates that the core strength should be approximately 80% of the specified strength to be accepted.

Much research has been done on the factors that may influence concrete compressive strength; however, little research has been done to relate the in-situ core strength to standard cube and cylinder strength. It has also been found that most of the research that has been done in attempt to relate compressive strengths has been on cylinder strength (Tuncan *et al.*, 2008; Ergün & Kürklü, 2012; Houry *et al.*, 2014). Therefore, there is little research on the relationship between standard cube, cylinder and in-situ core strength, with length-to-diameter ratio of 1.0.

Owing to this, further research needs to be done on this topic. But before further research may be done, a full understanding on the factors that may influence the compressive strength of cores must be done. A summary of the factors that may influence the relationship of cubes, cylinders and core strengths are listed below:

2.9.1 Summary of factors that influence the strength relationship of cubes/cylinders and cores

The length/diameter (l/d) ratio effects the compressive strength relationship between cubes, cores and cylinders. It was found that as the l/d ratio of a core decreases, the strength of the core gradually increases and the phenomenon can be more prominent in smaller cores. (Almusallam *et al.*, 2003; Tuncan *et al.*, 2008; Omer *et al.*, 2010). Therefore, this could create differences in the strength relationship. There have been several equations that have been derived to relate the l/d ratio; however, the one used in SANS 5865:1994 can be referred to in Eq.2-6. This equation may be used if the core prepared l/d ratio that does not fall between 0.9-1.1. The l/d ratio of 1.0 is stipulated in SANS 5865:1994 as it is the most accurate when comparing the core strength to the cube strength, as the aspect ratio will remain constant. However, when comparing core

strength to cylinder strength the preferred l/d ratio is 2.0. A l/d ratio of 2.0 is often difficult to obtain due to the constraints of the element that is cast. Factors are generally given in standards that relate the core strength, with varying l/d ratios, to cylinder strength. However, little research has been done on relating a cylinder and a core both with a l/d ratio of 1.0.

$$f_{corrected} = f_{measured} \times \left[\frac{2.5}{1.5 + \frac{d}{l}} \right] \quad (\text{Eq.2-6})$$

d	=	Core Diameter, mm
l	=	Core length, mm
$f_{corrected}$	=	Corrected strength (MPa)
$f_{measured}$	=	Measured Strength (MPa)

The diameter size of the core plays a large factor in in-situ compressive strength testing. The core diameter generally determines the geometric size of the core as a l/d ratio is stipulated. Therefore, the diameter size is normally governed by the size of the member. The diameter of the core also governs the significance that the maximum aggregate size may contribute to the strength properties. In literature, it is commonly found that cores with a diameter smaller than 100 mm can produce strengths that are 15% less than cores with a diameter of 100 mm or larger. This is due to the damage to the concrete matrix during coring (Tuncan *et al.*, 2008). Therefore, the diameter size of a core can play a significant role when comparing its strengths to cylinder and cube strengths. It is expected that the most accurate comparison between cores and cubes is when the core diameter is equal to the breadth of the cube. Therefore, it is predicted that the most accurate comparison between cylinders and cores, with a l/d ratio of 1.0, would be when there are equal diameter sizes, but additionally, there are reduced effects on the cores due to drilling damages. Thus, the most accurate comparison would be a 100 mm diameter or larger.

Concrete that is placed on site is compacted in a different manner compared to a standard specimen. The degree of compaction may differ due to the different compaction methods. On site during a concrete pour, a poker vibrator is commonly used to expel the excess air from large volumes of concrete; whereas, when standard cubes or cylinders are cast they are either compacted using a poking method or, if available, a vibrating table. The degree of compaction of a standard specimen, due to its size, is more consistent compared to a cast element on site, where there will be increase variation in compaction due to the larger surface area. Therefore, the strength of a standard cube or cylinder may be higher compared to the core due to the variations in the degree of compaction. However, SANS 5865:1994 does include a factor which can compensate for excess voids when attempting to relate the in-situ core strength to standard cube and cylinder strength.

The manner in which a core and cylinder is prepared can severely affect the compressive strength. The preparation of the bearing ends is a technical procedure that needs time and experience, to ensure smooth and flat bearing surfaces. Although, there are standards that

stipulate the procedures in which the ends should be prepared, it has been found that they are not strictly adhered to (Smith, 2014). During an investigation by Bugai *et al.* (2012), on the importance of plane end-bearing surface preparation, it was found that poorly prepared capped ends can reduce the core strength by 46.6% compared to the standard cube strength. However, further investigation indicated that when the core ends were properly prepared, the strength was only reduced by 4.7%. Therefore, the preparation of the plane and bearing ends play an important role in the relationship between core, cube and cylinder compressive strengths.

The curing of concrete on a construction site differs to that in a laboratory. Curing is the time given to ensure the maximised hydration reaction has occurred. Over time concrete gradually gains strength. The strength is gained by the hydration reactions in which cementing compounds and water create a strengthening by-product which occupies the water filled pores in the concrete. Therefore, to ensure maximised curing no water must escape from the concrete. In a laboratory, standard specimens are fully submerged in water to ensure saturation and a maximised hydration reaction; whereas, on a construction site the structural elements cannot be submerged so other methods of curing are used. Methods used to retain the water in the concrete on site are: covering the concrete surface with industrial cling-wrap or wet hessian, sprinkling of water or membrane curing. However, the curing of concrete on site can be ineffective because the concrete does not gain its true strength due to moisture evaporation. Figure 2-21 shows the compressive strength of concrete with different curing methods and periods. Therefore, standard cubes and cylinders, that are cured by submerging, may possess a higher strength compared to an in-situ cores, due to maximized curing; whereas, on-site the curing may not have been fully completed.

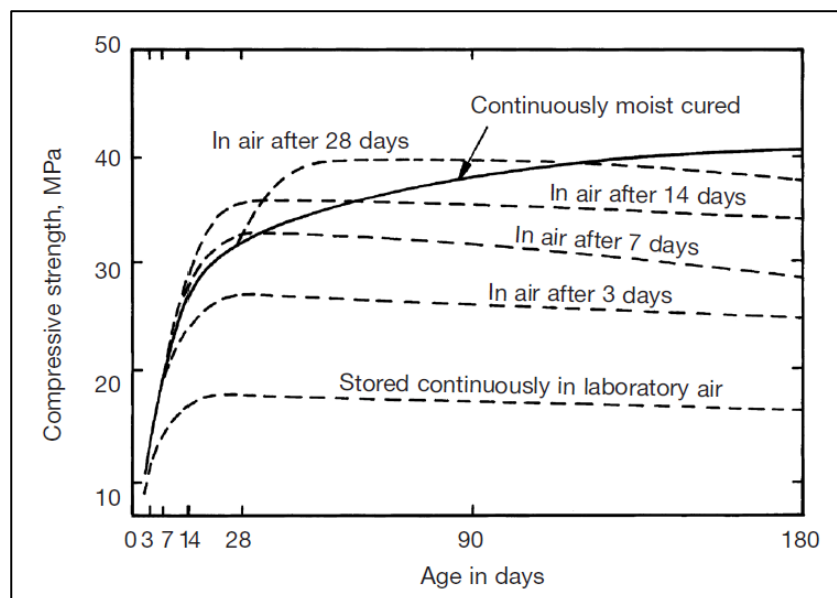


Figure 2-21 – Compressive strength of concrete dried in laboratory air after preliminary moist curing (Kellerman, 2009)

The presence of reinforcing in concrete cores can significantly alter the strength. It has been found that the presence of reinforcing can reduce the measured strength up to 10%; however, the

variable size, location and bond of the reinforcing makes it virtually impossible to accurately predict the true compressive strength. There have been several formulae created to attempt to predict the true strength of the concrete cores; however, as discussed in Section 2.7.8, SANS 5865:1994 provides a factor which can be used. Nevertheless, the presence of reinforcing in a concrete core is an important factor to consider when relating specified, cube and core strength.

Overall, there are a number of factors that may affect the strength of concrete cores. Owing to the variability in core strength, this may influence the relationship between standard cube/cylinder strength and in-situ core strength. In literature, a lot of research has been done on the influences on cores that are cast, compacted, cured and drilled in conditions similar to practice; thus, obtaining in-situ compressive strength. However, little research has been done on cores that are created, cured and drilled under laboratory conditions. Therefore, this comparison will give a good idea, which factors may affect core strength obtained on site compared to a laboratory.

3. Methodology

3.1 Introduction

This chapter provides insight into the methodology that was followed during the experimental investigation.

The research began with an informative study on the testing of concrete compressive strength using three configurations: i) cubes ii) cores and iii) cylinders. The literature review formed the basis of the research by providing general understanding and broader background knowledge on concrete compressive strength testing. Additionally, it provided understanding on the possible factors that may differentiate the compressive strength of cubes, cores and cylinders. The resources that were used in the informative study included published literature in the form of journals, National Standards such as the South African Bureau of Standards, text books, reports and online resources.

The informative literature study provides insight on the factors that must be concentrated on during the experiment investigation. An experimental program was designed to investigate and compare the compressive strengths of cubes, cores and cylinders, with an aspect ratio of 1.0. It was important that all specimens and elements were cast, cured, prepared and tested in the same controlled environment. Additionally, the program was designed to investigate whether concrete cubes, cores and cylinders with the same geometric dimensions would produce similar compressive strengths. Specifically, relating cube versus core and cylinder versus core compressive strengths. The investigation also included analysing crack patterns and mechanical behaviour of different size specimens; as well as how the moulded specimens failed versus the core specimens.

A statistical analysis was completed on all collected data. This statistical analysis was done in attempt to identify outliers, relate the data that was collected to one another and determine significance within results. From the findings, a discussion on the data was completed followed by the final conclusions.

3.2 Experimental work

An experimental program was designed to investigate the relationship amongst cube, core and cylinder compressive strengths. As found in literature, there are several factors that may influence the compressive strength of the three category types differently. Consequently, this experimental program was designed to investigate the influences that common variables may have on the compressive strength of cubes, cores and cylinders. This was done in attempt to identify a universal relationship between cubes, cores and cylinders, with an aspect ratio of 1.0. The casting, curing, preparation and testing methods were completed in strict accordance to the guidelines that were stipulated in the *South African National Standards (SANS)*.

3.2.1 Mix proportions

The concrete mix proportions are listed in Table 3-1. PPC Surebuild CEM II 42.5N was used in all mixes. A 50/50 split of crusher sand and dune sand was used as the fine aggregate. Two different coarse aggregate types were used to analyse the potential effect that aggregate type may have on compressive strength. The coarse aggregate types used were greywacke and quartzitic sandstone, locally sourced from the Western Cape. The three maximum coarse aggregate sizes which were used were 9.2, 19.2 and 26.5mm, as illustrated in Figure 3-1. This was used to analyse the influence that the maximum aggregate size and aggregate type had on the compressive strength of concrete. It aided in identifying the influences of drilling damages to the cores; and the possible influences that this may have had on the relationship between core strength and moulded cube and cylinder strength. A water reducing admixture, Chryso Premia 310, was used to aid with workability and improve consolidation of the fresh concrete. All elements including the beams were compacted using a vibrating table; thus, ensuring the same method of compaction. After 24 hours, the specimens were de-moulded and subjected to moist curing for 28 days. The specimens were cured by immersion at a temperature of $22 \pm 3^{\circ}\text{C}$. The concrete was designed to have a characteristic strength of 30 and 50 MPa respectively.

Additionally, the influence of multiple strength levels was investigated. The additional two strengths were 60 and 75 MPa. These strength levels were created only using the 19 mm greywacke aggregate. Therefore, 14 different concrete mixes were created in total.

It must be noted; the mass of water and coarse aggregate was kept constant throughout all the concrete mixes. This was to ensure effective comparison in compressive strengths and minimise variable factors between mixes.

Table 3-1 – Proportions and properties of mix design

Mixture	Mix proportions (kg/m ³)				Properties		
	Coarse Aggregate	Fine Aggregate	Cement	Water	w/c ratio	Aggregate type	Maximum aggregate size (mm)
A	1100.0	914.4	225.0	180.0	0.80	Greywacke	9.2
B	1100.0	813.1	346.2	180.0	0.52	Greywacke	9.2
C	1100.0	914.4	225.0	180.0	0.80	Greywacke	19.2
D	1100.0	813.1	346.2	180.0	0.52	Greywacke	19.2
E	1100.0	914.4	225.0	180.0	0.80	Greywacke	26.5
F	1100.0	813.1	346.2	180.0	0.52	Greywacke	26.5
G	1100.0	726.3	450.0	180.0	0.40	Greywacke	19.2
H	1100.0	600.9	600.0	180.0	0.30	Greywacke	19.2
I	1100.0	914.4	225.0	180.0	0.80	Sandstone	9.2
J	1100.0	813.1	346.2	180.0	0.52	Sandstone	9.2
K	1100.0	914.4	225.0	180.0	0.80	Sandstone	19.2
L	1100.0	813.1	346.2	180.0	0.52	Sandstone	19.2
M	1100.0	914.4	225.0	180.0	0.80	Sandstone	26.5
N	1100.0	813.1	346.2	180.0	0.52	Sandstone	26.5



Figure 3-1 – Different maximum aggregate sizes in relation to 150mm diameter cylinders

3.2.2 Details of test specimens

The dimensions of the cast elements used in the experimental investigation are indicated in Table 3-2 (Column 1). The cast beams are illustrated in Figure 3-2 a). The cores were drilled, from either cast beams or cubes, to the specimen diameters that are indicated in Figure 3-2 (Column 3).

The beams were sufficiently big enough to allow the core to be drilled and removed comfortably leaving 10 mm from the mould walls. This ensured the wall effect was eliminated from cored samples. The cylinders were approximately filled to three quarters of their height due to the sample being prepared to an l/d ratio of 1.0. The cylinder moulds and core drill bits used are illustrated in Figure 3-3.

Table 3-2 – Number of samples and mould sizes created for each concrete mix

Mould type	Mould Dimension (mm)	Specimen dimension (mm)	No. of Specimens
Cube	100x100x100	100x100x100	5
Cube	150x150x150	Φ 50 L 50	5
Beam	500x100x100	Φ 68 L 68	5
Beam	1000x180x150	Φ 102 L 102	5
Beam	1000x180x180	Φ 143 L 143	5
Cylinder	Φ 70 L 140	Φ 70 L 70	5
Cylinder	Φ 100 L 200	Φ 100 L 100	5
Cylinder	Φ 150 L 300	Φ 150 L 150	5



Figure 3-2 – a) Beam moulds b) Final cast specimens with varying diameter sizes



Figure 3-3 – Cube and varying size cylinder moulds and various core drill bits used

Once the samples were cast, they were compacted using a vibration table, covered using a plastic film and left to cure in laboratory conditions for 24 hours. After this period the moulds were stripped and the concrete samples were submerged in water for 21 days. The larger beam samples were unable to fit in the curing tanks; however, they were wrapped in hessian, saturated every alternative day and covered with plastic, hence, effectively keeping the beams saturated to simulate water curing. After 21 days, the beam and cube cast elements were cored. The cores were placed back in the curing tank until day of testing, at 28 days. Coring of the beams may be seen in Figure 3-4 a).

3.2.3 Preparation of specimens

The cores were drilled from beam samples at 21 days and placed back in the curing tank until 28 days. Within the seven-day period, the cores and cylinders were prepared for testing. Preparation of the cores and cylinders consisted of trimming and grinding the samples to the correct dimensions. A diamond tipped core drill bit, saw and grinder were used for the preparation of the samples. Standards such as SANS 5865:1994 are put in place as a guideline to establish uniformity in a testing environment and to reduce the variation of test results. All guidance for the preparation of concrete core and cylinder specimens were conducted in accordance to SANS 5865:1994 – Section 6 *Preparation of cores*:

- *Trimming* – The concrete saw was used to cut off both ends of the core and the casting end of the cylinder, perpendicular to the axis of specimen. This was to ensure the samples do not contain any concrete from the top 20% or any surface laitance. The samples were cut to a size with an l/d ratio of 1.05 to leave additional length for grinding.
- *Dimensions* – The diameter (d_c) of each core and cylinder was taken as the average of six measurements, to the nearest 1 mm. Each measurement was taken in pairs at right angles to each other, near the middle and near the quarter-points of the core's length. The maximum and minimum lengths of each core and cylinder was measured.

- *Grinding* – Preparation of core and cylinder ends were done using the grinding method, as illustrated in Figure 3-4 b). The cores and cylinders were ground to an l/d ratio of 1.0. The grinding of the specimens was done to ensure that the specimens' planes are 0.5 mm/m and square to the axis of the sample to within 0.5° . SANS 5865:1994 stipulates these end conditions so that planeness and perpendicularity will achieve a uniform transfer of load directly through the specimen.

3.2.4 Testing of specimens

The testing of the cores was done in accordance to SANS 5865:1994. The cubes and cylinders were tested according to SANS 5863:2006. The investigation was performed using an INSTRON 1000RD-E4-H2 hydraulic dynamic testing machine. The samples were removed from the curing tank and were tested in a saturated-surface-dry state. After each test the platens and test specimens' ends were swiped thoroughly to ensure that there was no debris left behind. All the specimens were loaded without shock at a uniform rate of $0.3 \text{ MPa/s} \pm 0.1 \text{ MPa/s}$ until the specimen reached failure, as shown in Figure 3-4 c).

Once the specimen was tested, a visual analysis of the specimen was completed to ensure the correct failure. The manner in which the specimen failed was visualized and important notice was taken on how the aggregate and concrete matrix interacted at failure. A visual inspection on the fracture mechanical aspects and failure locations at the core boundary was done. This was completed by comparing the failure that was witnessed with that of the standard hour-glass failure pattern. Additional analysis was done on the crack path i.e. through the interfacial transition zone, aggregate or both.

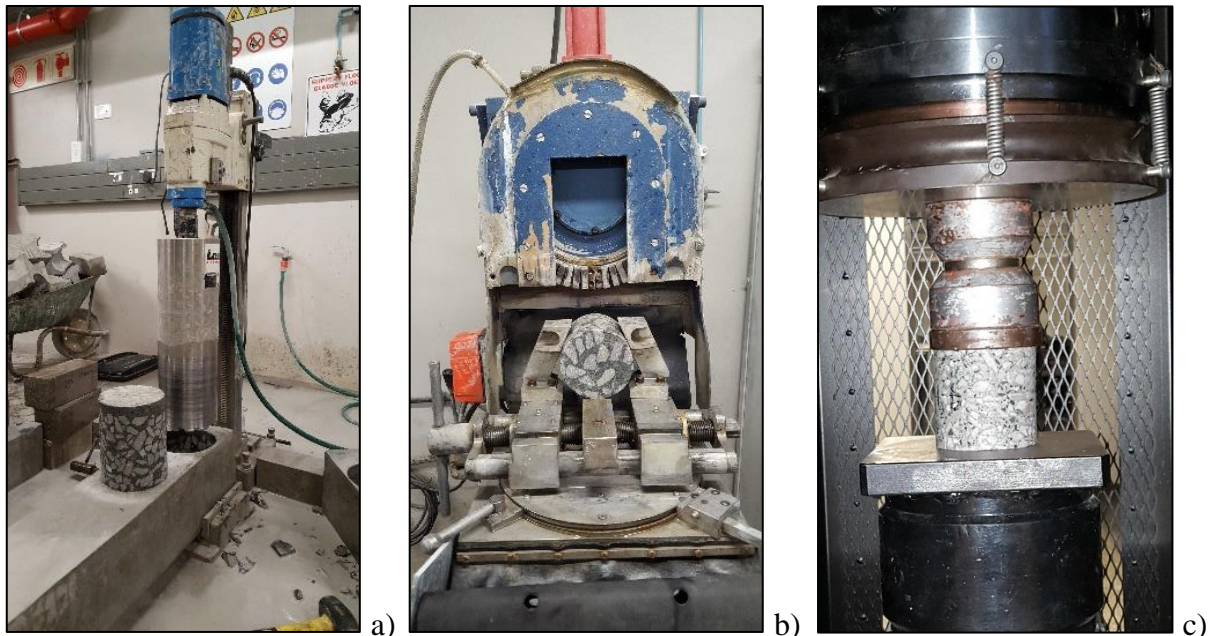


Figure 3-4 – a) Coring sample b) Preparation of sample (Grinding) c) Compressive strength testing



Figure 3-5 – One complete batch of prepared cubes, cores and cylinders

3.3 Data analysis

The experimental investigation was designed to find a relationship in mean compressive strengths between a moulded cube, cylinder and a drilled core, with a l/d ratio of 1.0. The aim of the investigation was to see if the three sample categories would produce similar compressive strengths if they were cast, cured, prepared and tested under the same controlled conditions. Therefore, besides calculating the descriptive statistical data such as the mean and standard deviation of each batch; additional statistics were performed to identify if the three specimen categories would produce significantly different strengths.

A one-way ANOVA, Analysis of Variance, was the statistical method chosen to identify if there was a significant difference in compressive strengths. This statistical method was chosen as it tests if there is a statistically significant difference between two means, for a specific category. Specifically, it tests the null hypothesis to identify if the mean strengths are similar or not.

Before the ANOVA was performed each batch of results were analysed for outliers. The statistical method that was used to identify the outliers was the Grubb's test. Where an outlier was identified, the individual test result was discarded.

Once the outliers were discarded, a one-way ANOVA was performed between two batches of results. During the investigation, the influence of aggregate type, aggregate size, diameter size and strength level of the concrete was investigated. For example, when comparing the strengths of the different diameter sizes an ANOVA was done between the strength of the 70 - 100, 100 – 150 and 70 – 150 mm core diameters of the same batch of concrete. The ANOVA was done using Microsoft Office Excel 2016.

During an ANOVA, it is assumed that the results are normally distributed and the variance in results of the samples are approximately the same. For this data analysis, it was assumed that these assumptions hold true.

The ANOVA test is a method of testing a hypothesis. The null hypothesis indicates that the population means of all the samples are similar; however, the alternative hypothesis would be that there is a significant difference between the data groups. The significance was determined using p-values, probability-values, which determines the probability of getting the result if there is no difference in the mean of the two batches. Therefore, if the p-value is small this indicates that there is a significant difference in the means. But the limit of significance depends on the confidence level chosen.

To determine whether the mean for one set of results was significantly different from another, the significance level needed to be less than 0.05 for a confidence level of 95%. Therefore, if the p-value was less than the significance level of 0.05 the mean results were significantly different.

The ANOVA uses a sum of squares approach to determine if the means of two batches of results are significantly different. The sum of squares was used to check the variability of the samples and variability between the samples. The example below shows the one-way ANOVA of the strength results for 70 and 100 mm diameter cores for Mix A. This was done to illustrate the comparison of strength between core diameter size and how to determine if the results of two batches are significantly different.

Table 3-3 indicates the compressive strengths obtained for the core specimens.

Table 3-3 – Strength results for cube and 100mm diameter cores for Mix A

(A) 9 mm greywacke aggregate 30 MPa		
Specimen	Cube	Core
Core compressive strength (MPa)	30.9	33.6
	31.7	33.2
	30.3	29.5
	31.2	29.0
	32.2	35.8
Mean	31.3	32.2
Variance	0.5	8.4

The hypothesis statement would be as follows:

$$H_0 : \mu_{70} = \mu_{100} \text{ (Mean strengths are statistically similar)}$$

$$H_1 : \text{The means strengths are significantly different}$$

Where $\mu_{70} = \mu_{100}$ are the true population means for the 70 and 100 mm sample respectively.

Three sum of squares were calculated to analyse the variation between the data. First the total sum of squares (SST), then the sum of squares within the groups (SSW) and the sum of squares between the groups (SSB). The variation in the specimen strength was calculated with the sum of squares between groups.

$$SST = \sum_{i=1}^k (x_i - \bar{x})^2 \quad \text{Eq 3-1}$$

$$SSW = \sum_{i=1}^k (df) s_i^2 \quad \text{Eq 3-2}$$

$$SSB = \sum_{i=1}^k n_i (\bar{x}_i - \bar{\bar{x}})^2 \quad \text{Eq 3-3}$$

n_i	=	Number of values (SSB = 5; SSW = 10)
s_i	=	Variance
\bar{x}	=	Mean of each sample
$\bar{\bar{x}}$	=	Total mean for all the values from both samples
k	=	Number of samples

For SSW, each group has a degree of freedom equal to one less than their sample size (There are k samples). The total degrees of freedom is k less than the total sample size: $df = N - k$. For this example, the SSW equals 37.0 and the SSB is 2.304. From the sum of squares calculated the mean sum of squares MSW and MSB were calculated as follows.

$$MSW = \frac{SSW}{n-k} \quad \text{Eq 3-3}$$

$$MSB = \frac{SSB}{k-1} \quad \text{Eq 3-4}$$

Therefore, the MSW was 4.448 and the MSB is was 2.304. Using these values, the F value was calculated.

$$F = \frac{MSB}{MSW} \quad \text{Eq 3-5}$$

The F statistic is then compared to the F_{crit} value that is calculated from the degrees of freedom and found in the F distribution table. If the F value is higher than the F_{crit} value, the null hypothesis is rejected. In this example the F value was calculated to be 0.518.

For the one-way ANOVA, a significance level of 0.05 was used for a confidence interval of 95 %. A one-way ANOVA analysis was conducted between two different groups of specimens. Owing to the degrees of freedom the F_{crit} value was 5.317.

Therefore, the F is less than the F_{crit} so the null hypothesis was accepted. However, when using MS excel 2016 an addition p-value is calculated. The p-values relates to the F values and can be read off the F distribution graph. Using the p-value, the hypothesis can also be determined. The p-value is then compared to the significance level. If the p-value is less than the significance

level the null hypothesis is rejected but if it is greater than the significance level the null hypothesis is accepted.

As illustrated in this example the p-value that was obtained was 0.492. The p-value was compared to the significance level of 0.05. As seen, the p-value is greater than the significance level, therefore, the null hypothesis was accepted and it can be deduced that the mean compressive strength between the 70 and 100 mm diameter cores in Mix A were statistically similar.

4. Results

This chapter presents the results that were obtained during the experimental investigation. The measurement of each individual result can be referred to in Appendix A. It must be noted that all the cores fell within the prescribed length/diameter (l/d) ratio of 0.9-1.1; therefore, no l/d correction factors were used.

The mean results that were obtained during the experimental investigation are summarized in Table 4-1 and Table 4-2. In total 520 specimens were cast, cured, prepared and tested.

Table 4-1 – Summary of the mean compressive strength results and standard deviations of the greywacke specimens

Specimen Dimension (mm)	Mean Compressive Strength (MPa) and Standard Deviation															
	Concrete Mix															
Mix (Aggregate size, concrete strength)	A		B		C		D		E		F		G		H	
	09,30	09,50	19,30	19,50	26,30	26,50	19,60	19,75								
	Greywacke Coarse Aggregate															
100 mm Cube	31.3	0.7	54.7	2.1	30.8	1.2	51.2	1.3	30.2	0.6	49.1	2.9	63.8	1.1	74.6	4.0
50 mm diameter Core	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
70 mm diameter Core	32.7	1.1	57.7	1.8	31.4	1.3	50.5	3.5	35.7	3.2	53.8	2.0	66.9	0.8	73.2	4.7
100 mm diameter Core	32.2	2.9	45.4	1.3	33.9	1.5	54.3	0.8	32.5	1.0	47.2	0.5	61.8	3.7	72.5	2.8
150 mm diameter Core	28.7	5.9	45.8	4.2	32.6	0.9	48.4	3.8	29.2	0.8	49.1	2.1	61.7	3.8	71.1	3.5
70 mm diameter Cylinder	26.3	2.4	50.3	1.2	30.3	1.6	45.4	3.6	30.7	1.3	48.4	3.8	57.5	2.1	65.9	1.8
100 mm diameter Cylinder	30.4	3.2	59.7	1.2	28.1	0.8	48.2	1.9	29.7	1.8	46.6	1.4	62.4	1.7	72.2	0.9
150 mm diameter Cylinder	29.8	1.1	54.6	1.4	28.1	1.9	48.6	2.9	28.5	1.4	46.1	1.0	60.0	2.8	66.6	1.8

Table 4-2 – Summary of the mean compressive strength results and standard deviations of the quartzitic sandstone specimens

Specimen Dimension (mm)	Mean Compressive Strength (MPa) and Standard Deviation											
	Concrete Mix											
Mix (Aggregate size, concrete strength)	I		J		K		L		M		N	
	09,30		09,50		19,30		19,50		26,30		26,50	
	Quartzitic Sandstone Coarse Aggregate											
100 mm Cube	31.4	1.2	53.3	2.6	32.0	1.0	53.9	1.7	29.6	1.1	49.8	1.3
50 mm diameter Core	32.7	0.8	52.9	1.1	36.2	2.8	57.3	1.2	37.5	1.0	56.7	3.7
70 mm diameter Core	34.3	1.1	55.5	2.9	37.7	1.8	58.3	3.8	38.4	2.7	58.3	3.9
100 mm diameter Core	31.7	0.4	51.8	1.5	30.5	7.0	53.4	2.0	33.1	1.8	50.6	2.8
150 mm diameter Core	31.6	0.7	53.3	1.1	35.7	0.6	55.1	2.0	32.7	0.6	48.5	2.5
70 mm diameter Cylinder	31.2	1.6	52.3	2.0	29.4	2.9	55.6	1.3	32.0	2.6	48.9	3.5
100 mm diameter Cylinder	33.5	0.5	56.9	0.3	33.8	0.8	54.5	3.9	33.5	1.8	46.8	0.5
150 mm diameter Cylinder	32.8	0.6	53.6	1.1	31.1	1.8	52.8	1.4	29.2	1.8	48.0	2.5

As indicated in Table 4-1, the mixes labelled A – H represent the Greywacke specimens and in Table 4-2, Mixes I – N represent the Quartzitic sandstone mixes. The numbers under the mix labels indicate the maximum aggregate size followed by the design strength. The strength column is followed by the standard deviation of the mix

A summary of the results in Table 4-1 and Table 4-2 is illustrated in Figure 4-1, Figure 4-2, Figure 4-3, Figure 4-4 and Figure 4-5. These figures show the compressive strength with regard to the sample size and mix design. The error bars in the figures are the standard deviation of the compressive strength for each scenario. Figure 4-6 illustrates the tested specimens.

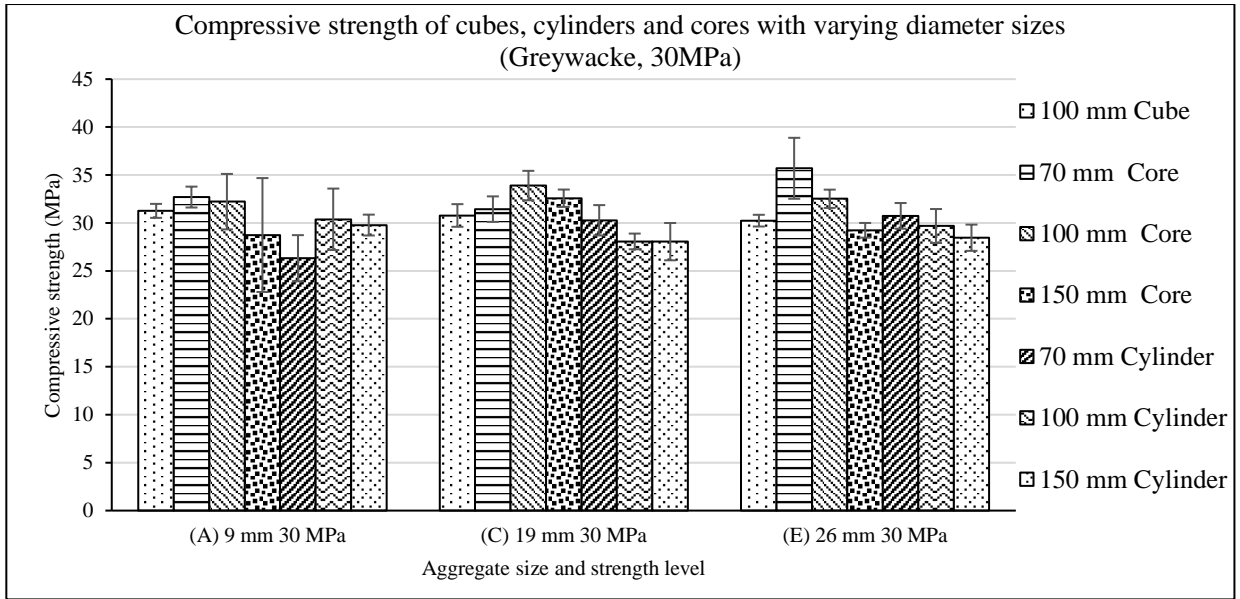


Figure 4-1 – Compressive strength results for greywacke mixes using 30 MPa strength level

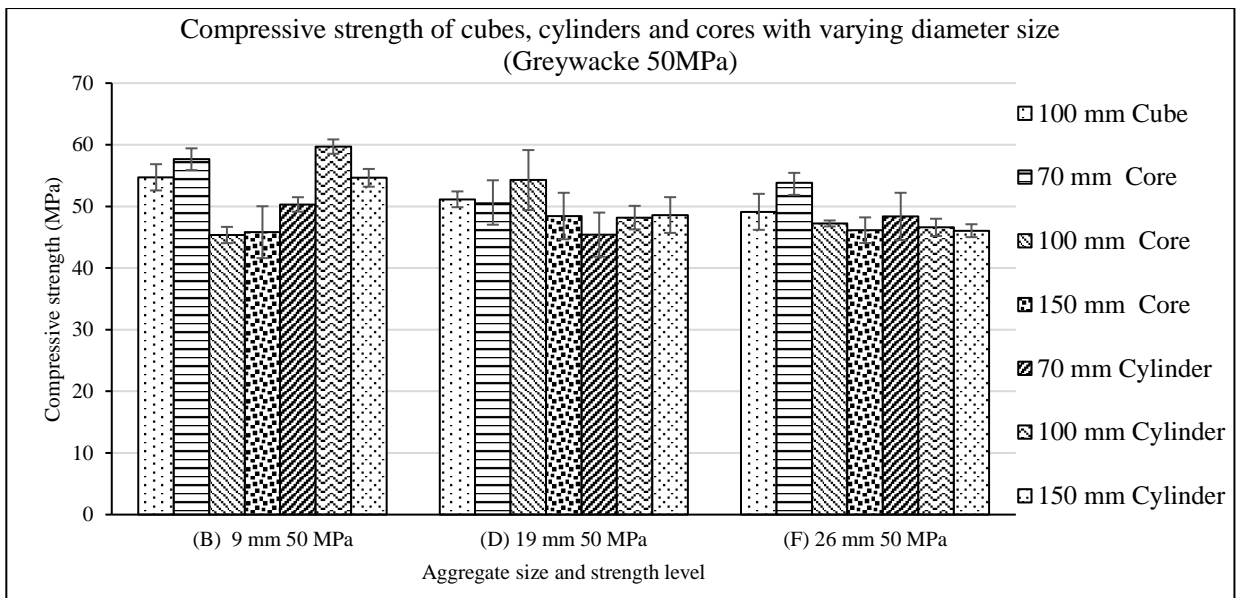


Figure 4-2 – Compressive strength results for greywacke mixes using 50 MPa strength level

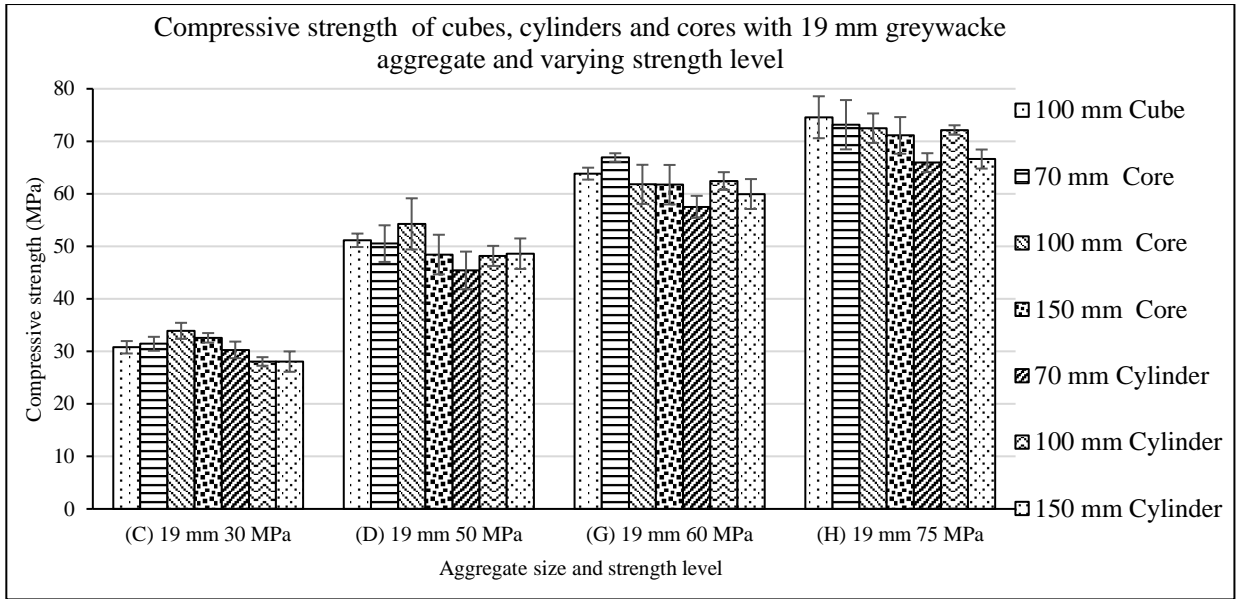


Figure 4-3 – Compressive strength results for greywacke mixes with varying concrete strength

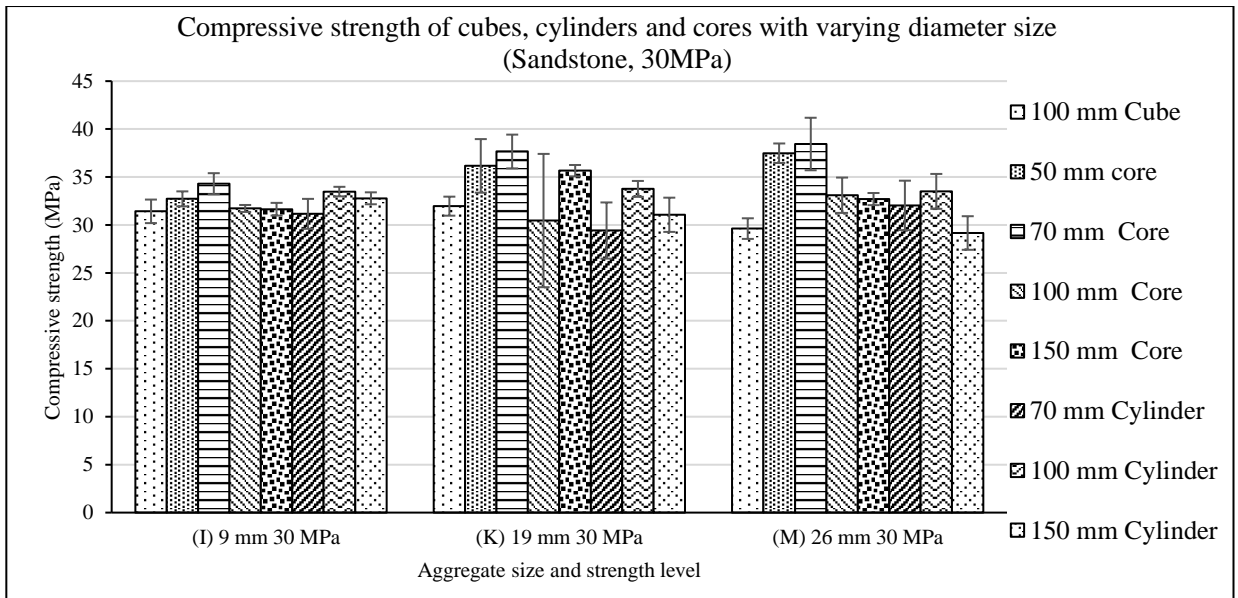


Figure 4-4 – Compressive strength results for sandstone mixes using 30MPa strength level

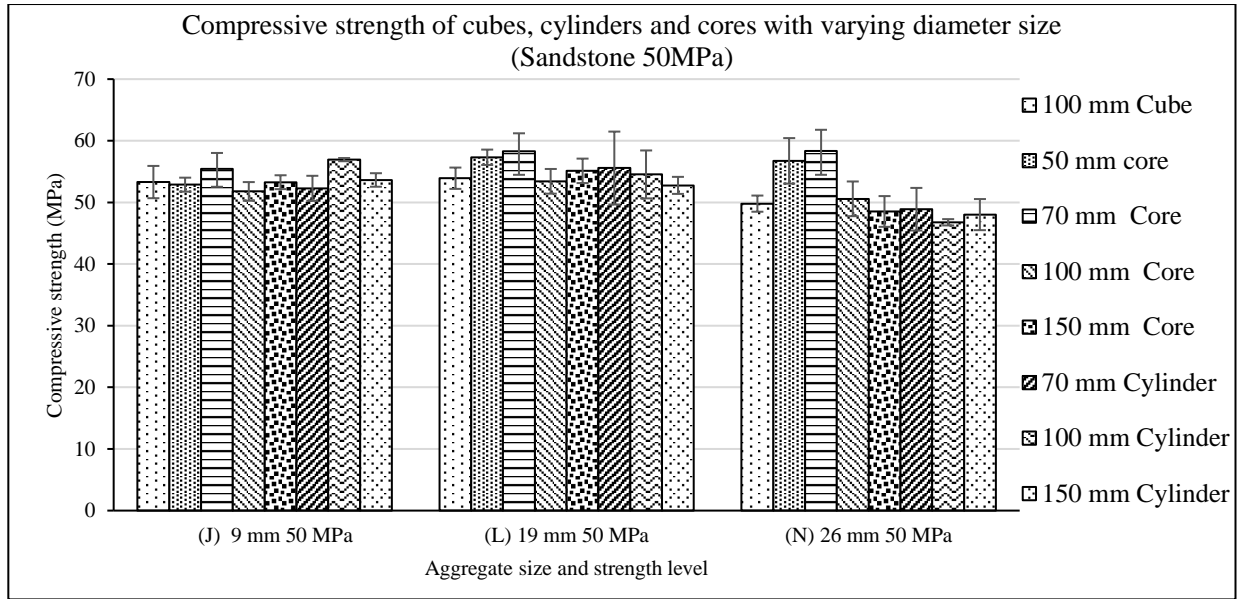


Figure 4-5 – Compressive strength results for sandstone mixes using 50 MPa strength



Figure 4-6 – Storage of tested specimens for analysis of crack patterns

5. Discussion of results

This chapter discusses the results that were obtained during the experimental investigation and the statistical analysis. It further relates the compressive strength of cubes, cores and cylinders, using the experimental data and statistical analysis.

It must be noted, for the statistical investigation, the p-values obtained by the ANOVA analysis, comparing the mean compressive strengths of different variables, were compared to the significance level to identify whether the hypothesis was accepted or rejected. During this analysis, a significance level of 0.05 was used for a confidence interval of 95%. A one-way ANOVA analysis was conducted between two different categories; thus, the F_{crit} value was 5.317.

5.1 Relationship between cube and core compressive strength

The main emphasis of this investigation was to find a universal relationship between standard cube, core and cylinder compressive strength, with a l/d ratio of 1.0. As discussed in Section 2.9, cubes and cores made from the same given concrete normally produce different compressive strengths due to a number of factors (Owens, 2012). Consequently, an experimental plan was created to compare the compressive strengths of cubes and cores, as well as to find factors that may influence the compressive strengths of the different samples.

During this study, the cube and core strengths were compared by eliminating as much variation as possible. The comparison was based on the 100 mm diameter core and 100 mm cube; thus, keeping the overall geometric dimensions constant. The only factor that may influence the strength results was the direction of loading. The cube was loaded perpendicular to the direction of casting; whereas, the core was loaded parallel. This was done to directly compare the core and cylinder strength, as discussed in Section 5.2.

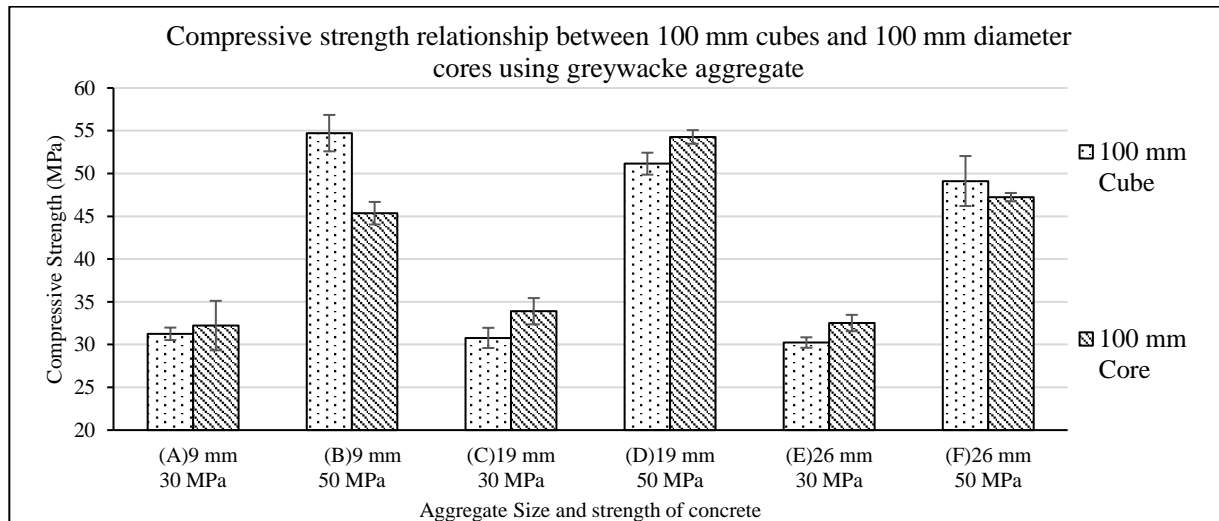


Figure 5-1 – Relating the compressive strength of cubes and cores using greywacke coarse aggregate

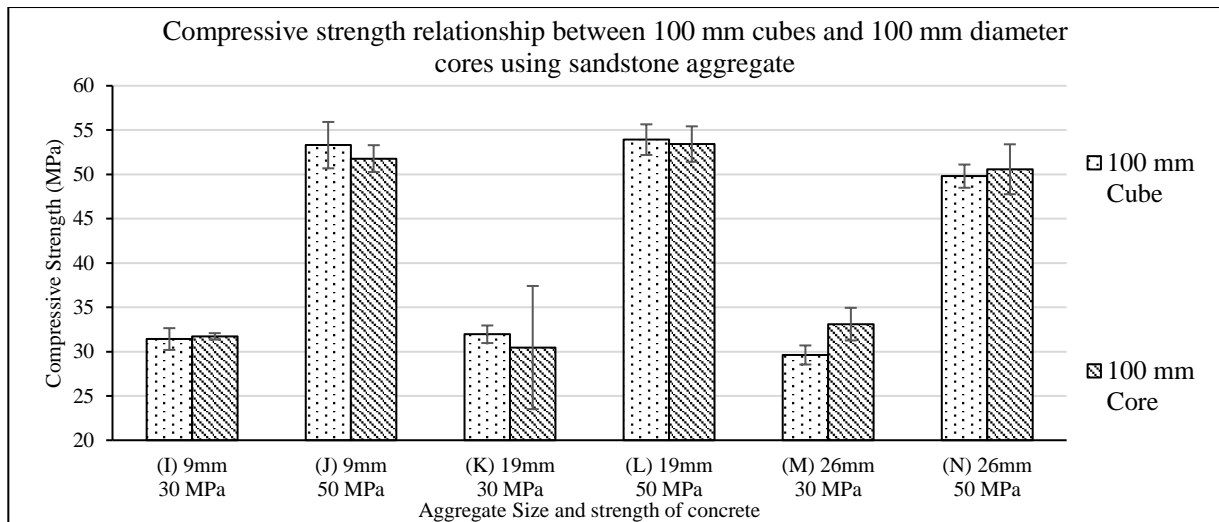


Figure 5-2 – Relating the compressive strength of cubes and cores using quartzitic sandstone coarse aggregate

Table 5-1 – p-values from ANOVA comparing mean compressive strengths of cubes and cores

Cube strength versus core strength		
$\alpha = 0.05$		
	Greywacke	Sandstone
9 mm 30 MPa	0.492	0.614
9 mm 50 MPa	0.000*	0.294
19 mm 30 MPa	0.007*	0.646
19 mm 50 MPa	0.001*	0.684
26 mm 30 MPa	0.002*	0.007*
26 mm 50 MPa	0.194	0.590

* indicates p is less than 0.05

Figure 5-1 and Figure 5-2 illustrated the mean compressive strengths of the 100 mm cubes and cores. The error bars illustrated on the graphs indicate the standard deviation of the mean compressive strengths. Table 5-1 indicate the p-values obtained by the ANOVA analysis of the cube and core compressive strength.

As indicated in the Figure 5-1 and Figure 5-2, there was no general trend between the cube and the core compressive strengths, from both types of aggregate. No general trend was able to be extracted from the data due to the similarity in the compressive strength of the two different specimen types. This was emphasised in Table 5-1 where the p-values obtained from the statistical analysis were predominantly greater than that of the significance level; thus, accepting the null hypothesis. This indicates that the compressive strengths of the 100 mm cubes and cores were predominantly statistically similar. Although, the greywacke aggregate may have produced a number of results that were significantly different, there was no general trend between the compressive strengths and the statistical analysis. Hence, it was deduced this was due to a scatter of results.

Overall, it was presumed that there was no significant difference between the compressive strength of the 100 mm cubes and 100 mm diameter cores. This was emphasized when comparing the strength ratio of the cubes and cores. It was calculated that the average core to cube ratio was 1.01 for both the greywacke and sandstone aggregate. These results were contradictory to what was found in literature; generally, there is a significantly reduced core strength compared to cube strength. The reason for the much lower reduction in strength compared to what is generally perceived was believed to be the manner in which the investigation was performed. The entire investigation was performed in laboratory conditions, where all the procedures that were performed were done in a controlled environment. Additionally, the casting, curing and testing procedures of all the concrete specimens were done in the same manner. As discussed above, there are a number of factors that may influence the strength of in-situ cores, which may not have influenced the core strength in this investigation.

Curing was one of the main factors for the reduced strength of in-situ cores. There are multiple methods and durations that concrete may be cured, depending on the environment in which it is cast. In a laboratory, the specimens are normally placed in a curing tank, where they are submerged in water for 28 days or until the day of testing, to ensure maximised reaction of hydration. However, on-site the method of curing is done by either wrapping or covering the element to prevent the loss of water, but is often not effective. Malhorta (1977) mentioned that the climate in which the element is initially cured has an influence on the compressive strength. The compressive strength of the in-situ concrete is significantly lower than that of the standard specimens tested at 28 days (Malhotra, 1977). These findings were emphasized during an investigation on the reliability of core strength by Khoury *et al.* (2014). Khoury *et al.* (2014) found that the core strengths obtained a compressive strength reduction of 17% compared to the design strength. However, it was observed in the figures that the slabs and beams were cast outdoors and covered with hessian as the curing method. Owing to the hot dry climate in the location where this investigation was held (Alexandria, Egypt), the curing methods used would have not been effective. As a result, variations in curing between standard specimens and core specimens were present. Consequently, this led to a reduced strength of the cores compared to the standard specimens. During the present investigation, all the concrete that was cast was cured in a saturated condition to ensure maximised hydration reaction. Owing to the same condition in which the concrete elements were cured it was believed that equal amounts of hydration was achieved; thus, emphasizing the statistically comparable mean compressive strengths between cubes and cores.

Another factor that may reduce the strength of in-situ cores is the method of compaction (Sangha & Dhir, 1975). There are different methods in which concrete may be compacted, which may influence the degree of compaction and the void ratios. Due to the large surface areas and volumes of concrete poured on a construction site, the most effective method of compaction is by using a poker vibrator. On-site the method in which a standard specimen is compacted is by hand, using a tampering steel rod. This method is as effective as a vibrating table due to the relatively small size of the mould. Due to the small size of a standard specimen, the degree of compaction will be more consistent. Consequently, cores that are obtained from site may have a

reduced compressive strength due to the variation in the degree of compaction over the element that is cast. It was noted in a number of investigations that slabs were cast in which cores were removed; thus, variation in compaction may have been the factor that reduced the strength of the cores. However, during this investigation a vibrating table was used to compact all the concrete in their moulds, to ensure the same degree of compaction between all samples. Owing to this, it was concluded that the degree of compaction had no influence on the compressive strength comparison between the cubes and the cores. Therefore, this emphasises the statistically similar strength between cubes and cores.

The final factor that may influence the strength of cores is drilling damages. Drilling damages were perceived to be one of the main factors that reduced the strength of concrete cores. During the drilling of cores, the drill bit induces shear stresses in the core, that is said to damage the concrete matrix and ITZ (Interfacial transition zone). As a result, these damages would reduce the strength of the core. The possible drilling damages to the core specimens may have been significantly reduced during this investigation due to the time and environment in which the cores were drilled. It was noted that during an investigation by Khoury *et al.* (2014), slabs and columns were cast from which the cores were drilled. Figures in Khoury's *et al.* (2014) investigation indicated that the core drill machine was moved along the slab; however, did not indicate if it was securely fastened during drilling. If the machine was not fastened properly, wobbling may have occurred and induced greater drilling damages to the cores, resulting in a reduced compressive strength. The core drilling machine that was used during the investigation was always securely fastened into the ground; thus, reducing wobbling of the machine. The drill bits that were used were sharp and well maintained, ensuring a clean cut through the element that was cast. The rate of revolution of the drill bit was adjusted according to the size of the sample being drilled. As a result, there was reduced coring damage induced to the cores, emphasizing the similar results obtained for the cube and core strengths.

It was concluded that the similarity in results between the cube and core strengths was due to the controlled environment and similar manner in which the concrete samples were cast, cured, prepared and tested. Overall, it was deemed that the compressive strength between cubes and cores of the same concrete (that is cast, cured prepared and tested in the same manner) will produce similar mean compressive strengths. Furthermore, it can be deduced that the difference in compressive strength between standard cubes and in-situ cores, removed from a construction site, may be attributed to the manner in which the concrete is compacted and cured on-site, as well as the manner in which cores are removed and prepared for testing.

It was found in SANS 10100-2:2014, for the acceptance of concrete in a structure, the mean in-situ core compressive strength from three cores must be at least 80% of the specified strength. Therefore, it was found during this investigation that the 80% factor is stipulated for the difference in curing between a standard specimen and in-situ concrete. Additionally, the factor is stipulated for the drilling damages that may occur on site, where anchoring the drill machine may be difficult.

Furthermore, there are a number of other factors that may influence the core strength, which would result in a different relationship between cube and core compressive strength. These factors include diameter size of the core, aggregate type and maximum aggregate size. These factors were further investigated and are discussed in depth below.

5.1.1 Diameter Size

The size of a sample plays an important role in concrete compressive strength. The diameter was an important consideration during this research as it influenced the specimen size since the length/diameter (l/d) ratio was restricted to 1.0. According to Griffith's hypothesis, as the standard specimen size increases, the compressive strength decreases, due to the higher possibility that there may be a flaw in the specimen. This factor is generally accepted for concrete strength testing. Furthermore, a number of factors including w/c ratio, elastic modulus, maximum aggregate size and aggregate type may also influence the strength of different size samples.

Generally, the inverse (to Griffin's hypothesis) is found when testing the compressive strength of in-situ cores with regard to the size of the specimen. This is commonly ascribed to the ratio of cut surface area to volume, which increases as the diameter decreases. Hence, there is a higher possibility of coring damage that may affect the concrete matrix in smaller cores compared to larger cores. Consequently, diameter size was an important aspect in this investigation.

Figure 5-3 and Figure 5-4 illustrates the influence of the diameter size on the compressive strength of the core specimens. These figures also included the cube compressive strength as a reference. Table 5-2 indicates the p-values obtained from the ANOVA analysis of the different diameter sizes.

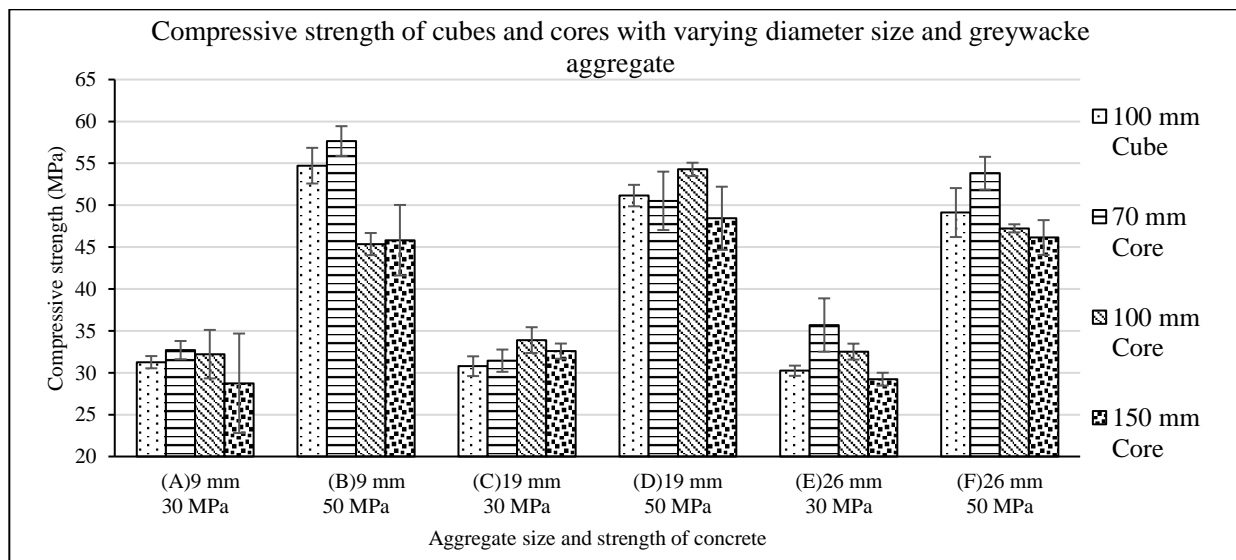


Figure 5-3 – Compressive strength of cubes and cores with varying diameter size and varying maximum aggregate size (Greywacke)

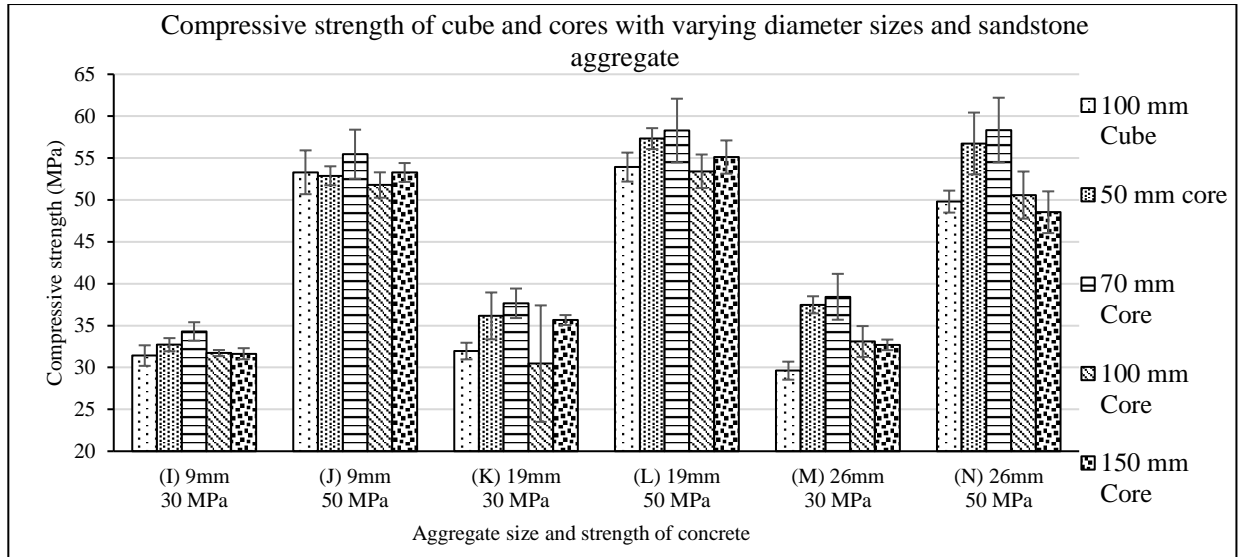


Figure 5-4 – Compressive strength of cubes and cores with varying diameter size and varying maximum aggregate size (Sandstone)

Table 5-2 – p-values from ANOVA comparing core diameter sizes

$\alpha = 0.05$						
	70-100	100-150	70-150			
(A) 9 mm 30 MPa	0.733	0.273	0.179	* indicates p is less than 0.05		
(B) 9 mm 50 MPa	0.000*	0.822	0.000*			
(C) 19 mm 30 MPa	0.027*	0.137	0.152			
(D) 19 mm 50 MPa	0.046*	0.009*	0.391			
(E) 26 mm 30 MPa	0.065	0.000*	0.002*			
(F) 26 mm 50 MPa	0.000*	0.282	0.000*			
	70-100	100-150	70-150	50-70	50-100	50-150
(I) 9 mm 30 MPa	0.001*	0.819	0.002*	0.031*	0.032*	0.046*
(J) 9 mm 50 MPa	0.037*	0.114	0.159	0.103	0.230	0.591
(K) 19 mm 30 MPa	0.055	0.134	0.043*	0.340	0.127	0.706
(L) 19 mm 50 MPa	0.035*	0.214	0.138	0.606	0.006*	0.069
(M) 26 mm 30 MPa	0.007*	0.658	0.002*	0.483	0.002*	0.000*
(N) 26 mm 50 MPa	0.007*	0.258	0.001*	0.522	0.018*	0.003*

The comparison of the 70 and 100 mm diameter cores may be seen in Table 5-2, column 2. It was noted that the p-values obtained from the statistical analysis were predominantly less than that of the significance level; thus, rejecting the null hypothesis. This indicates that the strengths of the 70 and 100 mm cores were significantly different. When comparing the strengths of the diameters in Figure 5-3 and Figure 5-4, it was found that the 70 mm core commonly produced a higher strength compared to the 100 mm core. It was calculated that the 70 mm core produced results that were, on average, 6.4% and 13.2% higher than that of the 100 mm core for the greywacke and sandstone aggregate mixes, respectively. Owing to the analysis indicating that

the mean results were primarily significantly different, it was deduced that overall, the 70 mm core obtains a compressive strength 9.8% higher than that of the 100 mm core.

Similar results were found during the comparison of the 70 mm and 150 mm diameter core strength. The ANOVA results of the 70 mm and 150 mm diameter cores may be seen in Table 5-2 column 4. According to the statistical analysis the mean strengths were predominantly different. However, less groups were rejected compared to the 70 – 100 mm core comparison. This was due to the larger standard deviation produced by the 150 mm greywacke cores. Similar to the 70 – 100 mm core comparison, the smaller 70 mm cores produced results that were on average 12.0% and 10.3% higher than that of the larger 150 mm cores, for the greywacke and sandstone aggregate mixes respectively. Owing to the analysis indicating that the mean results were primarily significantly different, it was deduced that overall the 70 mm core obtains a compressive strength 11.1% higher than that of the 150 mm core.

A different outcome was established when statistically comparing the strengths of 100 mm and 150 mm cores. The ANOVA results of the 100 mm and 150 mm diameter cores may be seen in Table 5-2, column 3. The p-values obtained from the analysis were predominantly greater than the significance level; thus, the null hypothesis was accepted. This indicates that the strength of the 100 mm and 150 mm cores were predominantly statistically similar. When comparing the compressive strengths of the different diameters cores, this occurrence was expected as the actual strengths were similar and the standard deviations overlapped. Owing to the analysis indicating that the mean results were statistically similar it was deduced 100 mm and 150 mm cores produce statistically comparable compressive strengths.

A 50 mm diameter core was introduced during the casting of the quartzitic sandstone batch. The ANOVA results of the 50 mm and 70 mm diameter cores may be seen in Table 5-2, column 5. The p-values produced were greater than the significance value; thus, the null hypothesis was accepted. This indicates that the strength of the 50 mm and 70 mm cores were statistically similar. However, when visually comparing the strengths of the different diameters, in Figure 5-4, it was clear that the 50 mm core produced a slightly lower strength compared to the 70 mm diameter core. Nevertheless, as a result of the statistical analysis it was deduced that 50 mm and 70 mm cores produce statistically comparable compressive strengths. Due to the similarity between the strengths of the 50 mm and 70 mm samples, the statistical results that were obtained and discussed above between the 70 – 100 mm and 70 – 150 mm were comparable to the 50 – 100 mm and 50 – 150 mm diameter cores.

The results obtained during this investigation were contradictory to findings commonly establish in literature. As mentioned in above, in previous research it was commonly found that as the core size decreases, there is a corresponding decrease in strength (Tuncan *et al.*, 2008; Omer *et al.*, 2010; Khoury *et al.*, 2014). The general assumption to these outcomes were; as the core diameter decreases, there was an increase in potential damage to the core during drilling. This is due to the increase in cut surface area to volume ratio in smaller cores. As discussed above, these possible drilling damages to the core samples may have been significantly reduced during this investigation due to the time, environment and machinery used to drill the cores.

Another factor that may have contributed to the conflicting results was the age at which the cores were drilled. During the drilling procedure, direct shear stresses are applied to the concrete samples by the core drill. Concrete is a heterogeneous material and contains elements that are stiffer than others. The coarse aggregate encompasses a higher stiffness compared to the hardened cement paste, in normal concrete. Therefore, during drilling shear forces attempt to shift the coarse aggregate. Concrete that has a high w/c ratio or is at an early age strength may not contain a strong ITZ between the coarse aggregate and the concrete matrix. Thus, during the drilling, disruptions to the concrete matrix and ITZ may occur which will lead to a reduced strength of the specimen. An investigation by Arioz *et al.* (2007) and Tunçan *et al.* (2008) concluded that coring at an early age (7 days) will have negative influence on the compressive strength due to the induced damages to the concrete matrix. It was further concluded that these damages at an early age were more prominent in smaller cores due to the increased cut surface area to volume ratio. However, during the present investigations the coring damages were reduced as the cores were drilled at 21 days. It was believed that at 21 days the concrete matrix and ITZ would have gained sufficient strength to resist damages during coring. Owing to the 70 mm cores obtaining the highest strength, it was concluded that the influence of early age coring was eliminated during this study. However, cores are rarely taken before 28 days. Normally, cores are only taken if the standard 28-day compressive strength does not conform with specifications or the strength of an old structure is unknown. Therefore, the influence of early age coring is generally eliminated in practice as well.

With regard to the comparison of the 100 – 150 mm core size, it was deduced that the mean compressive strengths were comparable. This result was similar to the outcomes found in literature (Tokyay & Özdemir, 1997; Omer *et al.*, 2010; Khoury *et al.*, 2014). It is said that as the specimen size increases the factors that may influence the strength of the specimen decrease.

From the investigation of the influence of core diameter size, it was found that the 70 mm diameter core produced the highest compressive strength compared to the 50 mm, 100 mm and 150 mm diameters cores. The 50 – 70 mm and 100 – 150 mm core comparison both obtained results that deemed their mean strengths statistically comparable. Therefore, the concluding remarks of the core compressive strength with respect to diameter size were contradictory to what is generally found in literature. It was found that the smaller the specimen, the higher the compressive strength. It was also found that core specimens, 100 mm in diameter or larger, will produce similar compressive strength results. Owing to the discussion in Section 5.1, the 100 mm core still provides the most comparable strengths to the 100 mm cube.

5.1.2 Aggregate size

Another aspect that was investigated in this study was the effect that the maximum aggregate size has on the relationship between cube and core compressive strength. The maximum aggregate size plays an important role in the compressive strength of standard specimens and drilled cores. As the size of the aggregate reduces, the amount of entrapped air increases. According to ACI 211.1-91, there is an increase of 1.5% entrapped air when using a nominal maximum aggregate size of 10 mm compared to 25 mm. As mentioned above, previous

investigations found that the reduced in-situ compressive strength obtained by a core may be due to the drilling damages. These drilling damages are created by the shear forces produced during coring that may cause disruptions in the ITZ. Therefore, the larger the surface area of aggregate being drilled through, the increased possibility of disruptions to the ITZ.

SANS 5865:1994 Clause 5.3 stipulates that the minimum core size must be three times the maximum size of the coarse aggregate. This is to ensure that the specimen tested has a relatively homogenous matrix. However, this study included core samples that failed to meet this criterion.

During the investigation, the strengths obtained by the concrete using different maximum aggregate sizes were compared to each other with respect to the same aggregate type and same specimen diameter. It was also important to consider the collective response of compressive strength by the maximum aggregate size and the size of the specimen being tested.

Figure 5-5 and Figure 5-6 illustrates the influence of maximum aggregate size on the compressive strength of the cube and core specimens, with respect to diameter size. Table 5-3 indicates the p-values obtained from the ANOVA analysis of the different maximum aggregate sizes.

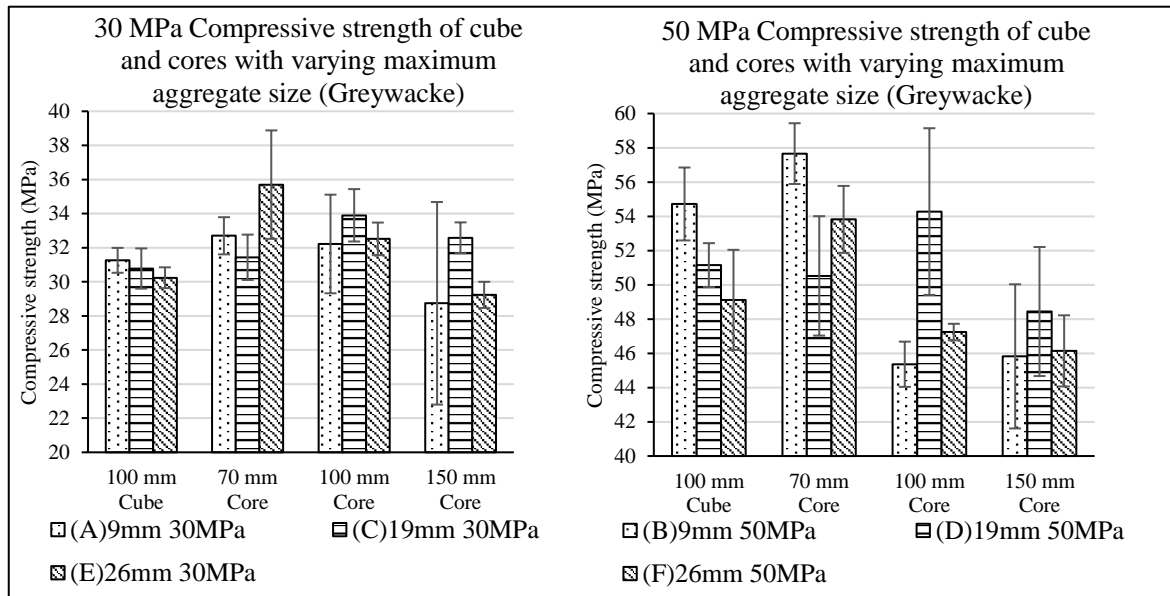


Figure 5-5 – Compressive strength of cubes and cores with varying maximum aggregate size using greywacke coarse aggregate

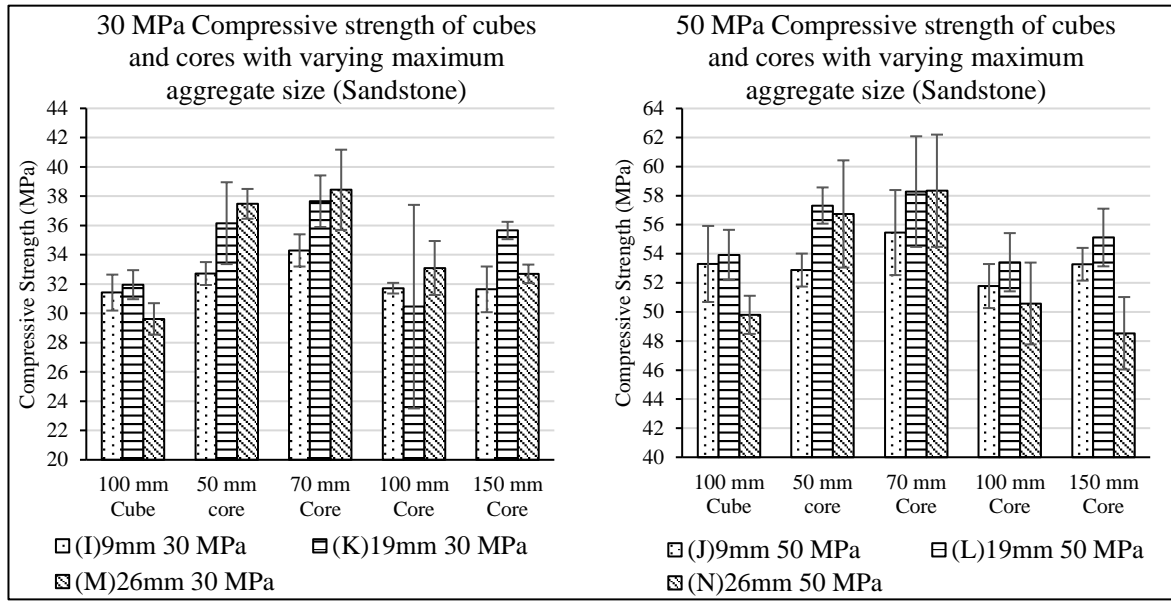


Figure 5-6 – Compressive strength of cubes and cores with varying maximum aggregate size using sandstone coarse aggregate

Table 5-3 – p-values from ANOVA comparing varying maximum aggregate sizes

Aggregate			
$\alpha = 0.05$			
Greywacke 30 MPa			
	9mm - 19mm	19mm - 26mm	9mm - 26mm
Core 70	0.122	0.025*	0.078
Core 100	0.284	0.126	0.831
Core 150	0.191	0.000*	0.858
Sandstone 30 MPa			
Core 50	0.029*	0.350	0.000*
Core 70	0.007*	0.607	0.014*
Core 100	0.696	0.435	0.139
Core 150	0.000*	0.000*	0.032*

Aggregate			
$\alpha = 0.05$			
Greywacke 50 MPa			
	9mm - 19mm	19mm - 26mm	9mm - 26mm
Core 70	0.004*	0.102	0.012*
Core 100	0.000*	0.000*	0.017*
Core 150	0.330	0.266	0.882
Sandstone 50 MPa			
Core 50 mm	0.000*	0.748	0.056
Core 70 mm	0.225	0.981	0.220
Core 100 mm	0.182	0.103	0.426
Core 150 mm	0.109	0.002*	0.005*

* indicates p is less than 0.05

Figure 5-5 and Figure 5-6 illustrate the influence that maximum aggregate size may have on the compressive strength of concrete. It was noticed that the maximum aggregate size has an influence on the compressive strength in conjunction with the diameter size of the specimen and the type of aggregate used.

During the analysis of the smaller specimens (70 mm diameter) it was evident that with the increase in maximum aggregate size, the mean compressive strengths were predominantly significantly different. Although there was no dominant trend in the greywacke aggregate, there was a distinct trend in the sandstone aggregate. It was apparent that as the maximum aggregate size increased the strength of the specimen increased. It was found that for the greywacke aggregate, the 19 mm maximum aggregate size produced the lowest strength compared to the

other aggregate sizes; however, this was assumed to be a scatter in the results. It was found that the 26 mm maximum aggregate size of the sandstone aggregate produced the highest strength. It was calculated that there was a 6% increase in strength when increasing the maximum aggregate size from 9 to 26 mm.

From the analysis, the 100 mm and 150 mm cores produced statistically similar results and strength trends, with respect to the mean compressive strength, with different maximum aggregate sizes. As the core size increased to 100 mm diameter or larger, it was established that there was less of an effect from the differences in maximum aggregate size. Figure 5-7 illustrates the ratio of compressive strength with regard to diameter size. It can be seen that the 100/150 mm strength ratio, with regard to most the aggregate sizes, was nearest to 1.0; thus, emphasizing the similarity in results. The statistical results emphasized this as the different aggregate sizes produced mean compressive strengths that were statistically similar for the 100 mm and 150 mm core specimens. The similarity in mean strength was often a result of the large standard deviation in the results. It was apparent in Figure 5-5 and Figure 5-6 that the 19 mm maximum aggregate size often produced the highest compressive strength compared to the other maximum aggregate sizes. However, based on the statistical analysis, it was deduced that the difference in maximum aggregate size had little effect on the strengths of 100 mm and 150 mm core specimens.

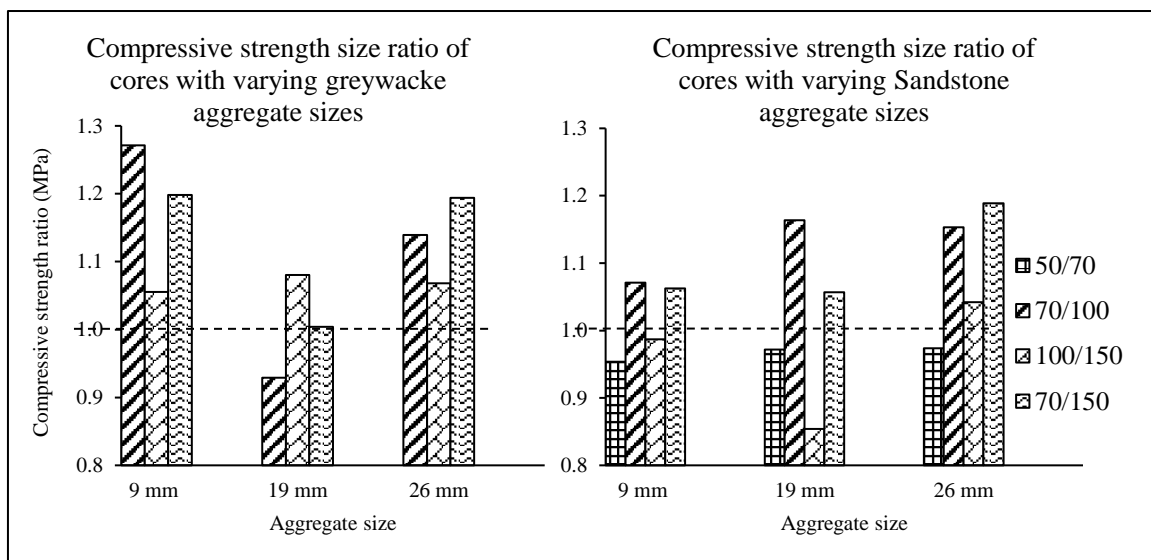


Figure 5-7 – Compressive strength size ratio of cores with varying maximum aggregate sizes

Overall, it was established that the maximum aggregate size does have an effect on the compressive strength of cores; however, the influence of the maximum aggregate size on the strength of the concrete was in coherence with the diameter size of the core. The findings observed in this investigation were contradictory to what was found in literature. In literature, it is understood that as the maximum aggregate size increases and the specimens size decreases, there should be a decrease in compressive strength. The proposed reason for the decrease in strength is the increased drilling damages that may be attributed to the large aggregate particles. However, the opposite was observed in the present investigation. A possible reason for this contradictory outcome was the minimal drilling damages inflicted on the smaller diameter

samples due to the controlled conditions in which the cores were drilled, as discussed in Section 5.1.1. Although different aggregate types were used, similar trends were witnessed between the different aggregate sizes. The trends were slightly more clear with the use of the sandstone aggregate. This may be due to the different aggregate properties. From literature, it was believed that the stiffness of quartzitic sandstone is less than that of other aggregates such as greywacke. Therefore, less shear forces will be absorbed by the coarse aggregate during drilling which, will lead to smaller disruptions in the ITZ. This could be a reason why the trend was less prominent in the greywacke aggregate.

The increased strength in the smaller cores with large aggregate sizes may be attributed to the interaction that the aggregate had on the stress flow during loading. It is well known that the stress flow and crack pattern in concrete under load will flow through the path of least resistance i.e. through the weaker ITZ. However, it was found in smaller cores, such as the 50 mm and 70 mm diameter, that the stress flow was forced into the hour glass shape due to the small size of the specimen and the fixity of the core edges to the platens. Therefore, it was often found that the crack pattern flowed through the aggregate and not the ITZ due to the less failure energy required. Thus, the aggregate strength would have an influence on the compressive strength. Due to the coarse aggregate generally being the strongest material in normal strength concrete, the aggregate will influence the strength in these situations. Whilst the compressive strength was higher in these situations, it was believed that it was a false idea of the concrete strength as the aggregate had a large influence. This was discussed in further detail below.

As stipulated in SANS 5865:1994, the minimum diameter of the core must be three times the maximum aggregate size; however, the preferable diameter size is 100 mm. It was noticed for the specimen diameters that did not obey these stipulations, although the results were contradictory to what was generally found in literature, the strengths were significantly higher than that of the specified and cube strength. This emphasizes that the interpretation and equating of small core specimens that do not obey the stipulation, in SANS 5865:1994, will produce estimated strengths that are significantly different to the standard tests. It was also found that core specimens with a diameter 100 mm or larger produce the most similar, with regard to all maximum aggregate sizes, compressive strength results compared to 100 mm cube. Thus, emphasizing for the most accurate comparison in cube and core strength, the dimensional size should be 100 mm or greater; or the diameter size of the core and breadth of the cube must remain constant.

It is important to be aware of the difficulties when relating the strength of cores, of various sizes, to the strength of a standard test. It is also authoritative to obey the stipulations and recommendations that are given in national standards to obtain the most comparable results when testing and interpreting core compressive strength as well as attempting to relate it to the standard specimen strength.

5.1.3 Concrete strength level

The final aspect that was considered in this investigation was the effect that strength class may have on the influence of core strength, with respect to multiple dimensional sizes, as well as, the relationship between cube and core compressive strength. During this investigation, only 19 mm greywacke coarse aggregate size was used. The strength levels selected were 30, 50, 60 and 75 MPa.

Figure 5-8 illustrates the influence of the diameter size on the compressive strength of the core and cube specimens with increasing concrete strength level. Table 5-4 indicates the p-values obtained by the ANOVA analysis comparing the mean compressive strengths of various core diameter sizes and the mean compressive strengths of cubes and cores, as the strength level increases.

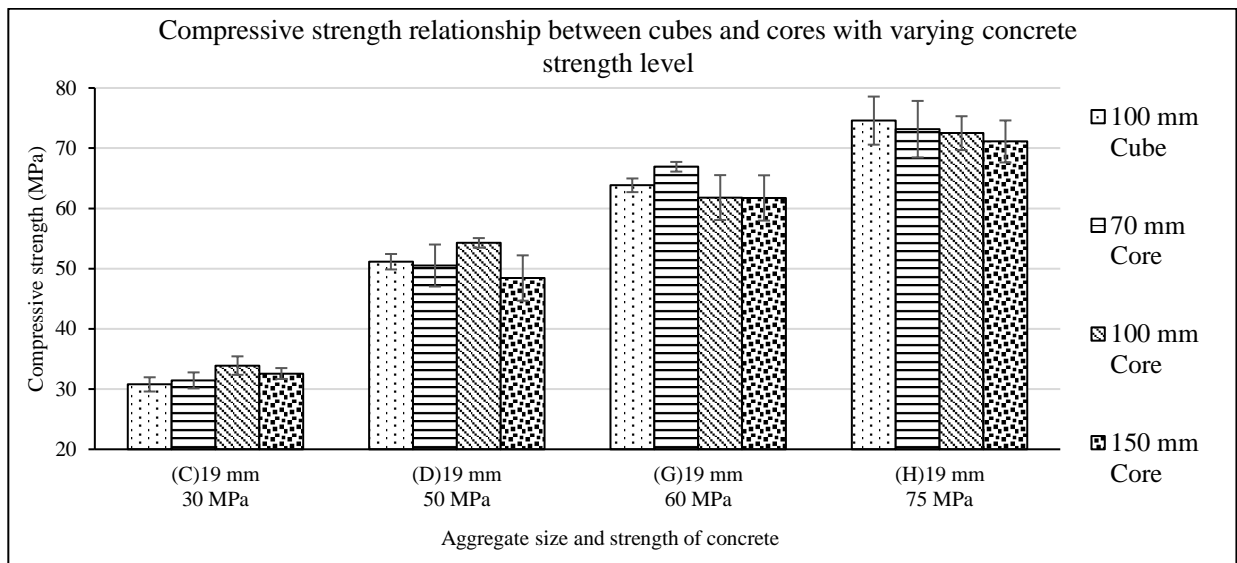


Figure 5-8 – Compressive strength of cubes and cores with varying diameter sizes using greywacke coarse aggregate

Table 5-4 – p-values from ANOVA comparing compressive strengths of different size core specimens as well as cubes and cores

Cube versus Core				Cores			
$\alpha = 0.05$				$\alpha = 0.05$			
	Cube - 70	Cube - 100	Cube - 150		70-100	100-150	70-150
(C) 19 mm 30 MPa	0.431	0.007*	0.027*	(c) 19 mm 30 MPa	0.027*	0.137	0.152
(d) 19 mm 50 MPa	0.7103	0.001*	0.1615	(d) 19 mm 50 MPa	0.046*	0.009*	0.391
(g) 19 mm 60 MPa	0.001*	0.2755	0.2662	(g) 19 mm 60 MPa	0.017*	0.980	0.017*
(h) 19 mm 75 MPa	0.6202	0.3686	0.1826	(h) 19 mm 75 MPa	0.794	0.458	0.458

* indicates p is less than 0.05

As demonstrated in Figure 5-8 and Table 5-4, the cube and core mean compressive strengths were compared to each other. As shown in Table 5-4, the null hypothesis was predominately accepted; thus, indicating that the mean compressive strengths were statistically similar.

However, it was distinguished at the 30 MPa strength levels that mean results between the cubes and the cores were predominantly significantly different. But, as the strength level increased, these results gradually became statistically similar. This may have been due to the smaller coefficient of variation in the lower strength concrete, as seen in Figure 5-9. Therefore, there was less standard deviation in which the results could overlapped. The higher strength results obtained by the cores compared to the cube, at 30 MPa, was due to the direction of cast. The cubes were loaded perpendicular to the direction of cast; whereas, the cores were loaded parallel. The higher strength concrete specimens were not effected as significantly. This was a result of the low w/c ratio causing a reduction in internal bleeding and strengthening of the ITZ.

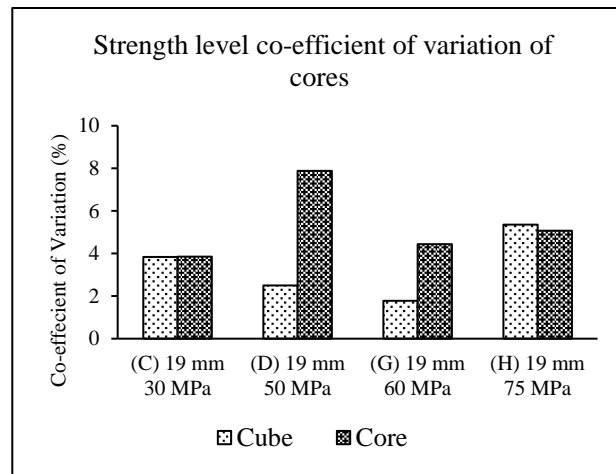


Figure 5-9 – Strength level co-efficient of variation

Therefore, as the strength level of concrete increases, there was a decrease in mean compressive strength variation between cores and cubes. As a result, there was an increase in the similarity between mean compressive strength results of various diameter sizes and cube strengths. Additionally, as the strength increases to values exceeding 50 MPa, there was no significant difference between the mean compressive strength of cubes and cores. This was expected as the increase in strength level would strengthen the concrete matrix and ITZ; thus, reducing potential damages to the core during drilling. Additionally, there would be a reduced influence due to the direction of cast versus loading as the bleeding would be reduced. However, as the strength level increases, there is a greater standard deviation in compressive strength results in a single batch.

Table 5-4 indicates similar statistical results as discussed in Section 5.1.1, where the mean strength of the 70 mm and 100 mm diameter cores produced results that were predominantly significantly different and the 100 mm and 150 mm cores, statistically similar.

When analysing the compressive strengths, there was no trend in the strength difference between the 70 mm and 100 mm core as the strength level increased. However, as discussed in Section 5.1.1, it was found that the 70 mm core obtained a significantly higher strength than the 100 mm core. Although the data for the 30 and 50 MPa strengths show otherwise, this was due to a scatter in results. As the strength level increases, the difference in strengths between the size of the specimens reduces. This was emphasized as the strength level of the 75 MPa batch produced results that were all statistically similar.

It was noted, the comparison of the 100 mm and 150 mm core mean compressive strengths were statistically similar. This was predicted following the results that were obtained in Section 5.1.1. It was observed (although not statistically different) that the 100 mm cores were slight stronger than the 150 mm cores. It was found that the 100 mm cores were on average 4.5% higher in strength, which is consistent with literature. As a result of the statistical analysis being predominantly similar and the small difference in strength, it was deduced that the 100 mm and 150 mm cores produced comparable results as the strength level increased.

It could be argued that as the concrete strength level increases, the mean compressive strength obtained from different size core specimens gradually becomes similar. This phenomenon was witnessed as the p-values increased with the increase in strength level. Finally, the 75 MPa mean strengths were deemed statistically similar with respect to all core sizes and all core size strengths versus cube strengths. Therefore, as the strength level increases, the mean strength variation between specimen type and size decreases. This was expected as the increase in strength level would strengthen the concrete matrix and ITZ.

5.2 Relationship between cylinder and core compressive strength

Further investigation in this study was done on the relationship between cylinder and core compressive strength. This was done to analyse the affect that the wall of a moulded cylinder would have on the compressive strength of concrete compared to the wall of a drilled core. In literature, it is commonly found that the compressive strength of cores are usually lower than the compressive strengths of cylinders, due to several factors that can influence core strength such as drilling damages and site curing, as discussed in Section 5.1 (Neville, 2011). Normally, the strength relationship between cores and cylinders are done with an aspect ratio of 2.0, which commonly intensifies the influences on core strength. However, during this study the cylinder and core strengths were compared using a l/d ratio of 1.0. This was to remain in the scope of testing core compressive strength in South Africa. Furthermore, the strength comparison of the cylinders and cores was done using matching diameter sizes to reduce the affect that size may have on concrete strength.

Figure 5-10, Figure 5-11 and Figure 5-12 illustrate the mean compressive strengths of the cores and cylinders. The error bars illustrated on the graph indicate the standard deviation of the mean compressive strength. Table 5-5 indicate the p-values obtained by the ANOVA analysis of the mean strengths of the cores and cylinders.

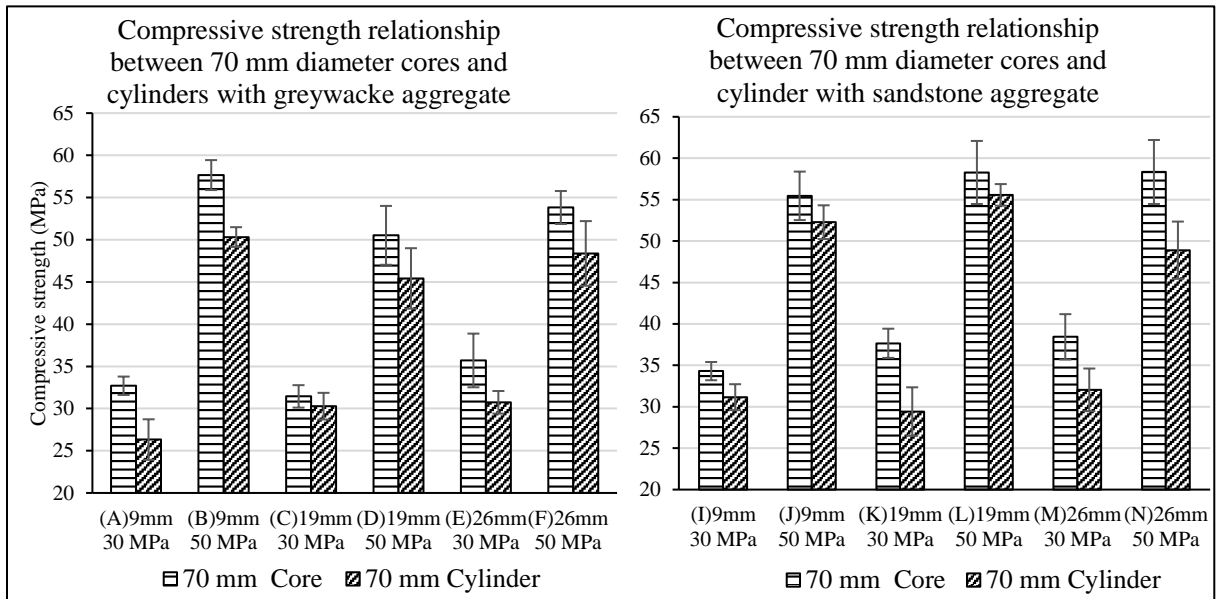


Figure 5-10 – Relating the compressive strength of cores and cylinders with a 70 mm diameter

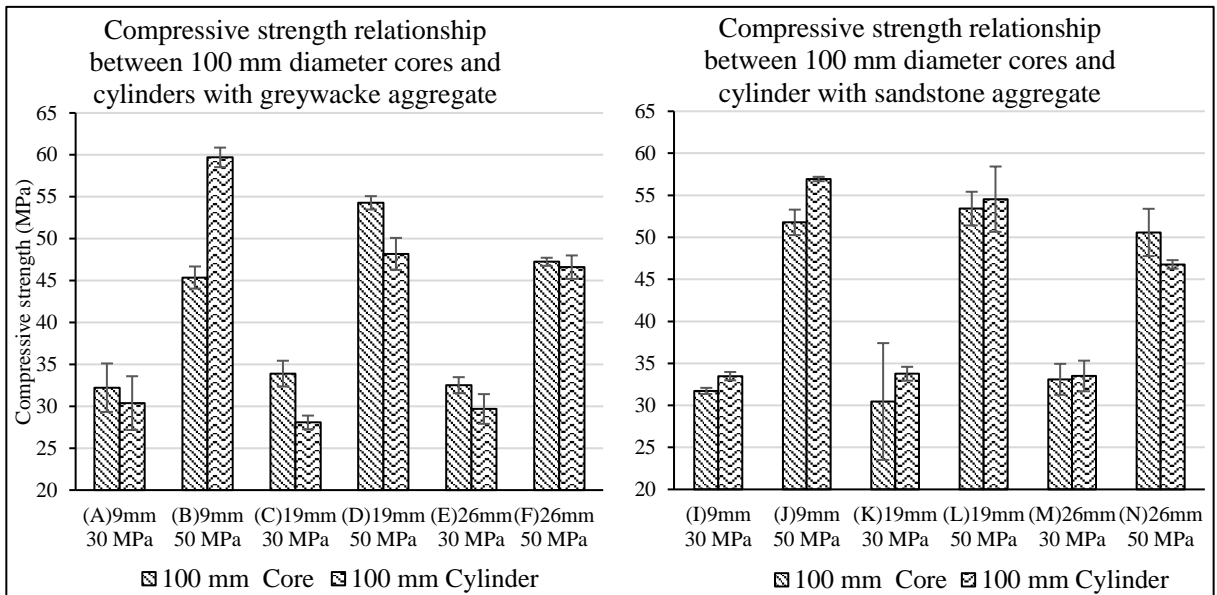


Figure 5-11 – Relating the compressive strength of cores and cylinders with a 100 mm diameter

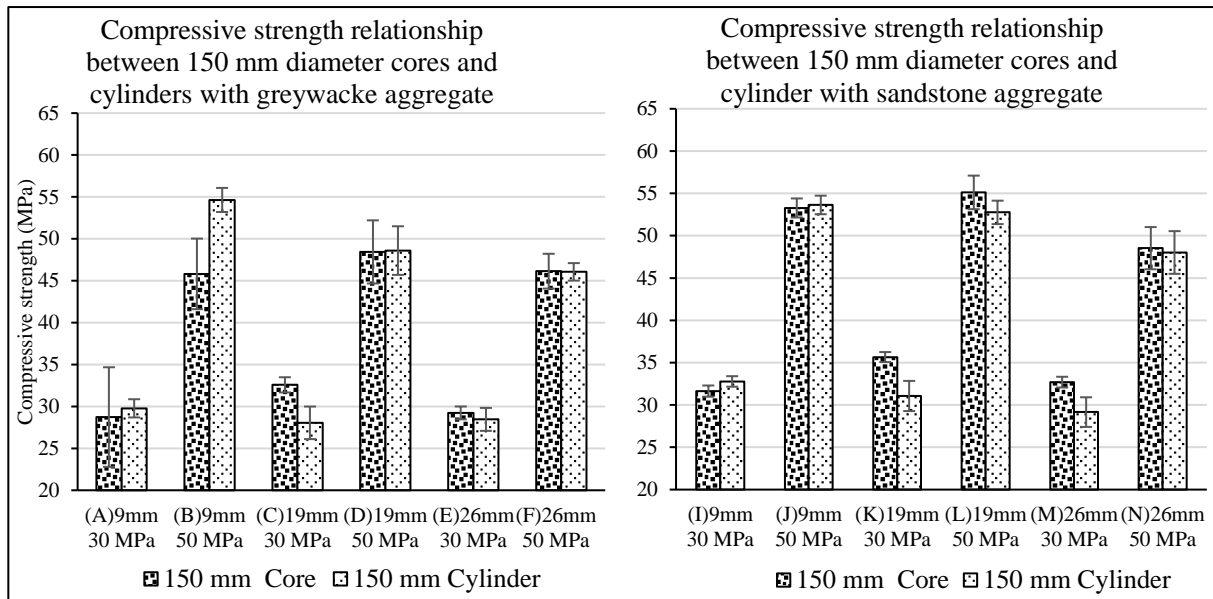


Figure 5-12 – Relating the compressive strength of cores and cylinders with a 150 mm diameter

Table 5-5 – p-values obtained from the ANOVA comparing mean compressive strengths of cores and cylinders and core and cylinder diameter size

(A) Core and Cylinders				(B) Cylinder sizes			
$\alpha = 0.05$				$\alpha = 0.05$			
	70	100	150		70-100	100-150	70-150
(A) 9 mm 30 MPa	0.000*	0.368	0.710	(A) 9 mm 30 MPa	0.045*	0.702	0.011*
(B) 9 mm 50 MPa	0.000*	0.000*	0.002*	(B) 9 mm 50 MPa	0.000*	0.000*	0.001*
(C) 19 mm 30 MPa	0.245	0.000*	0.001*	(C) 19 mm 30 MPa	0.022*	0.981	0.064
(D) 19 mm 50 MPa	0.052	0.000*	0.942	(D) 19 mm 50 MPa	0.167	0.794	0.161
(E) 26 mm 30 MPa	0.012*	0.013*	0.302	(E) 26 mm 30 MPa	0.317	0.258	0.029*
(F) 26 mm 50 MPa	0.022*	0.362	0.940	(F) 26 mm 50 MPa	0.357	0.509	0.162
(I) 9 mm 30 MPa	0.006*	0.000*	0.023*	(I) 9 mm 30 MPa	0.013*	0.085	0.063
(J) 9 mm 50 MPa	0.081	0.000*	0.622	(J) 9 mm 50 MPa	0.001*	0.000*	0.225
(K) 19 mm 30 MPa	0.001*	0.323	0.001*	(K) 19 mm 30 MPa	0.013*	0.015*	0.316
(L) 19 mm 50 MPa	0.166	0.583	0.061	(L) 19 mm 50 MPa	0.583	0.363	0.008*
(M) 26 mm 30 MPa	0.005*	0.739	0.003*	(M) 26 mm 30 MPa	0.331	0.005*	0.073
(N) 26 mm 50 MPa	0.004*	0.017*	0.755	(N) 26 mm 50 MPa	0.209	0.309	0.658

* indicates p is less than 0.05

During the compressive strength analysis between cylinders and cores, it was found that the diameter size had a large influence on the strength. This was due to different factors that influenced the cylinder and the core compressive strengths.

As illustrated and indicated in Figure 5-10 and Table 5-5 (A), column 2, the 70 mm core produced compressive strengths that were significantly different and higher compared to the cylinder. The core strength ranges between 3.8% and 28.0% higher than the cylinder strength with an average of 14.7%. At first this was considered to be unusual as it was expected that the

cylinder and core would produce similar strength. However, when comparing the compressive strength of different size cylinders, it was found that this was not the case. It was found that 70 mm diameter cylinder produced the lowest compressive strength compared to the larger cylinders. It was calculated that the 70 mm cylinder produced results that were on average 3.8% lower than that of the 100 mm cylinder. While, as discussed in Section 5.1.1, the opposite was witnessed for the core strengths. Therefore, the diameter size of cylinders and cores had an opposite effect on the compressive strength; thus, emphasizing the statistical significant difference and high difference in compressive strength.

It was noticed that as the diameter size increased the relationship between the cylinder sizes; and core and the cylinder compressive strengths began to converge. As indicated in Table 5-5 (A), with the increase in diameter size to 100 mm, the significant difference in compressive strengths between the cylinders and cores became less (although, overall still significantly different). Additionally, there was a trend with regard to the aggregate type used. The greywacke batch produced core strengths that were 4.4% higher than the cylinders; however, the sandstone batch produced cylinder strengths that were 3.2% higher than the core. Although, the different aggregate types produced results that were different to each other, it was observed that the strength difference decreased. Furthermore, it was also noted that in Table 5-5 (B), the comparison between the 100 – 150 mm diameter cylinders was predominantly significantly similar. Therefore, with the increase in size of the specimen, there was a decrease in strength variation between cores and cylinders; thus, further supporting the less significant difference.

The mean compressive strengths of the 150 mm diameter core and cylinders were illustrated in Figure 5-12 and the ANOVA results were indicated in Table 5-5. It was noticed that with the increase in specimen size, the mean strength difference was reduced, resulting in statistically similar core and cylinder compressive strengths. This emphasizes that as the specimen size increased, the compressive strength between a cylinder and a core with a l/d ratio of 1.0 merged. It was noticed that there was a trend in the strength level increase. The 50 MPa batches mainly produced results that were statistically similar compared to the 30 MPa batches. Therefore, owing to an increase in diameter size and an increase in strength, the relationship between cylinders and cores became more comparable which, was consistent with literature.

It was observed that the specimen size has an effect on the strength of cylinders and cores. It was found with cylinders that with a decrease in specimen size there was a decrease in strength, which was opposite to what was observed with core strength and is contradictory to what is commonly found in literature. It is generally found in literature that as the specimen size decreases the compressive strength increases, as a result of there being less chance of a flaw within the concrete matrix. It was found that the “wall effect” may be a possible reason for the findings in the present investigation.

A possible reason for the observed (although not statistically significant) reduced strength of the 70 mm diameter cylinders was attributed to the ‘wall effect’. The wall effect, explained by Tokyay & Özdemir (1997), is “*The quantity of mortar required to fill the space between the particles of the coarse aggregate and the wall of the mould is greater than that necessary in the*

interior of the mass and therefore in excess of the mortar available even in a well-proportioned mix.” The wall effect is said to affect compactibility of the concrete and is more prominent in smaller specimens due to the larger surface area to volume ratio (Tokyay & Özdemir, 1997). An investigation compiled by Tokyay & Özdemir (1997), on the specimen shape and size effect on the compressive strength of higher strength concretes, obtained similar results to what was found in this study and it was also concluded that it was due to the wall effect. Tokyay & Özdemir (1997) further investigated the influence of the wall effect by adding additional 10% mortar to the concrete specimens during casting. It was found that with the additional mortar the compressive strength of a small cylinder (75 x 150 mm) increased by up to 8.6%. Therefore, it was deduced that the reduced strength of the 70 mm diameter cylinder was due to the reduced compactibility owing to the wall effect.

As the diameter size increased, it was found that the mean cylinder compressive strengths became statistically similar. Additionally, the cylinder and core strengths progressively converged. This result was similar to the observations found in the increased size of core specimens (Section 5.1.1) and similar to the outcomes found in literature (Tokyay & Özdemir, 1997; Omer *et al.*, 2010; Khoury *et al.*, 2014).

Overall, it was deduced that the diameter size effects the relationship between cores and cylinders, with a l/d ratio of 1.0. It was found that as the diameter size increased, the difference between the core and cylinder compressive strength decreased. It was also noticed that once the diameter size increases to 150 mm, the comparison between cylinder and core compressive strengths became statistically comparable, this was due to the reduced number of factors that may influence the compressive strength with the increase in size.

Additionally, it was also concluded that the 70 mm diameter cylinder produced results that were significantly different and lower than that of the 100 mm cylinder sizes. This was due to the wall effect that influenced the compactibility of smaller size specimens. As the size of the cylinders increased the compressive strengths became statistically similar.

5.2.1 Aggregate size

During the analysis of relating cores and cylinders, it was found that maximum aggregate size had a different influence on compressive strength of cylinders compared to the cores. Figure 5-13 and Figure 5-14 illustrates the influence of maximum aggregate size on the compressive strength of cylinders with respect to diameter size. Table 5-6 indicates the p-values obtained from the ANOVA analysis of the different diameter sizes.

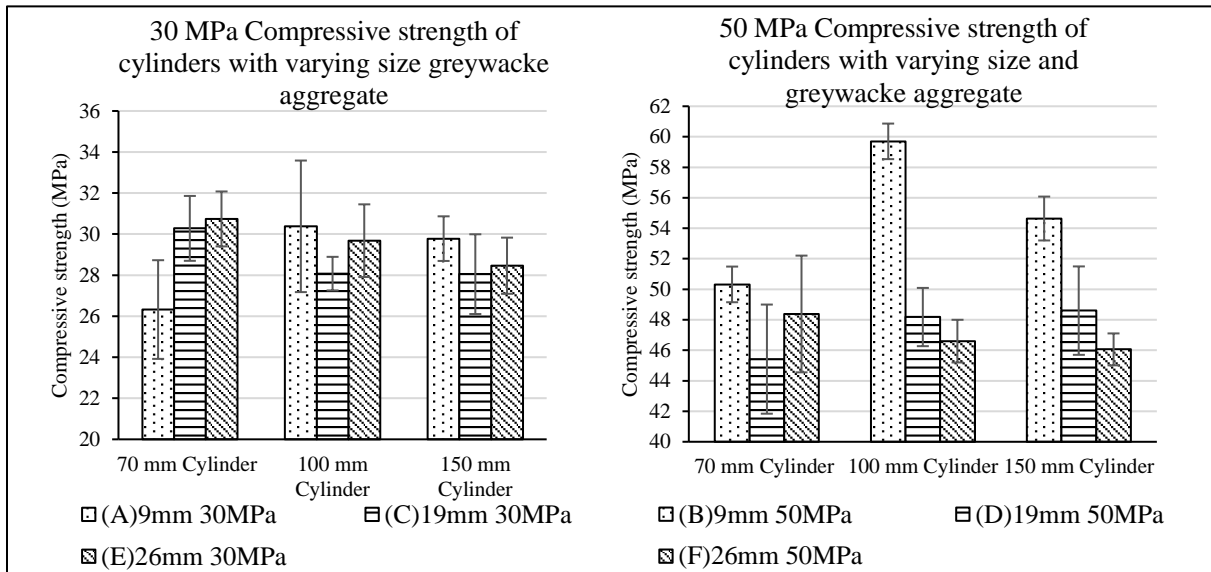


Figure 5-13 – 30 and 50 MPa compressive strength comparison of cylinders with varying specimen size and maximum aggregate size using greywacke coarse aggregate

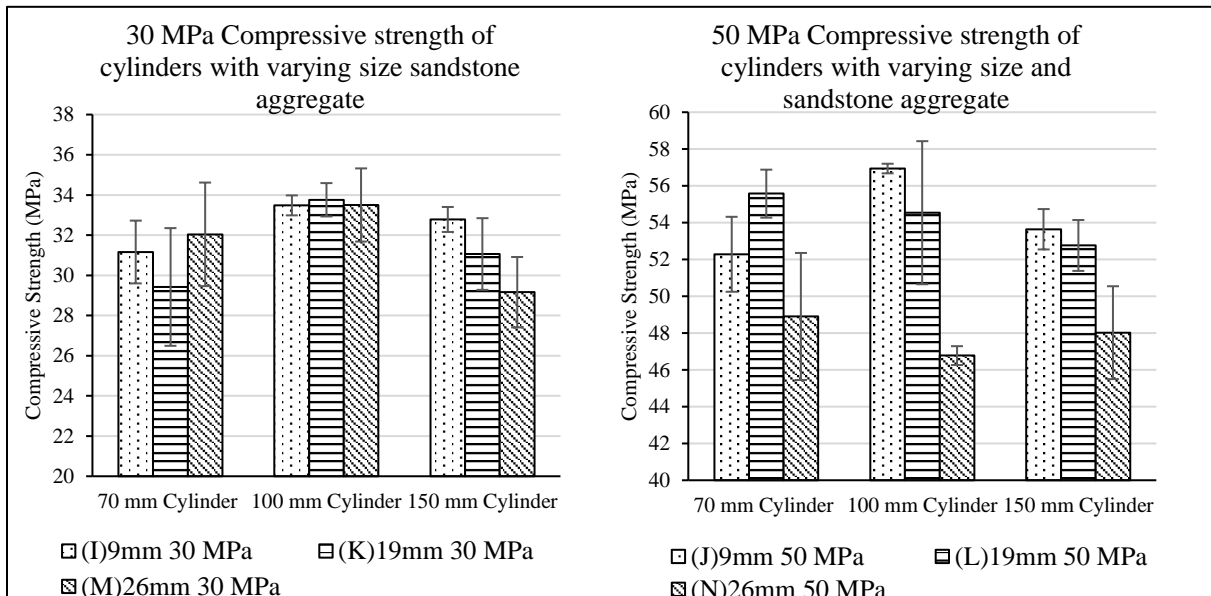


Figure 5-14 – 30 and 50 MPa compressive strength comparison of cylinders with varying specimen size and maximum aggregate size using quartzitic sandstone coarse aggregate

Table 5-6 – p-values from ANOVA comparing mean strength of cylinders with various maximum aggregate sizes

Aggregate				Aggregate			
Greywacke 30 MPa				Greywacke 50 MPa			
$\alpha = 0.05$				$\alpha = 0.05$			
	9mm - 19mm	19mm - 26mm	9mm - 26mm		9mm - 19mm	19mm - 26mm	9mm - 26mm
Cylinder 70	0.010*	0.633	0.004*	Cylinder 70	0.020*	0.242	0.310
Cylinder 100	0.155	0.097	0.680	Cylinder 100	0.000*	0.174	0.000*
Cylinder 150	0.090	0.684	0.130	Cylinder 150	0.003*	0.103	0.000*
Sandstone 30 MPa				Sandstone 50 MPa			
Cylinder 70	0.275	0.172	0.532	Cylinder 70	0.013*	0.003*	0.096
Cylinder 100	0.535	0.779	0.982	Cylinder 100	0.206	0.002*	0.000*
Cylinder 150	0.076	0.128	0.002*	Cylinder 150	0.297	0.006*	0.002*

* indicates p is less than 0.05

During the analysis of the smaller specimens, it was evident that there was no general trend in strength with regard to the different maximum aggregate sizes. The statistical results obtained indicated that with an increase in maximum aggregate size from 9 mm to 19 mm there was a significant difference in strength. However, as the aggregate size increased from 19 mm to 26 mm the mean strengths of the 70 mm cylinders were statistically similar. Owing to there being no general trend in compressive strength, it was difficult to compare the relationship between core and cylinder specimens with regard to maximum aggregate size. The scattered influence of maximum aggregate size on the compressive strength of cylinders was linked to the wall effect, as described above. Due to the enhanced wall effect in smaller specimens, the variations in mean strength was attributed to a variation in compactibility between different aggregate sizes. This was further emphasized with the larger standard deviations of the 70 mm diameter cylinder compared to the larger diameter cylinders. The wall effect was not notice in the core specimens because they were removed from larger elements, where this effect would be eliminated. As a result, a trend in the 70 mm diameter core compressive strength was able to be obtained compared to no trend in the 70 mm diameter cylinders.

It was found that the 100 mm and 150 mm cylinders produced similar statistical results and strength trends with respect to the mean compressive strength with different maximum aggregate sizes. The statistical results for the 30 MPa strength level indicated that the mean compressive strengths were statistically similar for the 100 mm and 150 mm cylinders. The similarity in mean compressive strengths was often a result of overlapping standard deviations with respect to the multiple aggregate sizes. However, the statistical results for the 50 MPa strength level indicated that the mean compressive strengths of the different maximum aggregate sizes were statistically different. There was a dominant trend in the 50 MPa strength level with regard to the 100 mm and 150 mm diameter cylinders. It was evident that as the aggregate size decreased there was an increase in strength, as illustrated in Figure 5-13 and Figure 5-14. It was calculated that the 9 mm

maximum aggregate size produced an average compressive strength that was 10.6% and 20.0% higher than that of the 19 mm and 26 mm aggregate sizes respectively.

It was observed that the relationship between different maximum aggregate sizes and concrete strength in cylinders was opposite to what was witnessed in cores. As mentioned in Section 5.1.2, smaller core specimen sizes, such as the 50 mm and 70 mm diameters, obtained a significant trend in results that showed that as the maximum aggregate size increased the strength increased; however, in small cylinder specimens there was no general trend in compressive strength. Additionally, as the core specimen size increased to 100 mm diameter or larger there was no dominant trend in the compressive strength; however, with regard to cylinders there was a significant trend that indicated as the aggregate size decreased there was an increase in strength.

The opposite trend for the smaller diameter specimens was attributed to the increased influence of the wall effect in smaller cylinders. No plausible explanation could be found for the opposite trends in compressive strength of different maximum aggregate sizes for cores and cylinders. However, the trend that was observed for the cylinder specimens may be attributed to internal bleeding and larger ITZs.

The increased strength of cylinders, with smaller aggregate size may be caused by effects of internal bleeding and the size of the ITZ. For the duration of internal bleeding water tends to migrate upwards. This water gets trapped beneath the aggregate resulting in an increased porosity of the ITZ due to the increase in w/c ratio. Due to the reduced surface area of an individual small piece of coarse aggregate, there will be less water trapped beneath the aggregate compared to a large piece of aggregate. As a result, there will be a more even distribution of ponding over a large quantity of small aggregate compared to an uneven distribution of ponding under a large individual piece of aggregate. As a consequence, there will be a greater porosity in the location of the ITZ around a large piece of aggregate compared to smaller piece of aggregate. This will lead to a decrease in strength as the maximum aggregate size increases. Similar findings were obtained in an investigation completed by Elsharief *et al.* (2003) and discussed by Alexander & Sidney (2005). It was found that the smaller aggregate size produced a reduced porosity and an increase content of unhydrated cement; thus, increasing the strength of the concrete as the ITZ was similar to the HCP (Hardened Cement Paste). Whereas, larger aggregates will have an increased porosity in the surrounding ITZ which will lead to a point of weakness. It was also found that the influence was greater in lower w/c ratio mixes (Elsharief *et al.*, 2003). Therefore, the results found in the present investigation were consistent with literature.

5.3 Aggregate type

The water/cement (w/c) ratio of the concrete will determine the degree at which the aggregate will play a role in the compressive strength. In literature, it is agreed that as the strength level of concrete increases, the coarse aggregate will have a higher influence on the compressive strength (Bryan Perrie, 2009). The extent at which the coarse aggregate will influence the concrete is also based on the properties of the aggregate. Aggregate type may also have an effect on the strength of cored samples, as the aggregate elastic modulus properties may cause increased drilling

damages. During this investigation two coarse aggregate types were used: greywacke and quartzitic sandstone. Additionally, two concrete strengths were prepared: 30 MPa and 50 MPa.

Table 5-7 indicates the p-values obtained by the ANOVA analysis comparing the mean compressive strengths of the different aggregate types.

Table 5-7 – p-values from ANOVA comparing compressive strength of different aggregate types

Greywacke versus Sandstone - 30 MPa				Greywacke versus Sandstone - 50 MPa			
$\alpha = 0.05$				$\alpha = 0.05$			
	9 mm	19 mm	26 mm		9 mm	19 mm	26 mm
Cube	0.809	0.125	0.295	Cube	0.374	0.017*	0.648
Core 70 mm	0.039	0.000*	0.182	Core 70 mm	0.189	0.010*	0.048*
Core 100 mm	0.711	0.311	0.549	Core 100 mm	0.000*	0.393	0.031
Core 150 mm	0.310	0.000*	0.000*	Core 150 mm	0.005*	0.008*	0.138
Cylinder 70 mm	0.003*	0.579	0.346	Cylinder 70 mm	0.099	0.000*	0.827
Cylinder 100 mm	0.065	0.000*	0.010	Cylinder 100 mm	0.001*	0.011*	0.797
Cylinder 150 mm	0.001*	0.025	0.501	Cylinder 150 mm	0.251	0.020*	0.147

* indicates p is less than 0.05

Due to the strength level of concrete playing an important role in the degree in which aggregate properties influences compressive strength, the aggregate types were related by comparing mixes with the same strength levels, maximum aggregate size and geometry. The comparison was done on cores and cylinders, as it was assumed that the aggregate properties would have the same effect on both specimen types.

From the analysis of the 30 MPa strength class, it was indicated that the null hypothesis was predominantly accepted. Thus, indicating that the general mean strengths of the 30 MPa mixes using different types of aggregate were statistically similar. There was a number of cases where the null hypothesis was rejected but there was no trend in which these rejections could have been related. Therefore, it was deduced that for the 30 MPa strength class there was no significant difference between the mean compressive strengths of the different coarse aggregate type mixes. This similarity was expected due to the high w/c ratio. As mentioned above, the strength class of the concrete will determine the amount of influence the aggregate characteristics will have on the results; thus, due to the low strength class the aggregate did not have an effect on the overall compressive stress.

Contrarily, the analysis of the 50 MPa strength class indicated that there was a 50/50 split where the null hypothesis was accepted and rejected. It was found that the 9 mm and 26 mm maximum aggregate sizes generally produced mean compressive strengths that were statistically similar; however, the 19 mm maximum aggregate size was found to be the comparison where the null was dominantly rejected. When comparing the mean compressive strengths using the different aggregate types, it was found that the sandstone produced a higher strength for the 19 mm aggregate sizes. It was noted that the concrete using the sandstone aggregate obtained a

compressive strength slightly higher than the greywacke; however, the overlapping standard deviations of the 9 mm and 26 mm aggregate resulted in the mean results being statistically similar. It was calculated that the compressive strength increase of the sandstone aggregate mixes compared to the greywacke aggregate mixes were approximately 3.3, 10.3 and 3.2% for the 9, 19 and 26 mm aggregate sizes, respectively. Therefore, the statistical analysis outcome was complimented by the higher compressive strengths of the 50 MPa sandstone aggregate mixes, especially the 19 mm maximum aggregate size. As a result of the statistical analysis and strength difference, it was deduced that at a 50 MPa strength level the size of the coarse aggregate will determine the similarity in strengths of different aggregate types.

It was believed that the strength and elastic modulus of greywacke aggregate was higher than that of the quartzitic sandstone. During the analysis, this was portrayed as the sandstone mixes produced higher strengths compared to the greywacke, especially in the higher strength class. Therefore, the sandstone strength characteristics influenced the concrete strength more compared to that of the greywacke. Although at first these results seem contradictory, it was found that they were consistent with literature. Due to the lower elastic modulus of the sandstone there was a lesser difference in stiffness between the HCP and the aggregate. Therefore, during loading, smaller stress concentrations were formed at the ITZ due to the similar material stiffness's (Beushausen & Dittmer, 2015). Thus, the concrete specimens began to act more like a homogenous material under compressive loading compared to the greywacke aggregate. This was witnessed during this investigation as the crack pattern moved through the HCP and sandstone aggregate as one; whereas, with the greywacke, the crack pattern formed through the HCP and ITZ. Therefore, the sandstone aggregate would have provided increased strength characteristics to the test specimen. The crack pattern was further discussed in the next section.

5.4 Crack pattern

The mechanism of crack propagation in normal concrete, subjected to uniaxial compression, at ultimate failure is created by the formation of cracks in the cement paste and ITZ due to the presence of micro-cracks and flaws (Newman, 2003). The crack formation begins at the ITZ due to the stress concentrations that are formed between the cement paste and the aggregate because of the different material stiffness's (Chiaia *et al.*, 1998; Beushausen & Dittmer, 2015). As the strength of concrete increases there is a reduced difference in stiffness between the aggregate and the cement paste; additionally, the ITZ becomes denser. Consequently, the heterogeneous concrete becomes more of a homogenous material which makes the predictions and onset of micro-cracks more difficult to predict (Beushausen & Dehn, 2009).

During the experimental investigation, the concrete specimens' crack patterns were analysed after ultimate failure. The aspects that were concentrated on in cylinders and cubes were whether the correct failure crack pattern was seen. Additionally, further notice was taken once the moulded outer layer was removed, whether the cracks moved through the ITZ and cement paste or if they moved through the aggregate. With respect to cores, it was analysed if the cracks moved through the ITZ or aggregate on the surface of the core and additionally inside of the core. The crack propagation was expected to move through the ITZ or aggregate on the surface of the

core as there was no moulded wall of concrete mortar as in a cylinder. Therefore, this helped to visualise the crack propagation. The influence of concrete strength level, aggregate type, maximum aggregate size and specimen size was taken into account during the analysis.

Generally, it was found that the correct hour glass failure pattern was obtained for the cubes, cores and cylinders, as predicted. The larger the specimen size, the more apparent the hour glass failure. Figure 5-15 illustrated the hour glass failure of a cube and core specimen. Due to the aspect ratio of the specimens, in this investigation, the hour glass is often difficult to identify without removing the outer fractured concrete.



Figure 5-15 – Hour glass failure a) 100 mm cube b) 150 mm diameter core

The analysis of the crack patterns with regard to the increase in concrete strength level was done with 19 mm greywacke coarse aggregate and a strength level increase from 30 MPa to 75 MPa. It was found that the crack pattern results were consistent with literature. For lower strength levels (30 MPa) the crack patterns predominantly formed through the ITZ. As the concrete strength level increased to about 75 MPa, there were cracks that formed through both the aggregate and the ITZ. This was illustrated in Figure 5-16, there was evidence of cracked aggregate as well as cracked ITZs. As mentioned above, this was expected; because, as the strength level increases the difference in stiffness's between the aggregate and HCP reduces and the ITZ becomes denser. As a result, less failure energy is required to move through the aggregate compared to around the denser ITZ. This leads to a more homogenous concrete, emphasizing the crack movement through all the different materials in the concrete matrix.

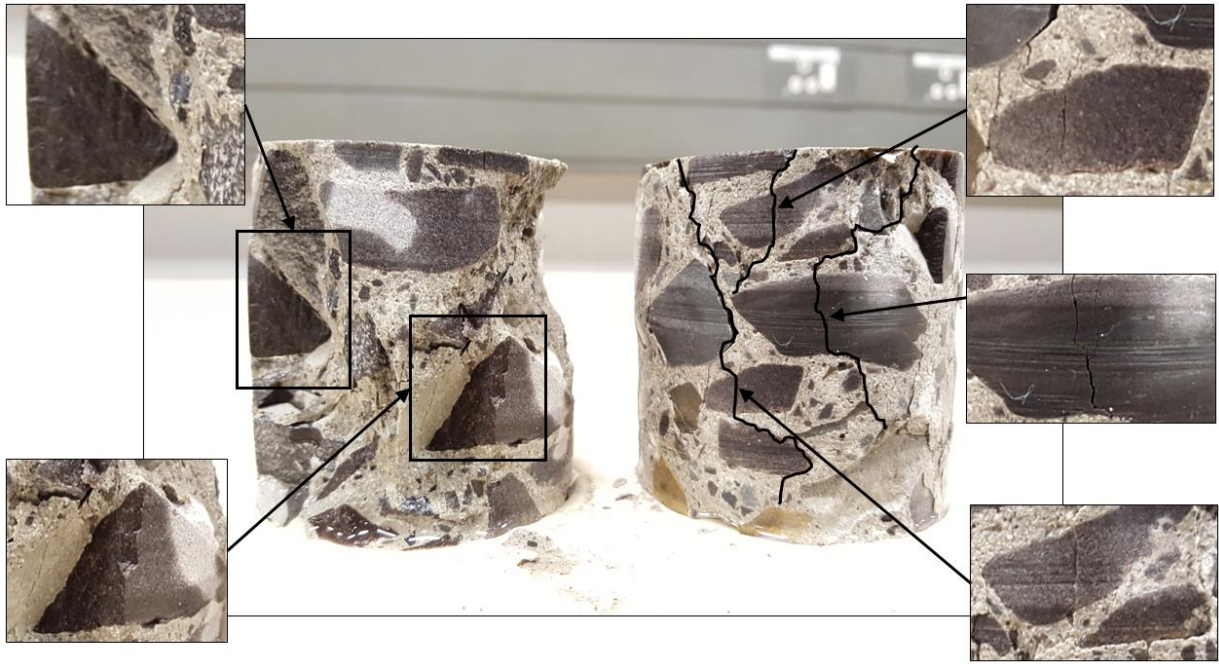


Figure 5-16 – 60MPa cores containing crack propagation through ITZ and aggregate

The aggregate type had an influence on the crack pattern of the concrete. As discussed in Section 5.3, the coarse aggregates investigated were greywacke and quartzitic sandstone, which are locally sourced in the Western Cape, South Africa. It is commonly believed that greywacke aggregate has strength and elastic modulus characteristics that are stronger than that of the quartzitic sandstone. Due to the lower elastic modulus of the sandstone, there was a lesser difference in stiffness between the HCP and the aggregate. Therefore, during loading, reduced stress concentrations were formed in the ITZ due to the similar material stiffness's (Beushausen & Dittmer, 2015). Thus, the sandstone aggregate concrete began to act more like a homogenous material under compressive load compared to the greywacke aggregate, especially with smaller maximum aggregate sizes. This was witnessed during the investigation with the lower strength concretes, the crack pattern moved through the HCP and sandstone aggregate as one; whereas, with the greywacke aggregate, the crack pattern formed through the HCP and ITZ. It must be noted, it was difficult to analyse the crack pattern in the concrete with sandstone aggregate, especially the small aggregate size, as the aggregate and cement paste contained a similar colour. Nevertheless, as the strength level increased to 50 MPa there was increased crack formations through both aggregate types; however, the greywacke crack propagation was still predominantly through the ITZ. As a result, the sandstone aggregate would have provided increased strength characteristics to the test specimen which was evident in Section 5.3 and the greywacke would provide less strength characteristics.

Additionally, it was found that the maximum aggregate size also has an influence on the crack pattern corresponding with the aggregate type. It was found that as the aggregate size decreased, there was an increase in the number of cracks when using greywacke aggregate. This was attributed to the increased surface area of aggregate and ITZ. As the maximum aggregate size increased, there was a decrease in the number of surface cracks and an increase in cracks

that form through the aggregate. This was attributed to the size of the aggregate and the fracture energy. As a result, the crack pattern was forced to move through the aggregate as less energy was required to move directly through it compared to through the ITZ. Furthermore, it is known that the crack propagation wants to take the shortest distance to the surface but at the same time the weakest links. Therefore, in low strength concrete with small aggregate sizes there is an increase in ITZ; thus, the crack propagation follows the weak ITZ. Furthermore, it was found that as the strength of the concrete increased there was an increase in cracks that flow through the aggregate. This was expected and is consistent with literature, as in high strength concrete with large aggregate the crack propagation will generally move through the shortest distance; thus, causing failure through the stone.

With regard to the sandstone aggregate, there was a decrease in the number of cracks as the maximum aggregate size decreased compared to the greywacke aggregate, as illustrated in Figure 5-17. This effect was attributed to the similar elastic moduli of the concrete and sandstone aggregate. This led to reduced stress concentrations in the ITZ. As a result, the smaller sandstone maximum aggregate size and HCP acted as a homogenous material. As the aggregate size increased to 19 mm, it was noticed that there was an increase in the number of cracks and it was also noticed that they were predominantly through the ITZ. However, as the maximum aggregate size increased to 26 mm, it was found that there was an increase in cracks through the sandstone aggregate which is similar to the greywacke aggregate.



Figure 5-17 – 70 mm diameter cores with 9 mm maximum aggregate size, greywacke left and quartzitic sandstone right

The specimen size also had a strong influence in the crack pattern. As illustrated in Figure 5-18 and Figure 5-19, although different aggregate types, both figures showed the 19 mm maximum aggregate size and a 30 MPa strength level. It was seen, as the specimen size decreased, there was an increase in cracking through the aggregate. This was attributed to the decrease in size of the specimen and retaining the same maximum aggregate size. At smaller sample sizes, a “detour” around the aggregate would largely extend the fracture path, which would need more energy. As a result, the fracture path moves directly through the aggregate. Consequently, there may be an increased compressive strength due to the increased interaction of the aggregate properties in the stress flow. With larger size specimens, such a “detour” has a comparatively smaller effect on the overall crack length; hence, the crack is more likely to occur in the ITZ and not through the aggregate. Thus, the aggregate will have no effect on the compressive strength.

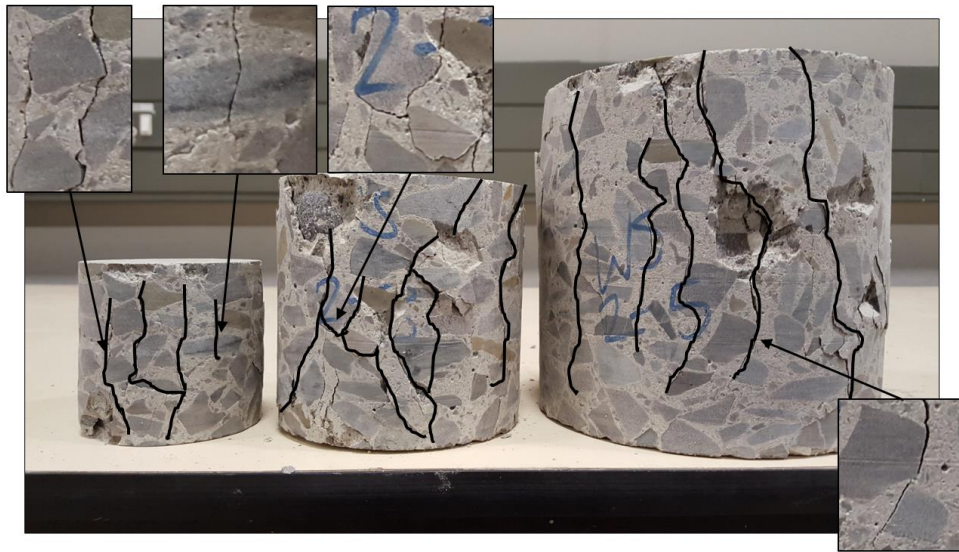


Figure 5-18 – Crack patterns of various size cores using greywacke aggregate

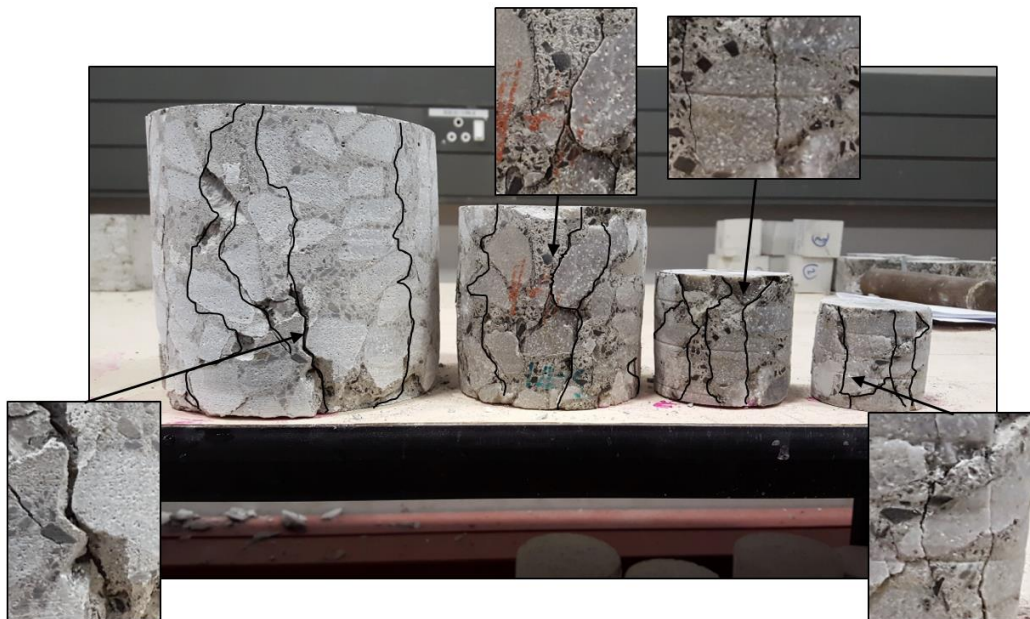


Figure 5-19 – Crack patterns of various size cores using sandstone aggregate

6. Conclusions and recommendations

6.1 Summary of observations and conclusions

In conclusion to the investigation on relating the compressive strength of cubes, cores and cylinders, with a l/d ratio of 1.0; it was established that there were several factors that influenced the relationship between the compressive strengths of the three categories. These factors included specimen size, maximum aggregate size, aggregate types and strength level. From the investigation, the following conclusions were drawn.

It was established that there was little difference between cube and core compressive strength using a 100 mm standard cube and 100 mm diameter core. It was found that the mean compressive strengths between the specimen types were prominently statistically similar. Furthermore, the similarities in mean strengths were emphasized with an average strength difference of 0.9% over all the mixes. Therefore, it was deduced that the compressive strengths of cubes and cores that are cast, cured, prepared and tested in controlled conditions with a 100 mm dimensional size will produce a similar mean compressive strength.

Furthermore, it was concluded that the difference between standard cube and in-situ core compressive strength, expected in practice, may be attributed to the influences of casting, compacting and curing conditions. Additionally, the influences in which cores are removed and prepared for testing may significantly affect the compressive strength results. Therefore, the 80% factor stipulated in SANS 10100-2:1994, to equate in-situ core strength to design strength, takes account of influences such as curing on site and drilling damages that may reduce the strength. It does, however, not relate to a difference in specimen type, as often assumed by structural engineers.

It was found that the core diameter size influences the compressive strength. It was concluded that as the core diameter decreases, there was an increase in compressive strength. It was generally found that the 70 mm diameter core produced the highest compressive strength compared to the 50, 100 and 150 mm diameter cores. The 50 – 70 mm and 100 – 150 mm core comparison both obtained results that deemed their mean compressive strengths statistically similar. Therefore, the relationship between cube and core strength must take into consideration the size of the core used.

From the investigation, it was established that the core diameter size and strength level had a strong influence on compressive strength in coherence with different maximum aggregate sizes used in the concrete. On the one hand, it was found that, at a 30 MPa strength level using greywacke aggregate, the mean compressive strengths produced were comparable between the multiple maximum aggregate sizes. On the other hand, specimens that had the 50 MPa strength level, obtained results that were predominately significantly different between different aggregate sizes. A different trend was established with the use of quartzitic sandstone aggregate. It was found that at 30 MPa strength level, the mean results were significantly different and at a 50 MPa strength level, the compressive strengths were comparable in relation to maximum

aggregate size. It was also established that as the size of the core decreased and the maximum aggregate size increased, the mean compressive strength increased. At 50 MPa the trend was still evident even though the mean strengths were statistically similar. This was due to the larger standard deviation of the smaller cores compared to the larger ones.

It was found that specimen diameters that did not obey the stipulations set out in SANS 5865:1994, with regard to the minimum diameter of a core being three times the maximum aggregate size, obtained strengths that were significantly higher than that of the cube results. Thus, emphasizing that the interpretation and equating of small core specimens that do not obey the stipulation in SANS 5865:1994 may produce estimated strengths that are significantly different to those obtained in standard tests.

The influence of concrete strength level on core strength was found to have an effect on the variation in mean compressive strength between different specimen sizes. It was established that as the strength level increased, there was a decrease in mean compressive strength variation between the various core diameter sizes. Therefore, there was an increased similarity in mean compressive strength between various diameter sizes as the strength increased. Additionally, as the strength level increased over 50 MPa there was no significant difference between the mean compressive strengths of cubes and cores.

Further investigation was done on the relationship between core and cylinder strengths, to analyse the effect that the cylinder wall may have on the compressive strength compared to the exposed aggregate wall of the core. It was concluded that the diameter size had a strong influence on the relationship between core and cylinder compressive strengths. It was found that as the diameter size increased the mean compressive strength became increasingly statistically similar. The 70 mm and 100 mm diameter specimens produced mean compressive strengths that were significantly different between cut cores and cast cylinders. As mentioned above, as the core diameter size decreased, the compressive strength increased; however, as the cylinder size decreased, the compressive strength decreased. Therefore, at smaller diameter sizes the compressive strength of the core was higher than that of the cylinder. However, the 150 mm diameter specimens produced mean compressive strengths that were statistically similar. This was attributed to the different trends in cylinder strength with varying diameter sizes compared to cores.

Additionally, the influence of the maximum aggregate size on the compressive strength of cylinders was also opposite to what was found with the core specimens. The influence of the maximum aggregate size was more distinct with regard to cylinders. It was found, at a 30 MPa strength level, that the mean compressive strengths were predominately statistically similar when comparing the multiple maximum aggregate sizes. Whereas, at a 50 MPa strength level, the compressive strength results were predominantly statistically significantly different. The 70 mm cylinder did not provide any trends in strength with respect to the various aggregate sizes. However, as the cylinder size increased and the maximum aggregate size increased the

compressive strength decreased. This trend was also found to be opposite in core strength with regard to various maximum aggregate sizes.

The coarse aggregate type had an influence on the compressive strength of the concrete. Two aggregate types were used, namely greywacke and quartzitic sandstone. It was found that the strength level of the concrete determines the extent that the aggregate characteristics will influence the concrete strength. It was found that as the strength level increased the influence of the aggregate characteristics were more profound. At the 30 MPa strength level, there was no difference in compressive strength between the concrete, using different aggregate types. At the 50 MPa strength level, it was established that the sandstone aggregate batches produced compressive strengths higher than the greywacke aggregate batches. This was assumed to be due to the reduced stress concentrations formed between the aggregate and the hardened cement paste due to the similar elastic moduli between the materials. It must be noted, that this was assumed as the elastic moduli of the aggregate types and cement paste was not tested.

6.2 Summarized conclusions

The analysis of test results obtained in this research allows the deduction of practically relevant conclusions that will assist in the interpretation of core strength results.

- The compressive strength of a 100 mm diameter core is statistically comparable to a standard 100 mm cube; as such, a core sample is equivalent to a cube sample of the same overall dimension.
- The 80% factor stipulated in SANS 10100-2:1994 to relate in-situ core strength to design strength is put in place for different curing methods between standard specimens and in-situ concrete as well as for coring damages.
- The diameter size of a core specimen influences the compressive strength. As the core diameter decreases from 100 mm, an increase in compressive strength can be expected. However, this is only true for specimens cored and prepared under controlled conditions.
- 100 mm and 150 mm diameter cores that are cured, prepared and tested in a controlled environment will produce statistically comparable compressive strengths.
- The maximum aggregate size influences the compressive strength of cores and cylinders in coherence with diameter size. As the core diameter decreases and the maximum aggregate size increases the compressive strength increases. Whereas, the opposite was found with the cylinder, the strength increases with an increase in diameter size and decrease in maximum aggregate size.
- 150 mm diameter cores and cylinders that are cured, prepared and tested in the same controlled condition, with an aspect ratio of 1.0, will produce statistically comparable mean compressive strengths.

- The diameter size influences the compressive strength of cylinders. As the cylinder diameter decreases, the compressive strength decreases. This is attributed to the wall effect at the specimen perimeter.

6.3 Recommendations

Based on the findings and conclusions of the literature and experimental investigation, the recommendations in practice and for future research work were made.

6.3.1 Practice

- In practice, it is authoritative that the stipulations and guidelines that are stated in the national standards are adhered to for accurate interpretation of results.
- It is authoritative that the practioner drilling, preparing and testing the core specimen is well educated in the national standards that are being adhered to. It is also important that experienced engineering judgement is used in order to interpret the results correctly.
- When comparing concrete cube and core compressive strengths, the most accurate comparison is when the geometric sizes remain consistent. Although, in practice a 150mm cube is used in the compliance test, it is difficult to remove a 150 mm core from a structural element. As a result, the preferable core diameter size is 100 mm as it was found that the 100 and 150mm diameter core produced statistically comparable results.
- Reduced core diameter sizes are not recommended as they produce variable results. This is a result of a number of variables that may influence small cores such as maximum aggregate size, aggregate type, core drilling damages and w/c ratios.
- Anchoring of the drilling machine is very important to reduce the amount of wobbling and damage to the core. Additionally, well maintained equipment and sharp drill bits are also of great importance for reduced damage to the core.

6.3.2 Future research work

For future research work it would be recommended that:

- The analysis of core strength from cast elements that simulate in-situ concrete curing. This will aid in the comparison of in-situ core and standard cube strength and validate the difference in compressive strength.
- For the comparison of core strength to moulded cylinder strength, an increased mortar content must be added to the cylinder in attempt to eliminate the wall effect that reduced the compactibility in the smaller specimens.
- A similar study is to be performed with a different aspect ratio, possibly 2.0, to investigate the how the compressive strength of cores and true cylinders may be affected.

- The use of a core drill that is not securely fasten to the ground to analyse if the damage to the core during core drilling is significantly increased due to wobbling.

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Appendix A:

Cast (A) 9 mm Greywacke 30 MPa

Core No.	Size	Height			Diameter						l/d ratio	Dimension Factor	Density [kg/m ³]	Weight [g]	Load [kN]	Compressive strength		Standard dev	
		1	2	Ave.	1	2	3	4	5	6						Ave.	Measured		Average
																	[MPa]		[MPa]
Cube 1	100	100.4	100.3	100.3	102.4	99.3	100.8	100.6	100.6	100.6				2426.4	2470.0	313.1	30.9	31.3	0.7
Cube 2	100	100.2	100.5	100.3	100.4	101.3	100.8	100.4	100.2	100.3				2394.8	2430.0	321.0	31.7		
Cube 3	100	100.4	100.3	100.3	100.3	101.2	100.8	100.0	100.0	100.0				2422.6	2450.0	305.2	30.3		
Cube 4	100	100.1	100.5	100.3	100.3	99.8	100.1	100.1	100.1	100.1				2423.1	2435.0	312.8	31.2		
Cube 5	100	100.1	100.2	100.1	97.3	97.3	97.3	100.3	100.2	100.3				2435.5	2380.0	314.1	32.2		
Core 1	70	69.1	69.5	69.3	68.4	68.2	68.3	68.4	68.2	68.1	68.3	1.0	1.0	2463.9	625.0	125.1	34.2	31.2	3.4
Core 2	70	67.7	67.3	67.5	68.4	68.4	68.3	68.7	68.4	68.1	68.4	1.0	1.0	2440.0	605.0	117.4	32.0		
Core 3	70	66.2	66.3	66.3	68.3	68.5	68.2	68.1	68.1	68.0	68.2	1.0	1.0	2458.0	595.0	92.4	25.3		
Core 4	70	67.7	67.3	67.5	68.4	68.0	68.4	68.4	68.4	68.3	68.3	1.0	1.0	2448.4	605.0	120.3	32.8		
Core 5	70	67.5	67.1	67.3	68.4	68.1	68.1	68.5	68.3	68.3	68.3	1.0	1.0	2458.2	605.0	116.2	31.8		
Core 1	100	101.0	100.8	100.9	102.1	102.1	102.2	102.1	102.1	102.2	102.1	1.0	1.0	2456.1	2030.0	275.2	33.6	32.2	2.9
Core 2	100	100.3	100.6	100.4	102.1	102.1	102.0	102.1	102.5	102.1	102.1	1.0	1.0	2448.0	2015.0	272.0	33.2		
Core 3	100	101.3	101.3	101.3	102.1	102.0	102.1	102.3	102.0	102.2	102.1	1.0	1.0	2463.8	2045.0	242.0	29.5		
Core 4	100	101.3	101.3	101.3	102.1	102.4	102.0	102.4	102.1	102.2	102.2	1.0	1.0	2455.6	2040.0	238.0	29.0		
Core 5	100	99.8	99.8	99.8	102.1	102.3	102.3	102.1	102.1	102.0	102.2	1.0	1.0	2438.5	1995.0	293.1	35.8		
Core 1	150	132.3	132.1	132.2	143.4	143.4	143.3	143.4	143.2	143.4	143.4	0.9	1.0	2463.0	5255.0	304.9	18.9	28.7	5.9
Core 2	150	131.7	131.1	131.4	143.3	143.4	143.4	143.4	143.4	143.4	143.4	0.9	1.0	2460.4	5220.0	509.5	31.6		
Core 3	150	135.8	135.5	135.6	143.3	143.4	143.4	143.2	143.3	143.3	143.3	0.9	1.0	2472.3	5410.0	457.2	28.3		
Core 4	150	131.1	131.5	131.3	143.8	143.5	143.4	143.3	143.3	143.4	143.5	0.9	1.0	2452.6	5205.0	491.5	30.4		
Core 5	150	134.4	134.9	134.6	143.2	143.4	143.2	143.4	143.4	143.3	143.3	0.9	1.0	2455.9	5335.0	556.1	34.5		

Core No.	Size	Height			Diameter								l/d ratio	Dimension Factor	Density [kg/m ³]	Weight [g]	Load [kN]	Compressive strength		Standard dev
		1	2	Ave.	1	2	3	4	5	6	Ave.	Measured						Average		
												[MPa]						[MPa]		
Cyl 1	70	67.5	66.8	67.1	70.5	70.5	70.7	70.4	70.4	70.2	70.5	1.0	1.0	2407.7	630.0	113.8	29.2	31.2	3.4	
Cyl 2	70	70.5	70.1	70.3	70.4	70.4	70.4	70.3	70.3	70.5	70.4	1.0	1.0	2449.5	670.0	92.5	23.8			
Cyl 3	70	69.8	69.1	69.5	70.3	70.5	70.6	70.5	70.1	70.3	70.4	1.0	1.0	2442.4	660.0	97.2	25.0			
Cyl 4	70	70.9	70.1	70.5	70.4	70.5	70.3	70.4	70.3	70.3	70.4	1.0	1.0	2427.1	665.0	33.4	8.6			
Cyl 5	70	70.3	70.8	70.6	70.4	70.5	70.7	70.4	70.4	70.2	70.4	1.0	1.0	2436.6	670.0	106.5	27.3			
Cyl 1	100	96.0	96.2	96.1	100.3	100.8	99.8	100.6	99.4	100.7	100.2	1.0	1.0	2459.3	1865.0	246.7	31.3	30.4	3.2	
Cyl 2	100	101.8	101.3	101.6	100.5	100.0	99.4	99.9	100.4	100.0	100.0	1.0	1.0	2467.7	1970.0	211.6	26.9			
Cyl 3	100	98.7	99.2	99.0	100.4	100.5	100.2	100.6	100.3	100.6	100.4	1.0	1.0	2455.5	1925.0	266.5	33.7			
Cyl 4	100	99.8	100.1	99.9	99.8	99.8	100.0	101.0	100.7	100.9	100.3	1.0	1.0	2443.3	1930.0	260.1	32.9			
Cyl 5	100	100.5	100.1	100.3	100.6	100.2	100.1	100.5	100.3	100.2	100.3	1.0	1.0	2459.5	1950.0	214.0	27.1			
Cyl 1	150	151.2	150.7	151.0	150.4	150.2	150.0	150.2	150.2	150.3	150.2	1.0	1.0	2442.5	6535.0	554.6	31.3	29.8	1.1	
Cyl 2	150	144.4	145.1	144.8	150.3	149.7	150.8	150.5	151.0	149.9	150.4	1.0	1.0	2437.3	6265.0	525.0	29.6			
Cyl 3	150	149.5	149.0	149.2	150.8	149.5	150.3	150.8	150.8	149.3	150.2	1.0	1.0	2453.2	6490.0	538.9	30.4			
Cyl 4	150	151.6	152.0	151.8	150.3	150.1	150.4	150.8	150.3	150.8	150.4	1.0	1.0	2462.8	6645.0	509.1	28.6			
Cyl 5	150	151.3	150.8	151.1	150.0	150.4	150.3	150.8	150.4	149.8	150.3	1.0	1.0	2461.8	6595.0	515.0	29.0			

Appendix A

William Smith

Relating concrete cube, core and cylinder compressive strengths that are cast, cured, prepared and tested in laboratory conditions

Cast (B) 9 mm Greywacke 50 MPa

Core No.	Size	Height			Diameter							l/d ratio	Dimension Factor	Density [kg/m ³]	Weight [g]	Load [kN]	Compressive strength		Standard dev
		1	2	Ave.	1	2	3	4	5	6	Ave.						Measured	Average	
																	[MPa]	[MPa]	
Cube 1	100	100.1	100.1	100.1	99.2	97.9	98.5	100.2	100.3	100.2			2503.8	2475.0	549.7	55.7	54.7	2.1	
Cube 2	100	100.1	100.2	100.2	101.4	101.4	101.4	100.1	100.1	100.1			2439.4	2480.0	532.7	52.5			
Cube 3	100	100.2	100.1	100.1	102.7	101.3	102.0	100.4	100.0	100.2			2432.4	2490.0	552.6	54.1			
Cube 4	100	100.1	100.4	100.2	100.9	101.4	101.1	100.0	100.3	100.1			2413.3	2450.0	586.8	57.9			
Cube 5	100	100.5	100.6	100.5	101.9	103.1	102.5	100.4	100.5	100.5			2348.1	2430.0	549.8	53.4			
Core 1	70	64.5	63.7	64.1	68.8	68.9	68.9	68.5	69.0	69.0	68.8	0.9	1.0	2619.9	625.0	219.6	59.0	57.7	1.8
Core 2	70	64.3	64.3	64.3	69.0	69.0	69.0	69.4	68.8	68.8	69.0	0.9	1.0	2518.2	605.0	223.8	59.8		
Core 3	70	65.7	66.1	65.9	69.6	69.3	69.3	69.3	69.0	69.0	69.3	1.0	1.0	2477.1	615.0	210.3	55.8		
Core 4	70	64.6	65.1	64.9	69.9	69.1	69.1	69.3	69.1	69.1	69.3	0.9	1.0	2454.0	600.0	217.4	57.7		
Core 5	70	64.6	66.8	65.7	69.2	69.2	69.2	69.6	69.0	69.1	69.2	0.9	1.0	2810.8	695.0	210.9	56.0		
Core 1	100	98.1	98.9	98.5	100.6	100.6	100.0	100.6	100.5	100.5	100.5	1.0	1.0	2447.1	1910.0	363.7	45.9	45.4	1.3
Core 2	100	100.4	99.5	99.9	100.8	100.8	100.6	100.6	100.9	100.8	100.8	1.0	1.0	2428.4	1935.0	350.8	44.0		
Core 3	100	98.5	98.6	98.5	101.0	100.5	100.6	100.6	100.6	100.6	100.7	1.0	1.0	2455.2	1925.0	374.1	47.0		
Core 4	100	100.3	100.8	100.6	101.0	100.5	100.7	100.6	100.6	100.6	100.7	1.0	1.0	2448.4	1960.0	350.1	44.0		
Core 5	100	99.4	100.3	99.9	100.5	100.7	100.5	100.6	100.7	100.7	100.6	1.0	1.0	2448.9	1945.0	364.7	45.9		
Core 1	150	137.9	136.4	137.2	143.4	143.4	143.6	143.4	143.2	143.2	143.3	1.0	1.0	2448.7	5420.0	710.6	44.0	45.8	4.2
Core 2	150	139.8	138.9	139.3	143.5	143.5	143.6	143.3	143.4	143.4	143.4	1.0	1.0	2469.4	5560.0	633.4	39.2		
Core 3	150	137.8	137.8	137.8	143.7	143.4	143.5	143.4	143.3	143.5	143.5	1.0	1.0	2453.4	5465.0	788.0	48.7		
Core 4	150	136.4	137.3	136.8	143.1	143.8	143.7	143.5	143.6	143.5	143.5	1.0	1.0	2448.4	5420.0	786.5	48.6		
Core 5	150	139.0	139.0	139.0	143.4	143.4	143.7	143.9	143.4	143.6	143.6	1.0	1.0	2449.6	5510.0	786.0	48.6		

Appendix A

William Smith

Relating concrete cube, core and cylinder compressive strengths that are cast, cured, prepared and tested in laboratory conditions

Core No.	Size	Height			Diameter								l/d ratio	Dimension Factor	Density [kg/m ³]	Weight [g]	Load [kN]	Compressive strength		Standard dev
		1	2	Ave.	1	2	3	4	5	6	Ave.	Measured						Average		
												[MPa]						[MPa]		
Cyl 1	70	69.8	70.7	70.3	70.5	70.3	70.3	70.5	70.3	69.2	70.2	1.0	1.0	2501.9	680.0	194.3	50.2	50.3	1.2	
Cyl 2	70	70.3	69.6	70.0	70.3	70.2	70.5	70.6	70.2	70.6	70.4	1.0	1.0	2516.7	685.0	197.3	50.7			
Cyl 3	70	69.8	69.7	69.7	70.2	70.5	70.2	70.4	70.3	70.3	70.3	1.0	1.0	2493.8	675.0	197.1	50.8			
Cyl 4	70	69.3	70.0	69.6	70.4	70.5	70.4	70.5	70.4	70.2	70.4	1.0	1.0	2491.2	675.0	188.4	48.4			
Cyl 5	70	68.6	68.9	68.8	70.5	70.2	70.4	70.4	70.3	70.2	70.3	1.0	1.0	2507.7	670.0	200.0	51.5			
Cyl 1	100	97.9	98.2	98.0	99.9	100.8	99.6	100.5	100.5	99.7	100.2	1.0	1.0	2460.5	1900.0	461.3	58.6	59.7	1.2	
Cyl 2	100	101.7	102.2	102.0	100.4	99.1	100.1	100.4	99.8	100.5	100.1	1.0	1.0	2470.2	1980.0	480.1	61.1			
Cyl 3	100	99.7	99.4	99.6	100.6	100.3	100.4	99.7	99.8	100.4	100.2	1.0	1.0	2476.1	1945.0	479.3	60.8			
Cyl 4	100	97.3	97.5	97.4	100.1	99.7	100.4	99.7	100.0	100.5	100.1	1.0	1.0	2475.5	1895.0	465.2	59.2			
Cyl 5	100	100.4	101.0	100.7	100.0	99.8	100.3	99.8	100.4	100.0	100.0	1.0	1.0	2469.7	1955.0	462.0	58.8			
Cyl 1	150	149.3	150.4	149.9	150.1	150.5	150.2	150.3	149.6	150.6	150.2	1.0	1.0	2492.7	6620.0	935.6	52.8	54.6	1.4	
Cyl 2	150	150.1	149.8	149.9	150.0	150.0	150.1	150.2	150.2	149.9	150.1	1.0	1.0	2481.2	6580.0	982.6	55.6			
Cyl 3	150	150.0	150.4	150.2	150.0	150.1	150.5	149.8	150.0	149.9	150.1	1.0	1.0	2596.1	6895.0	980.0	55.4			
Cyl 4	150	150.3	149.8	150.0	150.5	149.7	150.3	150.1	150.1	150.4	150.2	1.0	1.0	2474.7	6575.0	945.6	53.4			
Cyl 5	150	150.0	151.3	150.7	150.1	150.0	150.3	150.1	150.2	150.3	150.2	1.0	1.0	2473.6	6600.0	992.1	56.0			

Appendix A

William Smith

Relating concrete cube, core and cylinder compressive strengths that are cast, cured, prepared and tested in laboratory conditions

Cast (C)19 mm Greywacke 30 MPa

Core No.	Size	Height			Diameter						l/d ratio	Dimension Factor	Density [kg/m ³]	Weight [g]	Load [kN]	Compressive strength		Standard dev	
		1	2	Ave.	1	2	3	4	5	6						Ave.	Measured		Average
																	[MPa]		[MPa]
Cube 1	100	100.3	100.4	100.3	101.2	97.8	99.5	100.2	100.3	100.3				2383.3	2385.0	309.7	31.0	30.8	1.2
Cube 2	100	100.1	100.0	100.0	100.8	101.9	101.3	100.0	100.0	100.0				2342.4	2375.0	319.9	31.6		
Cube 3	100	100.0	100.0	100.0	101.7	100.7	101.2	100.0	100.0	100.0				2423.5	2450.0	303.1	30.0		
Cube 4	100	100.0	100.1	100.1	99.2	100.3	99.8	100.1	100.1	100.1				2446.7	2445.0	292.0	29.2		
Cube 5	100	100.3	100.2	100.2	99.4	99.4	99.4	100.2	100.1	100.1				2410.7	2405.0	320.0	32.1		
Core 1	70	68.8	69.5	69.2	68.5	69.0	68.7	68.7	68.7	68.6	68.7	1.0	1.0	2417.6	620.0	114.4	30.8	31.4	1.3
Core 2	70	67.7	67.7	67.7	68.8	69.9	68.8	68.6	68.6	68.5	68.9	1.0	1.0	2438.3	615.0	111.1	29.8		
Core 3	70	67.2	67.2	67.2	68.6	68.8	69.1	68.4	68.4	68.8	68.7	1.0	1.0	2450.7	610.0	117.6	31.8		
Core 4	70	67.5	67.8	67.6	68.7	68.9	68.8	69.0	69.0	69.1	68.9	1.0	1.0	2437.0	615.0	124.7	33.4		
Core 5	70	67.6	67.6	67.6	68.9	69.1	68.8	68.5	68.5	69.0	68.8	1.0	1.0	2447.3	615.0	116.8	31.4		
Core 1	100	102.4	102.3	102.3	102.1	102.1	102.1	102.1	102.0	102.2	102.1	1.0	1.0	793.8	665.0	286.9	35.0	33.9	1.5
Core 2	100	101.8	102.1	101.9	102.2	102.2	102.1	102.0	102.0	102.1	102.1	1.0	1.0	2450.6	2045.0	286.9	35.0		
Core 3	100	102.0	102.1	102.1	102.2	102.2	102.3	102.1	102.2	102.0	102.2	1.0	1.0	2455.3	2055.0	282.2	34.4		
Core 4	100	101.0	100.7	100.8	102.2	102.2	102.2	102.2	102.2	102.2	102.2	1.0	1.0	2460.5	2035.0	256.8	31.3		
Core 5	100	103.0	103.1	103.1	102.1	102.1	102.2	102.1	102.0	102.1	102.1	1.0	1.0	2472.2	2085.0	276.8	33.8		
Core 1	150	144.1	142.9	143.5	143.4	143.4	143.3	143.3	143.2	143.2	143.3	1.0	1.0	2452.3	5675.0	522.6	32.4	32.6	0.9
Core 2	150	145.0	144.9	144.9	143.3	143.4	143.3	143.2	143.2	143.2	143.3	1.0	1.0	2441.8	5705.0	528.1	32.8		
Core 3	150	143.7	143.6	143.7	143.3	143.3	143.3	143.5	143.4	143.3	143.3	1.0	1.0	2439.5	5655.0	543.3	33.7		
Core 4	150	142.5	142.6	142.6	143.5	143.4	143.4	143.4	143.3	143.2	143.4	1.0	1.0	2426.7	5585.0	502.9	31.2		
Core 5	150	144.0	144.3	144.1	143.2	143.3	143.2	143.3	143.4	143.5	143.3	1.0	1.0	2430.0	5650.0	528.8	32.8		

Appendix A

William Smith

Relating concrete cube, core and cylinder compressive strengths that are cast, cured, prepared and tested in laboratory conditions

Core No.	Size	Height			Diameter								l/d ratio	Dimension Factor	Density [kg/m ³]	Weight [g]	Load [kN]	Compressive strength		Standard dev
		1	2	Ave.	1	2	3	4	5	6	Ave.	Measured						Average		
												[MPa]						[MPa]		
Cyl 1	70	70.3	69.9	70.1	70.3	70.4	70.5	70.4	70.3	70.5	70.4	1.0	1.0	2455.0	670.0	121.2	31.1	30.3	1.6	
Cyl 2	70	69.3	69.8	69.6	70.2	70.5	70.4	70.3	70.3	70.3	70.3	1.0	1.0	2460.0	665.0	114.3	29.4			
Cyl 3	70	69.5	69.3	69.4	70.6	70.5	70.6	70.5	70.4	70.4	70.5	1.0	1.0	2436.1	660.0	110.9	28.4			
Cyl 4	70	70.5	70.1	70.3	70.6	70.3	70.4	70.5	70.3	70.5	70.4	1.0	1.0	2408.3	660.0	116.8	30.0			
Cyl 5	70	70.3	70.1	70.2	70.0	70.5	70.4	70.3	70.3	70.3	70.3	1.0	1.0	2424.0	660.0	126.1	32.5			
Cyl 1	100	101.3	100.9	101.1	99.9	100.0	100.0	100.0	100.0	100.0	100.0	1.0	1.0	2476.7	1965.0	72.0	9.2	24.3	8.5	
Cyl 2	100	100.0	99.8	99.9	100.1	100.4	99.7	99.9	99.9	99.9	100.0	1.0	1.0	2436.1	1910.0	211.5	26.9			
Cyl 3	100	100.9	101.0	101.0	100.4	100.2	100.5	100.3	100.1	100.4	100.3	1.0	1.0	2462.1	1965.0	227.4	28.8			
Cyl 4	100	100.7	101.0	100.9	99.6	99.7	99.7	99.6	99.8	99.9	99.7	1.0	1.0	2456.0	1935.0	220.9	28.3			
Cyl 5	100	101.7	101.6	101.7	99.9	100.1	100.1	100.6	100.6	99.7	100.2	1.0	1.0	2446.2	1960.0	223.4	28.3			
Cyl 1	150	151.2	151.4	151.3	150.1	150.3	150.4	150.3	150.4	150.0	150.3	1.0	1.0	2467.4	6620.0	536.7	30.3	25.3	6.3	
Cyl 2	150	150.1	151.0	150.5	150.5	149.9	150.5	150.7	150.6	149.5	150.3	1.0	1.0	2472.6	6604.0	453.6	25.6			
Cyl 3	150	147.3	146.9	147.1	150.5	150.5	150.1	150.1	150.6	150.8	150.4	1.0	1.0	2466.7	6450.0	507.2	28.5			
Cyl 4	150	151.6	151.7	151.6	150.3	150.2	150.0	150.1	150.1	150.0	150.1	1.0	1.0	2491.6	6685.0	256.5	14.5			
Cyl 5	150	152.5	151.7	152.1	149.8	150.1	150.2	150.1	150.4	150.1	150.1	1.0	1.0	2472.8	6655.0	492.6	27.8			

Appendix A

William Smith

Relating concrete cube, core and cylinder compressive strengths that are cast, cured, prepared and tested in laboratory conditions

Cast (D) 19 mm Greywacke 50 MPa

Core No.	Size	Height			Diameter							l/d ratio	Dimension Factor	Density [kg/m ³]	Weight [g]	Load [kN]	Compressive strength		Standard dev
		1	2	Ave.	1	2	3	4	5	6	Ave.						Measured	Average	
																	[MPa]	[MPa]	
Cube 1	100	100.3	100.3	100.3	99.5	100.0	99.7	100.5	100.4	100.5			2453.6	2465.0	510.1	50.9	49.4	4.1	
Cube 2	100	100.0	100.0	100.0	100.1	99.3	99.7	100.2	100.2	100.2			2413.8	2410.0	513.0	51.4			
Cube 3	100	100.4	100.1	100.2	99.1	101.1	100.1	100.3	100.6	100.4			2446.4	2465.0	529.9	52.7			
Cube 4	100	100.5	100.5	100.5	100.1	101.4	100.7	100.5	100.5	100.5			2427.6	2470.0	429.7	42.4			
Cube 5	100	100.3	100.3	100.3	100.0	96.3	98.1	100.5	100.5	100.5			2472.1	2445.0	489.6	49.6			
Core 1	70	69.3	69.3	69.3	68.9	68.8	68.8	68.8	68.7	68.8	68.8	1.0	1.0	2522.9	650.0	198.8	53.5	50.5	3.5
Core 2	70	68.3	68.6	68.4	69.1	68.8	68.7	68.9	68.9	68.9	68.9	1.0	1.0	2470.1	630.0	195.5	52.5		
Core 3	70	67.8	67.9	67.9	68.9	68.8	68.8	69.0	68.9	68.7	68.8	1.0	1.0	2474.8	625.0	170.5	45.8		
Core 4	70	69.3	69.1	69.2	68.9	69.0	68.8	68.8	68.9	68.0	68.7	1.0	1.0	2494.0	640.0	177.2	47.8		
Core 5	70	68.9	68.9	68.9	69.0	69.0	69.0	69.0	68.9	68.9	68.9	1.0	1.0	2486.9	640.0	197.7	53.0		
Core 1	100	101.1	101.7	101.4	102.2	102.1	102.1	102.1	102.0	102.1	102.1	1.0	1.0	2451.0	2035.0	449.2	54.9	52.1	4.9
Core 2	100	103.0	102.9	102.9	102.1	102.0	102.1	102.2	102.2	102.1	102.1	1.0	1.0	2456.6	2070.0	437.1	53.4		
Core 3	100	101.0	100.5	100.7	102.0	102.0	102.1	102.1	102.0	102.1	102.0	1.0	1.0	2464.0	2030.0	449.4	55.0		
Core 4	100	102.6	102.4	102.5	102.1	102.0	102.1	102.1	102.2	102.2	102.1	1.0	1.0	2454.5	2060.0	440.4	53.8		
Core 5	100	102.1	101.5	101.8	102.0	102.1	102.0	102.4	102.0	102.1	102.1	1.0	1.0	2423.9	2020.0	356.0	43.5		
Core 1	150	142.8	144.1	143.5	143.4	143.3	143.3	143.4	143.5	143.3	143.3	1.0	1.0	2462.0	5700.0	711.0	44.1	48.4	3.8
Core 2	150	145.0	145.3	145.1	143.3	143.4	143.2	143.3	143.3	143.3	143.3	1.0	1.0	2465.5	5770.0	807.4	50.1		
Core 3	150	141.2	141.6	141.4	143.3	143.4	143.3	143.3	143.3	143.3	143.3	1.0	1.0	2460.0	5610.0	841.9	52.2		
Core 4	150	142.8	143.6	143.2	143.3	143.1	143.3	143.3	143.4	143.1	143.2	1.0	1.0	2466.3	5690.0	720.9	44.7		
Core 5	150	144.1	143.9	144.0	143.7	143.6	143.7	143.3	143.4	143.5	143.5	1.0	1.0	2463.7	5740.0	826.7	51.1		

Appendix A

William Smith

Relating concrete cube, core and cylinder compressive strengths that are cast, cured, prepared and tested in laboratory conditions

Core No.	Size	Height			Diameter							l/d ratio	Dimension Factor	Density [kg/m ³]	Weight [g]	Load [kN]	Compressive strength		Standard dev
		1	2	Ave.	1	2	3	4	5	6	Ave.						Measured	Average	
																	[MPa]	[MPa]	
Cyl 1	70	68.2	68.6	68.4	70.5	70.6	70.7	70.6	70.3	70.4	70.5	1.0	1.0	2452.4	655.0	187.0	47.9	45.4	3.6
Cyl 2	70	69.1	69.0	69.1	70.2	70.2	70.5	70.4	70.3	70.4	70.3	1.0	1.0	2477.8	665.0	168.6	43.4		
Cyl 3	70	68.6	68.6	68.6	70.8	70.8	70.5	70.7	70.3	70.4	70.6	1.0	1.0	2478.0	665.0	157.3	40.2		
Cyl 4	70	69.7	70.0	69.8	70.3	70.5	70.7	70.6	70.4	70.3	70.5	1.0	1.0	2460.6	670.0	190.7	48.9		
Cyl 5	70	69.6	69.1	69.3	70.3	70.5	70.6	70.3	70.6	70.3	70.4	1.0	1.0	2478.8	670.0	182.0	46.7		
Cyl 1	100	99.2	98.9	99.0	100.1	100.0	100.1	100.1	100.0	99.8	100.0	1.0	1.0	2468.3	1920.0	407.6	45.3	48.2	1.9
Cyl 2	100	100.7	100.9	100.8	100.1	100.0	100.1	100.1	100.1	100.1	100.1	1.0	1.0	2465.4	1955.0	387.9	49.3		
Cyl 3	100	101.6	101.3	101.5	100.2	99.9	100.2	100.1	100.2	100.1	100.1	1.0	1.0	2454.7	1960.0	377.8	48.0		
Cyl 4	100	101.1	101.7	101.4	100.2	100.1	99.9	100.9	100.9	100.2	100.4	1.0	1.0	2437.6	1955.0	378.7	47.9		
Cyl 5	100	100.3	100.3	100.3	100.3	100.8	100.2	99.9	100.0	100.5	100.3	1.0	1.0	2443.0	1935.0	398.0	50.4		
Cyl 1	150	151.1	151.2	151.2	150.2	150.0	149.8	150.1	150.0	150.0	150.0	1.0	1.0	2472.5	6605.0	871.5	49.3	48.6	2.9
Cyl 2	150	151.2	150.3	150.7	150.1	150.2	149.9	149.5	149.0	149.1	149.6	1.0	1.0	2482.6	6580.0	900.5	51.2		
Cyl 3	150	153.5	152.9	153.2	150.0	150.1	150.3	150.1	149.0	150.0	149.9	1.0	1.0	2475.5	6695.0	773.1	43.8		
Cyl 4	150	152.4	151.9	152.2	150.0	150.2	150.4	150.1	150.1	149.9	150.1	1.0	1.0	2460.4	6625.0	855.2	48.3		
Cyl 5	150	150.5	150.5	150.5	149.7	150.2	150.3	149.8	150.0	150.1	150.0	1.0	1.0	2474.7	6585.0	891.2	50.4		

Appendix A

William Smith

Relating concrete cube, core and cylinder compressive strengths that are cast, cured, prepared and tested in laboratory conditions

Cast (E) 26 mm Greywacke 30 MPa

Core No.	Size	Height			Diameter						l/d ratio	Dimension Factor	Density [kg/m ³]	Weight [g]	Load [kN]	Compressive strength		Standard dev	
		1	2	Ave.	1	2	3	4	5	6						Ave.	Measured		Average
																	[MPa]		[MPa]
Cube 1	100	100.0	100.2	100.1	97.9	98.7	98.3	100.1	100.0	100.1			2502.5	2465.0	302.1	30.7	30.2	0.6	
Cube 2	100	100.6	100.3	100.5	100.8	100.1	100.5	100.1	100.2	100.1			2405.5	2430.0	303.7	30.2			
Cube 3	100	100.3	100.1	100.2	100.7	102.2	101.5	100.1	100.3	100.2			2409.4	2455.0	297.2	29.2			
Cube 4	100	100.4	100.3	100.4	100.7	99.1	99.9	100.2	100.3	100.3			2431.9	2445.0	306.3	30.6			
Cube 5	100	100.0	100.3	100.1	101.1	100.3	100.7	100.1	100.5	100.3			2388.3	2415.0	307.9	30.5			
Core 1	70	68.8	69.1	69.0	68.2	68.4	68.5	68.8	68.1	68.2	68.4	1.0	1.0	2488.6	630.0	127.7	34.8	35.7	3.2
Core 2	70	66.8	66.4	66.6	68.6	68.3	68.1	68.1	68.0	68.3	68.2	1.0	1.0	2483.9	605.0	140.1	38.3		
Core 3	70	68.2	68.1	68.1	68.3	68.4	68.4	68.2	68.3	68.2	68.3	1.0	1.0	2483.2	620.0	124.4	33.9		
Core 4	70	66.9	67.5	67.2	68.3	68.2	68.3	68.4	68.6	68.2	68.3	1.0	1.0	2475.7	610.0	117.0	31.9		
Core 5	70	65.4	65.8	65.6	68.4	68.3	68.4	68.4	68.4	68.4	68.4	1.0	1.0	2470.7	595.0	145.3	39.6		
Core 1	100	97.7	97.2	97.5	102.3	102.3	102.2	102.1	102.1	102.1	102.2	1.0	1.0	2465.8	1970.0	274.7	33.5	32.5	1.0
Core 2	100	100.2	99.1	99.7	102.0	102.2	102.0	102.3	102.2	102.2	102.1	1.0	1.0	2485.9	2030.0	258.1	31.5		
Core 3	100	102.0	101.9	101.9	102.1	102.0	102.2	102.1	102.1	102.2	102.1	1.0	1.0	2492.3	2080.0	271.6	33.2		
Core 4	100	98.5	98.5	98.5	102.3	102.3	102.3	102.2	102.4	102.2	102.3	1.0	1.0	2473.0	2000.0	270.3	32.9		
Core 5	100	101.6	101.8	101.7	102.2	102.3	102.2	102.1	102.2	102.2	102.2	1.0	1.0	2487.0	2075.0	258.0	31.5		
Core 1	150	129.3	129.4	129.4	143.6	143.5	143.9	143.6	143.4	143.6	143.6	0.9	1.0	2439.7	5110.0	498.1	29.5	29.2	0.8
Core 2	150	122.7	123.3	123.0	143.5	143.6	143.4	143.2	143.4	143.5	143.4	0.9	0.9	2453.7	4875.0	517.2	30.0		
Core 3	150	131.5	132.4	131.9	143.4	143.3	143.4	143.4	143.5	143.2	143.4	0.9	1.0	2448.0	5215.0	478.7	29.6		
Core 4	150	129.8	129.2	129.5	143.3	143.3	143.5	143.3	143.4	143.4	143.4	0.9	1.0	2440.9	5105.0	472.0	28.0		
Core 5	150	129.5	129.4	129.5	143.2	143.2	143.5	143.4	143.2	143.4	143.3	0.9	1.0	2439.6	5095.0	488.6	29.1		

Appendix A

William Smith

Relating concrete cube, core and cylinder compressive strengths that are cast, cured, prepared and tested in laboratory conditions

Core No.	Size	Height			Diameter						l/d ratio	Dimension Factor	Density [kg/m ³]	Weight [g]	Load [kN]	Compressive strength		Standard dev	
		1	2	Ave.	1	2	3	4	5	6						Ave.	Measured		Average
																	[MPa]		[MPa]
Cyl 1	70	69.8	70.4	70.1	70.6	70.5	70.6	70.6	70.4	70.7	70.6	1.0	1.0	2428.0	665.0	112.8	28.9	30.7	1.3
Cyl 2	70	71.7	70.9	71.3	70.7	70.5	70.6	70.7	70.7	70.4	70.6	1.0	1.0	2473.2	690.0	118.6	30.3		
Cyl 3	70	70.7	70.4	70.5	70.3	70.3	70.2	70.2	70.3	70.4	70.3	1.0	1.0	2468.8	675.0	119.6	30.8		
Cyl 4	70	68.3	68.9	68.6	70.8	70.3	70.7	70.4	70.3	70.4	70.5	1.0	1.0	2466.0	660.0	121.5	31.1		
Cyl 5	70	65.1	65.5	65.3	70.5	70.6	70.4	70.5	70.4	70.4	70.5	0.9	1.0	2492.8	635.0	127.1	32.6		
Cyl 1	100	100.0	99.4	99.7	100.5	100.0	100.1	99.9	100.3	100.1	100.1	1.0	1.0	2477.7	1945.0	223.1	28.3	29.7	1.8
Cyl 2	100	100.6	100.2	100.4	100.3	100.7	100.0	99.7	100.1	100.5	100.2	1.0	1.0	2475.7	1960.0	230.2	29.2		
Cyl 3	100	100.5	100.8	100.6	100.2	100.0	100.2	99.9	99.6	99.9	100.0	1.0	1.0	2486.8	1965.0	221.7	28.2		
Cyl 4	100	100.1	100.2	100.2	100.1	100.6	100.5	100.4	100.5	100.5	100.4	1.0	1.0	2488.8	1975.0	239.5	30.2		
Cyl 5	100	99.8	100.2	100.0	99.8	99.8	99.7	99.6	99.8	99.9	99.8	1.0	1.0	2489.1	1945.0	254.0	32.5		
Cyl 1	150	150.8	151.3	151.0	150.1	150.3	150.1	150.1	150.1	150.0	150.1	1.0	1.0	2474.5	6615.0	474.2	26.8	28.5	1.4
Cyl 2	150	150.6	150.4	150.5	150.1	150.1	150.0	150.3	149.9	150.2	150.1	1.0	1.0	2460.6	6550.0	505.9	28.6		
Cyl 3	150	150.5	149.8	150.1	149.5	150.6	149.9	150.7	149.7	150.7	150.2	1.0	1.0	2451.9	6520.0	487.6	27.5		
Cyl 4	150	150.5	151.3	150.9	150.2	149.9	150.0	150.3	149.9	150.2	150.1	1.0	1.0	2476.5	6610.0	535.5	30.3		
Cyl 5	150	150.7	151.3	151.0	150.2	149.8	150.3	150.3	149.8	150.1	150.1	1.0	1.0	2461.6	6575.0	514.8	29.1		

Appendix A

William Smith

Relating concrete cube, core and cylinder compressive strengths that are cast, cured, prepared and tested in laboratory conditions

Cast (F) 26 mm Greywacke 50 MPa

Core No.	Size	Height			Diameter							l/d ratio	Dimension Factor	Density [kg/m ³]	Weight [g]	Load [kN]	Compressive strength		Standard dev
		1	2	Ave.	1	2	3	4	5	6	Ave.						Measured	Average	
																	[MPa]	[MPa]	
Cube 1	100	100.1	100.1	100.1	99.2	97.9	98.5	100.2	100.3	100.2			2503.8	2475.0	549.7	55.7	54.7	2.1	
Cube 2	100	100.1	100.2	100.2	101.4	101.4	101.4	100.1	100.1	100.1			2439.4	2480.0	532.7	52.5			
Cube 3	100	100.2	100.1	100.1	102.7	101.3	102.0	100.4	100.0	100.2			2432.4	2490.0	552.6	54.1			
Cube 4	100	100.1	100.4	100.2	100.9	101.4	101.1	100.0	100.3	100.1			2413.3	2450.0	586.8	57.9			
Cube 5	100	100.5	100.6	100.5	101.9	103.1	102.5	100.4	100.5	100.5			2348.1	2430.0	549.8	53.4			
Core 1	70	64.5	63.7	64.1	68.8	68.9	68.9	68.5	69.0	69.0	68.8	0.9	1.0	2619.9	625.0	219.6	59.0	57.7	1.8
Core 2	70	64.3	64.3	64.3	69.0	69.0	69.0	69.4	68.8	68.8	69.0	0.9	1.0	2518.2	605.0	223.8	59.8		
Core 3	70	65.7	66.1	65.9	69.6	69.3	69.3	69.3	69.0	69.0	69.3	1.0	1.0	2477.1	615.0	210.3	55.8		
Core 4	70	64.6	65.1	64.9	69.9	69.1	69.1	69.3	69.1	69.1	69.3	0.9	1.0	2454.0	600.0	217.4	57.7		
Core 5	70	64.6	66.8	65.7	69.2	69.2	69.2	69.6	69.0	69.1	69.2	0.9	1.0	2810.8	695.0	210.9	56.0		
Core 1	100	98.1	98.9	98.5	100.6	100.6	100.0	100.6	100.5	100.5	100.5	1.0	1.0	2447.1	1910.0	363.7	45.9	45.4	1.3
Core 2	100	100.4	99.5	99.9	100.8	100.8	100.6	100.6	100.9	100.8	100.8	1.0	1.0	2428.4	1935.0	350.8	44.0		
Core 3	100	98.5	98.6	98.5	101.0	100.5	100.6	100.6	100.6	100.6	100.7	1.0	1.0	2455.2	1925.0	374.1	47.0		
Core 4	100	100.3	100.8	100.6	101.0	100.5	100.7	100.6	100.6	100.6	100.7	1.0	1.0	2448.4	1960.0	350.1	44.0		
Core 5	100	99.4	100.3	99.9	100.5	100.7	100.5	100.6	100.7	100.7	100.6	1.0	1.0	2448.9	1945.0	364.7	45.9		
Core 1	150	137.9	136.4	137.2	143.4	143.4	143.6	143.4	143.2	143.2	143.3	1.0	1.0	2448.7	5420.0	710.6	44.0	45.8	4.2
Core 2	150	139.8	138.9	139.3	143.5	143.5	143.6	143.3	143.4	143.4	143.4	1.0	1.0	2469.4	5560.0	633.4	39.2		
Core 3	150	137.8	137.8	137.8	143.7	143.4	143.5	143.4	143.3	143.5	143.5	1.0	1.0	2453.4	5465.0	788.0	48.7		
Core 4	150	136.4	137.3	136.8	143.1	143.8	143.7	143.5	143.6	143.5	143.5	1.0	1.0	2448.4	5420.0	786.5	48.6		
Core 5	150	139.0	139.0	139.0	143.4	143.4	143.7	143.9	143.4	143.6	143.6	1.0	1.0	2449.6	5510.0	786.0	48.6		

Appendix A

William Smith

Relating concrete cube, core and cylinder compressive strengths that are cast, cured, prepared and tested in laboratory conditions

Core No.	Size	Height			Diameter								l/d ratio	Dimension Factor	Density [kg/m ³]	Weight [g]	Load [kN]	Compressive strength		Standard dev
		1	2	Ave.	1	2	3	4	5	6	Ave.	Measured						Average		
												[MPa]						[MPa]		
Cyl 1	70	69.8	70.7	70.3	70.5	70.3	70.3	70.5	70.3	69.2	70.2	1.0	1.0	2501.9	680.0	194.3	50.2	50.3	1.2	
Cyl 2	70	70.3	69.6	70.0	70.3	70.2	70.5	70.6	70.2	70.6	70.4	1.0	1.0	2516.7	685.0	197.3	50.7			
Cyl 3	70	69.8	69.7	69.7	70.2	70.5	70.2	70.4	70.3	70.3	70.3	1.0	1.0	2493.8	675.0	197.1	50.8			
Cyl 4	70	69.3	70.0	69.6	70.4	70.5	70.4	70.5	70.4	70.2	70.4	1.0	1.0	2491.2	675.0	188.4	48.4			
Cyl 5	70	68.6	68.9	68.8	70.5	70.2	70.4	70.4	70.3	70.2	70.3	1.0	1.0	2507.7	670.0	200.0	51.5			
Cyl 1	100	97.9	98.2	98.0	99.9	100.8	99.6	100.5	100.5	99.7	100.2	1.0	1.0	2460.5	1900.0	461.3	58.6	59.7	1.2	
Cyl 2	100	101.7	102.2	102.0	100.4	99.1	100.1	100.4	99.8	100.5	100.1	1.0	1.0	2470.2	1980.0	480.1	61.1			
Cyl 3	100	99.7	99.4	99.6	100.6	100.3	100.4	99.7	99.8	100.4	100.2	1.0	1.0	2476.1	1945.0	479.3	60.8			
Cyl 4	100	97.3	97.5	97.4	100.1	99.7	100.4	99.7	100.0	100.5	100.1	1.0	1.0	2475.5	1895.0	465.2	59.2			
Cyl 5	100	100.4	101.0	100.7	100.0	99.8	100.3	99.8	100.4	100.0	100.0	1.0	1.0	2469.7	1955.0	462.0	58.8			
Cyl 1	150	149.3	150.4	149.9	150.1	150.5	150.2	150.3	149.6	150.6	150.2	1.0	1.0	2492.7	6620.0	935.6	52.8	54.6	1.4	
Cyl 2	150	150.1	149.8	149.9	150.0	150.0	150.1	150.2	150.2	149.9	150.1	1.0	1.0	2481.2	6580.0	982.6	55.6			
Cyl 3	150	150.0	150.4	150.2	150.0	150.1	150.5	149.8	150.0	149.9	150.1	1.0	1.0	2596.1	6895.0	980.0	55.4			
Cyl 4	150	150.3	149.8	150.0	150.5	149.7	150.3	150.1	150.1	150.4	150.2	1.0	1.0	2474.7	6575.0	945.6	53.4			
Cyl 5	150	150.0	151.3	150.7	150.1	150.0	150.3	150.1	150.2	150.3	150.2	1.0	1.0	2473.6	6600.0	992.1	56.0			

Appendix A

William Smith

Relating concrete cube, core and cylinder compressive strengths that are cast, cured, prepared and tested in laboratory conditions

Cast (G) 19 mm Greywacke 60 MPa

Core No.	Size	Height			Diameter							l/d ratio	Dimension Factor	Density [kg/m ³]	Weight [g]	Load [kN]	Compressive strength		Standard dev
		1	2	Ave.	1	2	3	4	5	6	Ave.						Measured	Average	
																	[MPa]	[MPa]	
Cube 1	100	100.4	100.5	100.4	100.6	102.4	101.5	100.3	100.6	100.5				2426.8	2485.0	653.8	64.1	63.8	1.1
Cube 2	100	100.3	100.4	100.4	100.6	100.2	100.4	100.3	100.0	100.2				2447.3	2470.0	655.1	65.1		
Cube 3	100	100.1	100.2	100.1	102.6	101.4	102.0	100.0	100.0	100.0				2448.0	2500.0	643.5	63.1		
Cube 4	100	100.3	100.1	100.2	101.2	102.6	101.9	100.4	100.6	100.5				2442.4	2505.0	637.8	62.3		
Cube 5	100	100.4	100.1	100.3	98.3	98.2	98.2	100.6	100.5	100.6				2453.4	2430.0	638.3	64.6		
Core 1	70	67.3	64.7	66.0	68.8	69.0	69.1	68.8	68.8	68.9	68.9	1.0	1.0	2560.1	630.0	251.3	67.4	66.9	0.8
Core 2	70	66.8	67.4	67.1	69.1	68.9	69.1	69.1	69.1	68.9	69.0	1.0	1.0	2469.3	620.0	252.1	67.4		
Core 3	70	66.7	66.9	66.8	68.9	69.0	68.8	69.0	68.8	68.6	68.9	1.0	1.0	2472.5	615.0	251.5	67.5		
Core 4	70	67.2	67.4	67.3	68.8	68.9	68.8	69.0	68.8	69.0	68.9	1.0	1.0	2470.8	620.0	244.6	65.6		
Core 5	70	66.9	66.7	66.8	69.1	68.9	69.2	69.1	69.2	69.0	69.1	1.0	1.0	2476.8	620.0	250.2	66.7		
Core 1	100	103.4	103.1	103.2	102.2	102.2	102.1	102.1	102.1	102.1	102.1	1.0	1.0	2465.4	2085.0	521.7	63.7	61.8	3.7
Core 2	100	102.9	103.7	103.3	102.1	102.1	102.1	102.1	102.1	102.1	102.1	1.0	1.0	2464.9	2085.0	542.7	66.3		
Core 3	100	102.8	102.5	102.7	102.0	102.1	102.0	102.1	102.0	102.1	102.1	1.0	1.0	2470.3	2075.0	477.6	58.4		
Core 4	100	101.6	102.2	101.9	102.0	102.1	102.1	102.2	102.2	102.1	102.1	1.0	1.0	2469.3	2060.0	470.6	57.5		
Core 5	100	103.3	103.4	103.3	102.1	102.1	102.1	102.2	102.2	102.2	102.1	1.0	1.0	2468.4	2090.0	516.7	63.1		
Core 1	150	136.6	136.2	136.4	143.4	143.3	143.4	143.4	143.6	143.4	143.4	1.0	1.0	2471.2	5445.0	1008.6	62.4	61.7	3.8
Core 2	150	131.8	131.2	131.5	143.6	143.6	143.6	143.4	143.4	143.5	143.5	0.9	1.0	2467.8	5250.0	1030.3	63.7		
Core 3	150	135.6	136.4	136.0	143.4	143.3	143.3	143.6	143.6	143.5	143.4	0.9	1.0	2479.7	5450.0	902.7	55.9		
Core 4	150	136.2	136.2	136.2	143.1	143.4	143.4	143.5	143.6	143.6	143.4	0.9	1.0	2464.1	5420.0	981.9	60.8		
Core 5	150	136.0	135.9	135.9	143.5	143.4	143.4	143.4	143.4	143.4	143.4	0.9	1.0	2477.3	5440.0	1064.4	65.9		

Appendix A

William Smith

Relating concrete cube, core and cylinder compressive strengths that are cast, cured, prepared and tested in laboratory conditions

Core No.	Size	Height			Diameter							l/d ratio	Dimension Factor	Density [kg/m ³]	Weight [g]	Load [kN]	Compressive strength		Standard dev
		1	2	Ave.	1	2	3	4	5	6	Ave.						Measured	Average	
																	[MPa]	[MPa]	
Cyl 1	70	71.1	70.7	70.9	70.4	70.3	70.3	70.5	70.4	70.3	70.4	1.0	1.0	2465.6	680.0	230.7	59.3	57.5	2.1
Cyl 2	70	70.6	70.8	70.7	70.0	70.1	70.5	70.4	70.4	70.3	70.3	1.0	1.0	2479.3	680.0	218.5	56.3		
Cyl 3	70	70.6	70.7	70.6	70.9	70.3	70.7	70.5	70.6	70.4	70.6	1.0	1.0	2479.1	685.0	233.2	59.6		
Cyl 4	70	70.5	70.7	70.6	70.4	70.3	70.5	70.3	70.1	70.5	70.4	1.0	1.0	2497.4	685.0	212.4	54.6		
Cyl 5	70	71.1	70.9	71.0	70.2	70.4	70.6	70.4	70.5	70.5	70.4	1.0	1.0	2476.8	685.0	225.1	57.8		
Cyl 1	100	102.1	102.0	102.0	99.5	100.2	99.9	100.0	99.7	99.9	99.9	1.0	1.0	2476.3	1980.0	502.8	64.2	62.4	1.7
Cyl 2	100	102.0	101.9	101.9	100.1	100.1	100.2	100.3	99.9	100.3	100.1	1.0	1.0	2472.5	1985.0	497.4	63.1		
Cyl 3	100	100.1	100.5	100.3	100.2	99.8	99.6	100.0	100.7	100.7	100.2	1.0	1.0	2466.3	1950.0	501.6	63.6		
Cyl 4	100	101.0	101.4	101.2	100.2	100.3	100.2	99.8	100.1	100.1	100.1	1.0	1.0	2484.0	1980.0	476.3	60.5		
Cyl 5	100	101.5	100.9	101.2	100.4	100.4	100.6	100.5	100.4	100.4	100.4	1.0	1.0	2469.2	1980.0	481.4	60.8		
Cyl 1	150	151.5	150.5	151.0	150.5	150.5	150.2	150.0	150.0	150.3	150.2	1.0	1.0	2478.4	6635.0	1123.4	63.4	60.0	2.8
Cyl 2	150	149.6	151.2	150.4	150.6	150.6	149.8	150.5	150.5	149.2	150.2	1.0	1.0	2475.3	6595.0	1031.5	58.2		
Cyl 3	150	151.1	151.7	151.4	150.3	150.3	150.1	150.2	150.0	149.9	150.1	1.0	1.0	2502.1	6705.0	1087.3	61.4		
Cyl 4	150	149.7	150.5	150.1	150.5	150.5	150.1	150.2	150.1	150.0	150.2	1.0	1.0	2488.3	6620.0	1076.6	60.7		
Cyl 5	150	152.9	152.4	152.6	150.5	150.5	150.2	150.2	149.9	150.2	150.2	1.0	1.0	2471.0	6685.0	994.8	56.1		

Appendix A

William Smith

Relating concrete cube, core and cylinder compressive strengths that are cast, cured, prepared and tested in laboratory conditions

Cast (H) 19 mm Greywacke 75 MPa

Core No.	Size	Height			Diameter							l/d ratio	Dimension Factor	Density [kg/m ³]	Weight [g]	Load [kN]	Compressive strength		Standard dev
		1	2	Ave.	1	2	3	4	5	6	Ave.						Measured	Average	
																	[MPa]	[MPa]	
Cube 1	100	100.1	100.2	100.2	100.9	102.2	101.6	100.0	100.4	100.2				2422.9	2470.0	716.3	70.4	74.6	4.0
Cube 2	100	100.0	100.1	100.0	99.4	99.9	99.6	100.1	100.2	100.2				2454.3	2450.0	743.1	74.5		
Cube 3	100	100.0	100.2	100.1	98.6	98.4	98.5	100.1	100.3	100.2				2451.6	2420.0	797.6	80.9		
Cube 4	100	100.3	100.0	100.2	100.0	100.3	100.1	100.1	100.2	100.1				2454.4	2465.0	751.6	75.0		
Cube 5	100	100.1	100.1	100.1	100.9	101.7	101.3	100.1	100.0	100.1				2453.5	2490.0	731.3	72.1		
Core 1	70	66.3	66.9	66.6	69.1	68.9	69.0	69.0	68.9	69.0	69.0	1.0	1.0	2492.0	620.0	293.3	78.5	73.2	4.7
Core 2	70	66.9	67.1	67.0	68.8	69.1	68.7	69.0	69.1	69.0	68.9	1.0	1.0	2481.2	620.0	266.1	71.3		
Core 3	70	67.7	68.1	67.9	68.9	68.7	68.8	68.8	69.0	68.8	68.8	1.0	1.0	2493.9	630.0	249.3	67.0		
Core 4	70	65.1	64.6	64.8	68.9	69.0	69.1	68.9	68.9	69.2	69.0	0.9	1.0	2476.9	600.0	288.6	77.2		
Core 5	70	67.7	68.2	67.9	68.8	69.0	68.9	86.6	68.8	69.1	71.9	0.9	1.0	2287.4	630.0	291.3	71.8		
Core 1	100	102.4	102.4	102.4	102.2	102.1	102.2	102.1	102.2	102.2	102.2	1.0	1.0	2449.6	2055.0	620.8	75.8	72.5	2.8
Core 2	100	103.6	103.8	103.7	102.3	102.1	102.0	102.7	102.1	102.2	102.2	1.0	1.0	2445.4	2080.0	588.8	71.8		
Core 3	100	102.3	101.9	102.1	102.1	102.2	102.4	102.1	102.1	102.1	102.1	1.0	1.0	2456.8	2055.0	597.9	73.0		
Core 4	100	103.4	103.4	103.4	102.1	102.1	102.0	102.1	102.2	102.2	102.1	1.0	1.0	2426.2	2055.0	558.3	68.2		
Core 5	100	102.3	102.2	102.2	102.1	102.1	102.0	102.1	102.1	102.0	102.1	1.0	1.0	2480.2	2075.0	603.1	73.7		
Core 1	150	143.2	142.3	142.8	143.5	143.6	143.5	143.3	143.5	143.3	143.4	1.0	1.0	2477.1	5715.0	1126.1	69.7	71.1	3.5
Core 2	150	143.5	144.8	144.1	143.4	143.9	143.5	143.5	143.2	143.5	143.5	1.0	1.0	2473.2	5765.0	1121.8	69.4		
Core 3	150	143.5	143.9	143.7	143.3	143.7	143.5	143.2	143.3	143.5	143.4	1.0	1.0	2479.2	5755.0	1214.5	75.2		
Core 4	150	142.6	143.1	142.9	143.6	143.3	143.6	143.4	143.5	143.5	143.5	1.0	1.0	2474.0	5715.0	1083.5	67.0		
Core 5	150	143.5	143.9	143.7	143.5	143.3	143.4	143.5	143.4	143.7	143.5	1.0	1.0	2477.2	5755.0	1201.1	74.3		

Core No.	Size	Height			Diameter								l/d ratio	Dimension Factor	Density [kg/m ³]	Weight [g]	Load [kN]	Compressive strength		Standard dev
		1	2	Ave.	1	2	3	4	5	6	Ave.	Measured						Average		
												[MPa]						[MPa]		
Cyl 1	70	68.8	69.2	69.0	70.6	70.4	70.5	70.6	70.3	70.3	70.5	1.0	1.0	2490.0	670.0	271.9	69.7	65.9	3.4	
Cyl 2	70	70.4	70.7	70.5	70.2	70.9	70.5	70.6	70.4	70.7	70.5	1.0	1.0	2466.8	680.0	256.1	65.5			
Cyl 3	70	70.1	70.6	70.4	70.2	70.5	70.5	70.4	70.3	70.3	70.4	1.0	1.0	2484.6	680.0	258.6	66.5			
Cyl 4	70	70.3	70.3	70.3	70.5	70.3	70.6	70.4	70.3	70.4	70.4	1.0	1.0	2466.2	675.0	235.8	60.6			
Cyl 5	70	71.3	71.0	71.1	70.3	70.4	70.5	70.6	70.3	70.4	70.4	1.0	1.0	2490.9	690.0	262.3	67.4			
Cyl 1	100	100.1	100.3	100.2	100.7	99.9	100.6	100.1	100.0	100.3	100.3	1.0	1.0	2458.3	1945.0	575.9	72.9	67.1	11.3	
Cyl 2	100	102.1	101.8	102.0	100.3	100.0	100.2	100.1	100.2	100.2	100.2	1.0	1.0	2476.9	1990.0	568.4	72.1			
Cyl 3	100	100.2	100.4	100.3	100.1	100.1	100.0	100.0	100.1	100.1	100.1	1.0	1.0	2466.6	1945.0	571.3	72.7			
Cyl 4	100	101.2	101.2	101.2	100.8	99.9	100.8	100.8	99.8	100.1	100.4	1.0	1.0	2485.0	1990.0	371.9	47.0			
Cyl 5	100	102.7	102.1	102.4	100.1	99.2	100.2	100.5	100.1	100.3	100.1	1.0	1.0	2477.3	1995.0	557.3	70.9			
Cyl 1	150	152.1	152.4	152.2	150.2	150.0	150.2	150.0	150.2	150.8	150.2	1.0	1.0	2484.1	6700.0	1156.0	65.2	66.6	1.8	
Cyl 2	150	152.1	152.4	152.3	150.2	150.1	150.2	149.7	150.3	150.2	150.1	1.0	1.0	2470.5	6655.0	1171.9	66.2			
Cyl 3	150	152.8	153.3	153.0	150.1	150.0	150.3	150.2	149.7	150.1	150.1	1.0	1.0	2484.1	6725.0	1183.4	66.9			
Cyl 4	150	152.3	152.6	152.5	150.2	150.4	149.9	150.0	149.7	150.1	150.1	1.0	1.0	2485.2	6700.0	1230.3	69.6			
Cyl 5	150	152.0	152.3	152.1	150.5	150.5	150.3	150.2	149.9	150.2	150.3	1.0	1.0	2479.8	6690.0	1156.5	65.2			

Appendix A

William Smith

Relating concrete cube, core and cylinder compressive strengths that are cast, cured, prepared and tested in laboratory conditions

Cast (I) 9 mm Quartzitic Sandstone 30 MPa

Core No.	Size	Height			Diameter							l/d ratio	Dimension Factor	Density [kg/m ³]	Weight [g]	Load [kN]	Compressive strength		Standard dev
		1	2	Ave.	1	2	3	4	5	6	Ave.						Measured	Average	
																	[MPa]	[MPa]	
Cube 1	100	100.1	100.0	100.1	101.6	101.3	101.5	100.4	100.0	100.2			2358.2	2400.0	339.1	33.3	31.4	1.2	
Cube 2	100	101.0	100.5	100.7	102.3	101.1	101.7	100.9	100.7	100.8			2342.7	2420.0	324.9	31.7			
Cube 3	100	100.3	100.1	100.2	101.6	102.7	102.2	100.1	100.0	100.0			2358.5	2415.0	319.7	31.3			
Cube 4	100	100.5	100.5	100.5	102.9	102.0	102.4	100.2	100.3	100.3			2373.7	2450.0	316.0	30.8			
Cube 5	100	100.6	100.7	100.7	102.1	102.6	102.4	100.3	100.5	100.4			2329.3	2410.0	308.4	30.0			
Core 1	50	49.5	49.4	49.4	52.3	52.2	52.6	52.4	52.4	52.4	52.4	0.9	1.0	2394.8	255.0	70.5	32.7	32.7	0.8
Core 2	50	49.9	50.3	50.1	52.3	52.0	52.1	52.1	52.1	52.1	52.1	1.0	1.0	2384.3	255.0	67.8	31.8		
Core 3	50	51.2	52.0	51.6	52.4	52.4	52.4	52.3	52.3	52.3	52.3	1.0	1.0	2387.2	265.0	73.0	33.9		
Core 4	50	50.1	50.6	50.3	52.2	52.0	52.4	52.2	52.2	52.4	52.2	1.0	1.0	2364.6	255.0	70.4	32.9		
Core 5	50	49.0	48.7	48.8	52.3	52.2	52.8	52.2	52.1	52.3	52.3	0.9	1.0	2383.4	250.0	69.4	32.3		
Core 1	70	66.0	65.7	65.9	68.9	68.9	68.9	68.9	68.9	69.0	68.9	1.0	1.0	2401.5	590.0	125.9	33.8	34.3	1.1
Core 2	70	64.8	64.9	64.8	69.2	69.2	69.0	69.2	69.2	69.2	69.2	0.9	1.0	2401.7	585.0	129.0	34.4		
Core 3	70	64.3	64.2	64.2	68.8	69.1	68.8	69.1	69.1	69.8	69.1	0.9	1.0	2387.1	575.0	122.8	32.7		
Core 4	70	62.4	62.3	62.3	69.1	69.1	69.3	68.4	68.9	68.2	68.8	0.9	1.0	2413.9	560.0	131.6	35.4		
Core 5	70	65.1	64.5	64.8	68.7	68.8	68.9	68.7	69.0	68.9	68.8	0.9	1.0	2408.5	580.0	130.9	35.2		
Core 1	100	98.6	98.6	98.6	100.5	100.9	100.4	100.8	100.9	100.9	100.7	1.0	1.0	2367.2	1860.0	253.9	31.9	31.7	0.4
Core 2	100	100.6	100.5	100.5	100.6	100.6	100.5	100.6	100.6	100.6	100.6	1.0	1.0	2391.5	1910.0	253.4	31.9		
Core 3	100	98.6	98.6	98.6	100.8	100.7	100.7	100.1	100.7	100.9	100.6	1.0	1.0	2384.4	1870.0	254.4	32.0		
Core 4	100	98.9	100.9	99.9	100.6	100.6	101.0	100.9	100.9	100.4	100.8	1.0	1.0	2405.0	1915.0	247.7	31.1		
Core 5	100	100.9	100.6	100.8	100.6	100.6	100.9	100.8	100.6	100.8	100.7	1.0	1.0	2391.9	1920.0	252.1	31.7		

Appendix A

William Smith

Relating concrete cube, core and cylinder compressive strengths that are cast, cured, prepared and tested in laboratory conditions

Core No.	Size	Height			Diameter							l/d ratio	Dimension Factor	Density	Weight	Load	Compressive strength		Standard dev
		1	2	Ave.	1	2	3	4	5	6	Ave.						Measured	Average	
														[kg/m ³]	[g]	[kN]	[MPa]	[MPa]	
Core 1	150	137.4	137.8	137.6	143.3	143.4	143.3	143.6	143.3	143.3	143.4	1.0	1.0	2396.8	5325.0	496.4	30.7	31.6	0.7
Core 2	150	137.4	135.6	136.5	143.1	143.4	143.8	143.3	143.5	143.4	143.4	1.0	1.0	2374.0	5235.0	512.7	31.7		
Core 3	150	135.2	136.0	135.6	143.2	144.0	143.4	143.3	143.2	143.2	143.4	0.9	1.0	2404.0	5260.0	520.6	32.3		
Core 4	150	135.6	135.0	135.3	143.8	143.8	143.2	143.3	143.6	143.8	143.6	0.9	1.0	2389.9	5235.0	506.3	31.3		
Core 5	150	135.1	136.1	135.6	143.1	143.0	143.2	143.3	143.6	143.3	143.3	0.9	1.0	2413.5	5275.0	519.1	32.2		
Cyl 1	70	67.9	67.9	67.9	70.6	70.2	70.2	70.4	70.3	70.2	70.3	1.0	1.0	2387.1	630.0	120.8	31.1	31.2	1.6
Cyl 2	70	67.9	68.0	68.0	70.3	70.4	70.4	70.3	70.3	70.3	70.3	1.0	1.0	2387.8	630.0	118.4	30.5		
Cyl 3	70	69.3	69.3	69.3	70.3	70.2	70.2	70.4	70.2	70.2	70.3	1.0	1.0	2399.9	645.0	124.5	32.1		
Cyl 4	70	70.1	69.2	69.6	70.6	70.5	70.5	70.5	70.1	70.2	70.4	1.0	1.0	2378.9	645.0	112.8	29.0		
Cyl 5	70	69.2	69.5	69.3	70.3	70.4	70.4	70.2	70.6	70.0	70.3	1.0	1.0	2395.7	645.0	128.6	33.1		
Cyl 1	100	98.6	98.2	98.4	99.9	100.1	99.7	99.9	100.1	99.8	99.9	1.0	1.0	2385.8	1840.0	258.3	33.0	33.5	0.5
Cyl 2	100	100.5	100.6	100.6	100.0	100.0	99.9	100.7	100.0	100.8	100.2	1.0	1.0	2363.1	1875.0	259.8	32.9		
Cyl 3	100	100.2	100.4	100.3	99.4	100.5	100.9	100.1	100.3	99.4	100.1	1.0	1.0	2395.4	1890.0	263.3	33.7		
Cyl 4	100	96.1	96.0	96.1	100.0	100.0	100.1	99.9	99.7	99.9	99.9	1.0	1.0	2515.5	1895.0	265.0	33.8		
Cyl 5	100	100.4	100.5	100.4	100.3	99.6	99.3	99.5	99.9	99.3	99.6	1.0	1.0	2419.9	1895.0	265.3	34.0		
Cyl 1	150	148.8	147.5	148.1	150.9	150.7	149.7	150.3	150.1	150.1	150.3	1.0	1.0	2391.1	6285.0	586.4	33.0	32.8	0.6
Cyl 2	150	150.9	149.8	150.3	149.6	150.4	149.5	150.9	150.0	150.0	150.1	1.0	1.0	2406.0	6395.0	562.4	31.8		
Cyl 3	150	147.5	148.0	147.8	150.2	149.8	150.3	150.3	150.5	150.0	150.2	1.0	1.0	2401.0	6285.0	579.1	32.7		
Cyl 4	150	149.1	150.3	149.7	149.9	150.1	150.0	150.5	149.8	150.3	150.1	1.0	1.0	2409.3	6380.0	591.9	33.5		
Cyl 5	150	150.0	149.5	149.8	149.8	150.7	150.8	150.1	150.0	150.0	150.2	1.0	1.0	2405.9	6385.0	583.9	32.9		

Appendix A

William Smith

Relating concrete cube, core and cylinder compressive strengths that are cast, cured, prepared and tested in laboratory conditions

Cast (J) 9 mm Quartzitic Sandstone 50 MPa

Core No.	Size	Height			Diameter							l/d ratio	Dimension Factor	Density [kg/m ³]	Weight [g]	Load [kN]	Compressive strength		Standard dev
		1	2	Ave.	1	2	3	4	5	6	Ave.						Measured	Average	
																	[MPa]	[MPa]	
Cube 1	100	100.0	100.2	100.1	104.6	103.7	104.1	99.7	100.0	99.9			2324.0	2420.0	518.8	49.9	53.3	2.6	
Cube 2	100	100.3	100.5	100.4	102.0	102.5	102.2	100.3	100.3	100.3			2389.9	2460.0	533.7	52.1			
Cube 3	100	99.9	99.9	99.9	101.5	103.3	102.4	99.7	100.0	99.8			2374.2	2425.0	540.1	52.8			
Cube 4	100	100.1	100.3	100.2	99.6	99.5	99.5	100.0	100.1	100.0			2420.7	2415.0	563.9	56.6			
Cube 5	100	100.0	100.5	100.3	99.6	100.5	100.0	100.1	100.4	100.2			2418.3	2430.0	552.4	55.1			
Core 1	50	52.0	51.5	51.8	52.6	52.5	52.6	52.5	52.4	52.5	52.5	1.0	1.0	2364.8	265.0	116.1	53.6	52.9	1.1
Core 2	50	51.3	51.4	51.3	52.5	52.5	52.4	52.3	52.3	52.3	52.4	1.0	1.0	2395.0	265.0	114.8	53.3		
Core 3	50	50.3	49.7	50.0	52.5	52.5	52.5	52.5	52.4	52.5	52.5	1.0	1.0	2356.9	255.0	117.1	54.1		
Core 4	50	50.9	50.6	50.7	52.4	52.5	52.3	52.2	52.3	52.2	52.3	1.0	1.0	2385.2	260.0	110.5	51.4		
Core 5	50	52.4	51.7	52.1	52.3	52.3	52.6	52.4	52.4	52.6	52.4	1.0	1.0	2357.8	265.0	112.2	52.0		
Core 1	70	66.2	66.6	66.4	69.0	69.0	68.9	68.9	69.1	68.8	68.9	1.0	1.0	2422.2	600.0	204.5	54.8	55.5	2.9
Core 2	70	65.7	65.7	65.7	68.9	69.0	69.3	69.2	69.3	69.6	69.2	0.9	1.0	2406.1	595.0	194.5	51.7		
Core 3	70	65.3	65.1	65.2	69.3	69.4	69.7	69.4	69.7	69.6	69.5	0.9	1.0	2424.9	600.0	205.4	54.1		
Core 4	70	65.6	65.4	65.5	69.0	69.2	69.1	68.2	68.2	69.1	68.8	1.0	1.0	2443.5	595.0	214.1	57.6		
Core 5	70	65.6	64.4	65.0	68.8	69.0	68.8	68.7	68.6	69.9	69.0	0.9	1.0	2430.8	590.0	220.7	59.1		
Core 1	100	101.5	101.1	101.3	100.4	100.6	100.4	100.8	100.4	100.6	100.5	1.0	1.0	2413.3	1940.0	421.8	53.1	51.8	1.5
Core 2	100	101.6	101.6	101.6	100.6	100.5	100.6	100.5	100.4	100.6	100.5	1.0	1.0	2410.5	1945.0	400.9	50.5		
Core 3	100	100.4	100.6	100.5	100.6	100.7	100.3	100.7	100.3	100.8	100.6	1.0	1.0	2406.1	1920.0	395.1	49.8		
Core 4	100	100.0	100.7	100.3	100.4	100.4	100.6	100.4	100.8	100.6	100.5	1.0	1.0	2411.9	1920.0	418.5	52.8		
Core 5	100	100.4	101.0	100.7	100.6	100.7	100.8	100.5	100.7	100.5	100.6	1.0	1.0	2411.8	1930.0	419.1	52.7		

Appendix A

William Smith

Relating concrete cube, core and cylinder compressive strengths that are cast, cured, prepared and tested in laboratory conditions

Core No.	Size	Height			Diameter							l/d ratio	Dimension Factor	Density [kg/m ³]	Weight [g]	Load [kN]	Compressive strength		Standard dev
		1	2	Ave.	1	2	3	4	5	6	Ave.						Measured	Average	
																	[MPa]	[MPa]	
Core 1	150	137.0	136.5	136.8	143.6	143.3	143.5	143.2	143.7	143.3	143.4	1.0	1.0	2403.8	5310.0	839.3	52.0	53.3	1.1
Core 2	150	139.4	138.7	139.1	143.4	143.6	143.4	143.8	143.7	143.6	143.6	1.0	1.0	2409.8	5425.0	860.3	53.1		
Core 3	150	140.7	140.9	140.8	143.5	143.3	143.4	143.3	143.3	143.2	143.3	1.0	1.0	2385.5	5420.0	850.2	52.7		
Core 4	150	136.1	136.4	136.3	143.4	143.3	143.4	143.4	143.3	143.4	143.4	1.0	1.0	2421.2	5325.0	887.5	55.0		
Core 5	150	139.3	140.0	139.7	143.8	143.4	143.4	143.4	143.9	143.6	143.6	1.0	1.0	2403.8	5435.0	867.5	53.6		
Cyl 1	70	69.5	68.8	69.2	70.4	70.5	70.5	70.4	70.3	70.4	70.4	1.0	1.0	2413.0	650.0	194.1	49.9	52.3	2.0
Cyl 2	70	68.4	68.6	68.5	70.4	70.2	70.6	70.4	70.4	70.6	70.4	1.0	1.0	2419.1	645.0	201.1	51.6		
Cyl 3	70	70.1	69.3	69.7	70.2	70.1	70.3	70.4	70.2	70.3	70.3	1.0	1.0	2405.7	650.0	198.3	51.1		
Cyl 4	70	70.1	70.4	70.2	70.8	70.3	70.7	70.4	70.3	70.4	70.5	1.0	1.0	2427.0	665.0	211.4	54.2		
Cyl 5	70	70.3	69.8	70.0	70.5	70.3	70.4	70.2	70.3	70.3	70.3	1.0	1.0	2407.6	655.0	212.2	54.6		
Cyl 1	100	101.3	101.2	101.2	100.3	100.4	100.2	100.2	100.5	100.1	100.3	1.0	1.0	2420.1	1935.0	448.9	56.8	56.9	0.3
Cyl 2	100	99.7	98.2	99.0	100.1	99.7	99.5	100.1	99.7	100.3	99.9	1.0	1.0	24437.6	18956.0	443.5	56.6		
Cyl 3	100	99.7	99.7	99.7	100.0	100.1	100.0	100.0	100.0	100.0	100.0	1.0	1.0	2426.4	1900.0	449.6	57.2		
Cyl 4	100	99.9	100.4	100.1	100.5	100.2	99.7	100.1	99.9	100.1	100.1	1.0	1.0	2424.9	1910.0	450.0	57.2		
Cyl 5	100	99.6	100.7	100.1	100.6	100.1	99.9	100.1	100.2	99.8	100.1	1.0	1.0	2423.0	1910.0	448.2	56.9		
Cyl 1	150	150.2	150.5	150.4	150.3	150.1	150.3	150.7	150.3	149.9	150.3	1.0	1.0	2420.8	6455.0	926.4	52.2	53.6	1.1
Cyl 2	150	150.8	150.9	150.8	150.1	150.0	150.3	149.4	150.5	149.9	150.0	1.0	1.0	2426.3	6470.0	957.0	54.1		
Cyl 3	150	149.7	149.7	149.7	150.2	150.3	150.4	149.6	150.2	150.1	150.1	1.0	1.0	2434.0	6450.0	956.1	54.0		
Cyl 4	150	150.1	150.5	150.3	150.3	151.0	150.1	150.5	150.5	149.9	150.4	1.0	1.0	2420.1	6460.0	976.1	55.0		
Cyl 5	150	151.6	151.1	151.4	150.3	150.5	149.9	150.1	150.1	150.2	150.2	1.0	1.0	2425.3	6500.0	937.6	52.9		

Appendix A

William Smith

Relating concrete cube, core and cylinder compressive strengths that are cast, cured, prepared and tested in laboratory conditions

Cast (K) 19 mm Quartzitic Sandstone 30 MPa

Core No.	Size	Height			Diameter							l/d ratio	Dimension Factor	Density [kg/m ³]	Weight [g]	Load [kN]	Compressive strength		Standard dev
		1	2	Ave.	1	2	3	4	5	6	Ave.						Measured	Average	
																	[MPa]	[MPa]	
Cube 1	100	100.2	100.2	100.2	97.2	97.2	97.2	100.1	100.1	100.1			2457.1	2395.0	324.8	33.4	32.0	1.0	
Cube 2	100	100.5	100.2	100.3	97.7	99.9	98.8	100.3	100.3	100.3			2409.9	2395.0	309.7	31.3			
Cube 3	100	100.2	100.3	100.3	99.7	100.2	100.0	100.4	100.3	100.4			2431.0	2445.0	323.3	32.2			
Cube 4	100	100.0	100.0	100.0	99.7	99.9	99.8	100.0	100.0	100.0			2340.9	2335.0	319.7	32.1			
Cube 5	100	100.1	100.4	100.2	101.6	101.5	101.5	100.4	100.5	100.4			2353.1	2405.0	314.1	30.8			
Core 1	50	52.1	51.7	51.9	52.7	52.8	52.7	53.0	52.7	52.5	52.7	1.0	1.0	2383.6	270.0	76.8	35.2	36.2	2.8
Core 2	50	50.6	51.0	50.8	52.4	52.5	52.5	52.4	52.5	52.3	52.4	1.0	1.0	2417.1	265.0	72.7	33.6		
Core 3	50	52.8	52.2	52.5	52.5	52.6	52.6	52.4	52.3	52.5	52.5	1.0	1.0	2423.2	275.0	74.6	34.5		
Core 4	50	50.3	49.3	49.8	52.5	52.7	52.6	52.7	53.0	52.5	52.7	0.9	1.0	2395.8	260.0	88.8	40.7		
Core 5	50	51.3	53.2	52.2	52.4	52.5	52.7	52.5	52.4	52.7	52.5	1.0	1.0	2428.9	275.0	79.8	36.8		
Core 1	70	66.6	67.0	66.8	68.7	68.8	69.0	68.7	68.8	68.8	68.8	1.0	1.0	2457.2	610.0	135.7	36.5	37.7	1.8
Core 2	70	65.9	66.1	66.0	69.5	69.6	69.5	68.3	68.4	68.3	68.9	1.0	1.0	2497.7	615.0	148.6	39.8		
Core 3	70	67.1	67.6	67.4	69.3	69.3	68.5	68.3	68.3	68.0	68.6	1.0	1.0	2508.8	625.0	131.4	35.5		
Core 4	70	64.2	64.7	64.5	68.8	68.8	68.8	68.6	68.6	68.6	68.7	0.9	1.0	2531.6	605.0	138.9	37.5		
Core 5	70	67.7	67.7	67.7	69.5	68.5	69.5	68.6	68.7	68.7	68.9	1.0	1.0	2396.1	605.0	145.3	39.0		
Core 1	100	96.7	96.2	96.4	100.8	100.8	100.9	101.0	100.7	100.7	100.8	1.0	1.0	2397.3	1845.0	227.9	28.6	30.5	7.0
Core 2	100	99.9	99.6	99.7	100.7	100.9	100.6	100.8	100.7	100.7	100.7	1.0	1.0	2435.5	1935.0	286.2	35.9		
Core 3	100	101.0	100.9	101.0	100.8	100.9	100.8	100.7	100.5	100.7	100.7	1.0	1.0	2380.4	1915.0	278.6	35.0		
Core 4	100	99.7	99.6	99.6	100.7	100.7	100.4	100.7	100.4	100.5	100.6	1.0	1.0	2407.8	1905.0	151.6	19.1		
Core 5	100	100.6	100.8	100.7	100.5	100.5	100.7	100.7	100.9	100.7	100.7	1.0	1.0	2408.0	1930.0	268.3	33.7		

Appendix A

William Smith

Relating concrete cube, core and cylinder compressive strengths that are cast, cured, prepared and tested in laboratory conditions

Core No.	Size	Height			Diameter						l/d ratio	Dimension Factor	Density [kg/m ³]	Weight [g]	Load [kN]	Compressive strength		Standard dev	
		1	2	Ave.	1	2	3	4	5	6						Ave.	Measured		Average
																	[MPa]		[MPa]
Core 1	150	138.2	138.7	138.5	143.5	143.4	143.4	143.5	143.7	143.5	143.5	1.0	1.0	2418.2	5415.0	565.0	34.9	35.7	0.6
Core 2	150	139.7	140.7	140.2	143.4	143.4	143.4	143.4	143.4	143.4	143.4	1.0	1.0	2400.1	5435.0	570.9	35.3		
Core 3	150	141.8	141.2	141.5	143.6	143.5	143.7	143.5	143.6	143.4	143.5	1.0	1.0	2352.5	5385.0	587.8	36.3		
Core 4	150	139.8	139.0	139.4	143.4	143.6	143.5	143.5	143.5	143.5	143.5	1.0	1.0	2415.8	5445.0	575.2	35.6		
Core 5	150	138.2	138.2	138.2	143.9	143.6	143.3	143.5	143.5	143.8	143.6	1.0	1.0	2463.7	5515.0	585.6	36.2		
Cyl 1	70	69.4	68.8	69.1	70.2	70.5	70.1	70.3	70.2	70.4	70.3	1.0	1.0	2425.4	650.0	126.9	32.7	29.4	2.9
Cyl 2	70	69.5	68.8	69.2	70.5	70.4	70.1	70.1	70.5	70.3	70.3	1.0	1.0	2419.0	650.0	114.2	29.4		
Cyl 3	70	69.3	69.3	69.3	70.5	70.2	70.5	70.2	70.3	70.2	70.3	1.0	1.0	2433.9	655.0	120.2	30.9		
Cyl 4	70	69.3	69.1	69.2	70.5	70.7	70.6	70.4	70.4	70.3	70.5	1.0	1.0	2408.4	650.0	114.2	29.3		
Cyl 5	70	69.3	68.5	68.9	70.3	70.3	70.2	70.4	70.4	70.7	70.4	1.0	1.0	2407.0	645.0	96.5	24.8		
Cyl 1	100	99.6	100.2	99.9	100.3	100.4	99.7	99.6	100.2	99.5	99.9	1.0	1.0	2412.4	1890.0	269.2	34.3	33.8	0.8
Cyl 2	100	99.9	100.0	100.0	100.1	99.9	100.0	99.9	99.9	100.2	100.0	1.0	1.0	2439.0	1915.0	256.0	32.6		
Cyl 3	100	98.8	98.9	98.9	100.6	100.1	99.6	100.6	100.3	100.3	100.2	1.0	1.0	2428.7	1895.0	262.8	33.3		
Cyl 4	100	99.4	100.1	99.7	100.1	100.1	99.8	99.8	99.9	100.1	100.0	1.0	1.0	2439.1	1910.0	272.1	34.7		
Cyl 5	100	95.5	95.9	95.7	99.8	100.1	100.0	100.0	100.2	100.0	100.0	1.0	1.0	2447.0	1840.0	266.7	33.9		
Cyl 1	150	150.5	150.3	150.4	150.1	150.3	150.0	150.5	149.9	150.1	150.2	1.0	1.0	2441.0	6500.0	537.5	30.4	31.1	1.8
Cyl 2	150	151.7	151.0	151.3	149.6	150.2	150.2	150.2	150.0	150.3	150.1	1.0	1.0	2445.1	6545.0	507.1	28.7		
Cyl 3	150	148.8	149.6	149.2	149.8	150.3	149.6	150.1	150.1	150.3	150.0	1.0	1.0	2436.8	6425.0	592.6	33.5		
Cyl 4	150	151.4	151.6	151.5	150.4	150.2	149.9	150.5	150.4	150.5	150.3	1.0	1.0	2435.8	6545.0	546.5	30.8		
Cyl 5	150	148.3	149.5	148.9	149.7	150.2	150.1	150.6	150.3	150.3	150.2	1.0	1.0	2435.3	6425.0	565.1	31.9		

Appendix A

William Smith

Relating concrete cube, core and cylinder compressive strengths that are cast, cured, prepared and tested in laboratory conditions

Cast (L) 19 mm Quartzitic Sandstone 50 MPa

Core No.	Size	Height			Diameter							l/d ratio	Dimension Factor	Density [kg/m ³]	Weight [g]	Load [kN]	Compressive strength		Standard dev
		1	2	Ave.	1	2	3	4	5	6	Ave.						Measured	Average	
																	[MPa]	[MPa]	
Cube 1	100	100.3	100.4	100.3	100.8	101.3	101.1	100.2	100.3	100.3				2439.9	2480.0	569.1	56.2	53.9	1.7
Cube 2	100	100.0	100.0	100.0	101.7	101.6	101.6	100.2	100.3	100.2				2395.0	2440.0	529.6	52.0		
Cube 3	100	100.3	100.3	100.3	103.1	102.8	103.0	100.3	100.2	100.3				2384.7	2470.0	565.0	54.7		
Cube 4	100	100.3	100.3	100.3	100.4	100.3	100.3	100.3	100.3	100.3				2407.9	2430.0	546.4	54.3		
Cube 5	100	100.2	100.0	100.1	101.6	101.7	101.7	100.2	100.3	100.2				2392.7	2440.0	533.7	52.4		
Core 1	50	53.5	54.0	53.8	52.7	52.6	52.7	52.7	52.6	52.7	52.7	1.0	1.0	2390.5	280.0	121.0	55.5	57.3	1.2
Core 2	50	52.5	52.5	52.5	52.5	52.5	52.7	52.6	52.7	52.6	52.6	1.0	1.0	2410.5	275.0	126.5	58.2		
Core 3	50	52.2	52.1	52.1	52.5	52.7	52.6	52.6	52.6	52.6	52.6	1.0	1.0	2427.4	275.0	125.5	57.8		
Core 4	50	53.4	51.6	52.5	52.9	52.7	52.6	52.2	52.2	52.5	52.5	1.0	1.0	2463.6	280.0	122.5	56.6		
Core 5	50	54.1	53.4	53.8	52.6	52.6	52.4	52.7	52.5	52.7	52.6	1.0	1.0	2357.2	275.0	127.0	58.5		
Core 1	70	67.4	66.4	66.9	69.5	69.1	69.3	69.7	69.3	68.0	69.1	1.0	1.0	2468.5	620.0	200.3	53.3	58.3	3.8
Core 2	70	67.9	67.2	67.6	69.6	69.6	69.7	68.6	68.8	69.7	69.3	1.0	1.0	2469.8	630.0	216.9	57.5		
Core 3	70	69.0	69.4	69.2	69.6	69.3	69.6	69.3	68.7	68.7	69.2	1.0	1.0	2479.2	645.0	239.7	63.8		
Core 4	70	68.6	69.2	68.9	69.4	69.2	69.4	69.5	69.4	69.4	69.4	1.0	1.0	2455.9	640.0	216.9	57.4		
Core 5	70	65.7	65.2	65.4	69.3	69.6	69.5	69.2	69.2	68.5	69.2	0.9	1.0	2458.3	605.0	223.5	59.4		
Core 1	100	98.0	97.4	97.7	100.7	100.8	100.7	100.6	100.6	100.4	100.6	1.0	1.0	2426.2	1885.0	422.5	53.1	53.4	2.0
Core 2	100	99.9	100.5	100.2	100.9	100.8	100.7	100.8	100.7	100.0	100.7	1.0	1.0	2446.4	1950.0	412.6	51.9		
Core 3	100	100.9	101.2	101.1	100.1	100.8	100.7	100.7	100.7	100.9	100.7	1.0	1.0	2418.7	1945.0	449.7	56.5		
Core 4	100	98.4	99.0	98.7	100.7	101.0	100.7	100.4	100.9	100.9	100.8	1.0	1.0	2427.4	1910.0	410.5	51.5		
Core 5	100	99.7	99.1	99.4	100.7	100.6	100.4	100.5	100.7	100.7	100.6	1.0	1.0	2442.9	1930.0	429.9	54.1		

Appendix A

William Smith

Relating concrete cube, core and cylinder compressive strengths that are cast, cured, prepared and tested in laboratory conditions

Core No.	Size	Height			Diameter							l/d ratio	Dimension Factor	Density [kg/m ³]	Weight [g]	Load [kN]	Compressive strength		Standard dev
		1	2	Ave.	1	2	3	4	5	6	Ave.						Measured	Average	
																	[MPa]	[MPa]	
Core 1	150	140.6	141.6	141.1	143.3	143.7	143.1	143.5	143.4	143.5	143.4	1.0	1.0	2448.4	5580.0	891.9	55.2	55.1	2.0
Core 2	150	141.1	141.3	141.2	143.7	143.5	143.5	143.6	143.5	143.4	143.5	1.0	1.0	2394.5	5470.0	926.5	57.3		
Core 3	150	140.1	141.1	140.6	143.5	143.3	143.1	143.5	143.7	143.4	143.4	1.0	1.0	2457.3	5580.0	876.1	54.2		
Core 4	150	140.8	141.6	141.2	143.5	143.4	143.4	143.6	143.5	143.3	143.5	1.0	1.0	2444.7	5580.0	915.4	56.6		
Core 5	150	138.2	137.6	137.9	143.5	143.5	143.4	143.6	143.7	143.1	143.5	1.0	1.0	2505.1	5585.0	844.8	52.3		
Cyl 1	70	70.1	69.7	69.9	70.3	70.3	70.3	70.4	70.4	70.2	70.3	1.0	1.0	2452.0	665.0	220.0	56.7	53.0	5.9
Cyl 2	70	67.9	67.1	67.5	70.6	70.2	70.2	70.3	70.3	70.2	70.3	1.0	1.0	2461.8	645.0	218.0	56.1		
Cyl 3	70	69.9	70.5	70.2	70.3	70.5	70.2	70.2	70.2	70.4	70.3	1.0	1.0	2457.9	670.0	208.5	53.7		
Cyl 4	70	71.6	71.7	71.7	70.3	70.2	70.3	70.1	70.2	70.1	70.2	1.0	1.0	2434.1	675.0	165.0	42.6		
Cyl 5	70	70.5	69.6	70.1	70.3	70.1	70.1	70.3	70.3	70.3	70.2	1.0	1.0	2504.4	680.0	216.0	55.8		
Cyl 1	100	100.1	100.3	100.2	100.3	100.0	100.2	100.0	99.7	100.0	100.0	1.0	1.0	2463.8	1940.0	424.3	54.0	54.5	3.9
Cyl 2	100	102.1	101.8	102.0	100.1	100.0	100.1	100.0	99.9	100.0	100.0	1.0	1.0	2385.0	1910.0	437.5	55.7		
Cyl 3	100	100.2	100.4	100.3	99.4	100.6	100.8	99.4	100.4	99.8	100.1	1.0	1.0	2370.7	1870.0	455.4	57.9		
Cyl 4	100	101.2	101.2	101.2	99.7	100.0	100.0	99.4	99.5	99.8	99.7	1.0	1.0	2429.0	1920.0	445.6	57.0		
Cyl 5	100	102.7	102.1	102.4	100.2	99.8	99.9	99.7	99.9	100.2	100.0	1.0	1.0	2390.2	1920.0	377.6	48.1		
Cyl 1	150	152.1	152.4	152.2	150.6	150.3	150.0	150.5	149.9	150.2	150.2	1.0	1.0	2397.8	6470.0	969.4	54.7	52.8	1.4
Cyl 2	150	152.1	152.4	152.3	150.3	150.1	150.2	150.1	150.1	150.0	150.1	1.0	1.0	2413.1	6505.0	920.5	52.0		
Cyl 3	150	152.8	153.3	153.0	150.3	150.3	150.0	150.2	150.1	150.1	150.2	1.0	1.0	2392.7	6485.0	903.7	51.0		
Cyl 4	150	152.3	152.6	152.5	150.2	149.8	150.2	150.4	149.7	150.1	150.1	1.0	1.0	2445.9	6595.0	935.4	52.9		
Cyl 5	150	152.0	152.3	152.1	150.5	149.7	150.0	150.0	150.3	149.9	150.1	1.0	1.0	2411.9	6490.0	940.6	53.2		

Appendix A

William Smith

Relating concrete cube, core and cylinder compressive strengths that are cast, cured, prepared and tested in laboratory conditions

Cast (M) 26 mm Quartzitic Sandstone 30 MPa

Core No.	Size	Height			Diameter							l/d ratio	Dimension Factor	Density [kg/m ³]	Weight [g]	Load [kN]	Compressive strength		Standard dev
		1	2	Ave.	1	2	3	4	5	6	Ave.						Measured	Average	
																	[MPa]	[MPa]	
Cube 1	100	100.0	100.2	100.1	99.5	98.7	99.1	100.1	100.0	100.1			2387.2	2370.0	299.3	30.2	29.6	1.1	
Cube 2	100	99.7	99.7	99.7	101.4	100.1	100.8	99.6	99.6	99.6			2413.8	2415.0	306.2	30.5			
Cube 3	100	99.9	100.0	100.0	100.8	102.2	101.5	100.1	100.0	100.1			2363.9	2400.0	288.0	28.4			
Cube 4	100	100.2	100.1	100.1	98.7	99.1	98.9	99.9	100.1	100.0			2373.2	2350.0	301.3	30.5			
Cube 5	100	100.2	100.2	100.2	99.5	100.3	99.9	100.3	100.1	100.2			2382.5	2390.0	285.3	28.5			
Core 1	50	50.7	50.8	50.7	52.7	52.6	52.7	52.9	52.6	52.8	52.7	1.0	1.0	2438.0	270.0	84.9	38.9	37.5	1.0
Core 2	50	50.1	50.5	50.3	52.7	52.7	52.9	52.9	52.6	52.1	52.6	1.0	1.0	2375.9	260.0	80.0	36.8		
Core 3	50	51.4	50.8	51.1	52.8	52.7	52.9	52.7	52.7	52.7	52.7	1.0	1.0	2421.5	270.0	81.7	37.4		
Core 4	50	52.0	51.6	51.8	52.6	52.6	52.7	52.8	52.8	53.0	52.8	1.0	1.0	2385.8	270.0	83.1	38.0		
Core 5	50	51.5	49.3	50.4	52.6	52.6	52.9	52.6	52.7	52.9	52.7	1.0	1.0	2410.5	265.0	79.2	36.3		
Core 1	70	64.5	65.2	64.8	68.7	68.8	68.7	68.7	68.8	68.7	68.7	0.9	1.0	2432.6	585.0	137.0	36.9	38.4	2.7
Core 2	70	67.8	67.2	67.5	68.7	68.7	68.7	68.6	68.8	68.8	68.7	1.0	1.0	2440.5	610.0	152.0	41.0		
Core 3	70	66.4	67.4	66.9	68.5	68.8	68.7	68.8	68.8	68.7	68.7	1.0	1.0	2458.4	610.0	128.0	34.5		
Core 4	70	68.5	68.3	68.4	68.7	68.7	68.7	68.8	68.6	68.8	68.7	1.0	1.0	2446.2	620.0	151.0	40.7		
Core 5	70	66.7	65.5	66.1	68.7	68.7	68.7	68.9	68.7	68.8	68.7	1.0	1.0	2445.1	600.0	145.0	39.1		
Core 1	100	99.1	99.3	99.2	100.6	100.6	100.9	100.7	100.7	100.5	100.7	1.0	1.0	2443.0	1930.0	268.3	33.7	33.1	1.8
Core 2	100	100.8	100.3	100.5	100.8	100.2	100.8	100.7	100.7	100.6	100.7	1.0	1.0	2437.2	1950.0	260.0	32.7		
Core 3	100	96.8	95.9	96.3	100.7	100.7	100.9	100.8	100.7	100.9	100.8	1.0	1.0	2421.2	1860.0	247.6	31.0		
Core 4	100	100.6	100.7	100.6	100.6	100.4	100.6	100.6	100.6	100.8	100.6	1.0	1.0	2443.4	1955.0	285.2	35.9		
Core 5	100	98.0	98.1	98.1	100.5	100.5	100.8	100.7	100.7	100.6	100.6	1.0	1.0	2437.0	1900.0	256.2	32.2		

Appendix A

William Smith

Relating concrete cube, core and cylinder compressive strengths that are cast, cured, prepared and tested in laboratory conditions

Core No.	Size	Height			Diameter							l/d ratio	Dimension Factor	Density [kg/m ³]	Weight [g]	Load [kN]	Compressive strength		Standard dev
		1	2	Ave.	1	2	3	4	5	6	Ave.						Measured	Average	
																	[MPa]	[MPa]	
Core 1	150	141.1	141.2	141.1	143.7	143.5	143.4	143.5	143.7	143.6	143.6	1.0	1.0	2416.6	5520.0	545.7	33.7	32.7	0.6
Core 2	150	139.8	140.7	140.3	143.5	143.6	143.6	143.6	143.5	143.6	143.6	1.0	1.0	2433.6	5525.0	526.2	32.5		
Core 3	150	137.9	138.0	138.0	143.5	143.4	143.5	143.6	143.2	143.4	143.4	1.0	1.0	2433.5	5425.0	518.5	32.1		
Core 4	150	140.9	140.7	140.8	143.4	143.4	143.6	143.5	143.6	143.4	143.5	1.0	1.0	2431.6	5535.0	532.3	32.9		
Core 5	150	139.9	139.4	139.7	143.4	143.5	143.6	143.5	143.9	143.7	143.6	1.0	1.0	2427.8	5490.0	523.6	32.3		
Cyl 1	70	70.0	70.5	70.3	70.3	70.4	70.3	70.2	70.2	70.2	70.3	1.0	1.0	2438.4	665.0	113.5	29.3	32.0	2.6
Cyl 2	70	71.3	70.0	70.6	70.6	70.3	70.2	70.4	70.2	70.3	70.3	1.0	1.0	2423.0	665.0	122.0	31.4		
Cyl 3	70	69.6	68.7	69.2	70.2	70.2	70.5	70.3	70.4	70.2	70.3	1.0	1.0	2440.3	655.0	137.0	35.3		
Cyl 4	70	70.4	70.5	70.4	70.7	70.5	70.2	70.3	70.3	70.2	70.4	1.0	1.0	2427.6	665.0	117.0	30.1		
Cyl 5	70	70.4	70.9	70.7	70.1	70.5	70.0	70.2	70.4	70.3	70.2	1.0	1.0	2430.1	665.0	132.0	34.1		
Cyl 1	100	99.4	99.9	99.7	100.2	100.2	100.2	100.1	100.1	99.9	100.1	1.0	1.0	2435.2	1910.0	268.3	34.1	33.5	1.8
Cyl 2	100	100.1	99.6	99.8	99.8	100.1	100.2	100.3	100.2	99.9	100.1	1.0	1.0	2438.3	1915.0	260.0	33.0		
Cyl 3	100	100.6	101.6	101.1	100.2	99.8	100.2	99.8	99.9	100.4	100.0	1.0	1.0	2434.7	1935.0	247.6	31.5		
Cyl 4	100	100.0	100.4	100.2	99.9	100.3	100.1	100.1	99.9	99.6	100.0	1.0	1.0	2434.0	1915.0	285.2	36.3		
Cyl 5	100	98.0	98.5	98.3	100.1	100.1	100.2	100.2	99.8	99.9	100.0	1.0	1.0	2447.1	1890.0	256.2	32.6		
Cyl 1	150	149.5	149.9	149.7	150.0	150.1	150.1	150.1	150.2	150.0	150.1	1.0	1.0	2441.6	6465.0	535.5	30.3	29.2	1.8
Cyl 2	150	151.0	150.0	150.5	150.0	150.5	150.9	149.9	150.5	149.8	150.3	1.0	1.0	2452.7	6545.0	547.6	30.9		
Cyl 3	150	152.9	152.1	152.5	150.2	150.1	150.2	150.0	150.3	150.0	150.1	1.0	1.0	2441.4	6590.0	490.1	27.7		
Cyl 4	150	150.1	149.8	149.9	150.4	149.8	150.4	150.3	150.0	150.2	150.2	1.0	1.0	2439.8	6480.0	475.8	26.9		
Cyl 5	150	149.4	150.0	149.7	149.6	150.3	149.5	150.0	150.1	150.0	149.9	1.0	1.0	2437.6	6440.0	529.8	30.0		

Appendix A

William Smith

Relating concrete cube, core and cylinder compressive strengths that are cast, cured, prepared and tested in laboratory conditions

Cast (N) 26 mm Quartzitic Sandstone 50 MPa

Core No.	Size	Height			Diameter							l/d ratio	Dimension Factor	Density [kg/m ³]	Weight [g]	Load [kN]	Compressive strength		Standard dev
		1	2	Ave.	1	2	3	4	5	6	Ave.						Measured	Average	
																	[MPa]	[MPa]	
Cube 1	100	99.9	99.9	99.9	99.7	99.8	99.7	100.0	99.9	100.0				2389.2	2380.0	509.0	51.1	49.8	1.3
Cube 2	100	100.4	100.4	100.4	101.1	101.0	101.0	100.1	100.3	100.2				2404.5	2445.0	520.0	51.3		
Cube 3	100	100.0	100.0	100.0	100.5	100.1	100.3	100.2	100.2	100.2				2401.4	2415.0	496.0	49.3		
Cube 4	100	100.2	100.2	100.2	101.8	101.9	101.8	100.2	100.2	100.2				2385.3	2440.0	498.0	48.8		
Cube 5	100	100.2	100.1	100.2	100.7	99.0	99.9	100.6	100.2	100.4				2393.2	2405.0	487.0	48.5		
Core 1	50	50.4	49.0	49.7	52.6	52.7	52.6	52.5	52.5	52.4	52.5	0.9	1.0	2412.5	260.0	117.5	54.2	56.7	3.7
Core 2	50	50.6	49.7	50.1	52.8	52.9	52.8	52.5	52.8	52.9	52.8	0.9	1.0	2416.5	265.0	124.1	56.7		
Core 3	50	49.5	49.5	49.5	52.7	52.8	52.8	52.7	52.9	52.9	52.8	0.9	1.0	2445.9	265.0	131.2	59.9		
Core 4	50	51.9	51.7	51.8	52.9	53.0	52.9	52.8	52.8	52.9	52.9	1.0	1.0	2418.3	275.0	133.4	60.8		
Core 5	50	51.7	51.7	51.7	52.4	52.6	52.4	52.5	52.6	52.6	52.5	1.0	1.0	2413.1	270.0	112.8	52.1		
Core 1	70	69.1	68.1	68.6	68.6	68.8	68.7	68.7	68.7	68.7	68.7	1.0	1.0	2457.8	625.0	234.6	63.3	58.3	3.9
Core 2	70	64.5	65.7	65.1	68.6	69.0	68.4	68.6	68.6	68.7	68.6	0.9	1.0	2448.5	590.0	211.6	57.2		
Core 3	70	67.1	64.6	65.8	68.6	68.8	68.6	68.7	68.7	68.7	68.7	1.0	1.0	2522.1	615.0	201.0	54.3		
Core 4	70	64.7	63.9	64.3	68.7	68.6	68.7	68.5	68.7	68.5	68.6	0.9	1.0	2460.3	585.0	227.0	61.4		
Core 5	70	66.1	66.3	66.2	68.5	68.6	68.5	68.6	68.6	68.6	68.6	1.0	1.0	2453.6	600.0	205.0	55.5		
Core 1	100	101.5	100.9	101.2	100.8	100.5	100.6	100.8	100.8	100.7	100.7	1.0	1.0	2462.3	1985.0	393.5	49.4	50.6	2.8
Core 2	100	99.7	99.8	99.7	100.8	100.7	100.6	100.7	100.6	100.6	100.7	1.0	1.0	2451.3	1945.0	394.7	49.6		
Core 3	100	97.3	96.8	97.0	100.8	100.7	100.6	100.8	100.9	100.8	100.8	1.0	1.0	2449.1	1895.0	425.0	53.3		
Core 4	100	100.3	99.7	100.0	100.4	100.6	100.6	100.8	100.7	100.6	100.6	1.0	1.0	2465.1	1960.0	426.2	53.6		
Core 5	100	99.4	100.2	99.8	100.9	100.9	100.8	100.9	100.8	100.8	100.8	1.0	1.0	2446.6	1950.0	375.1	47.0		

Appendix A

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Relating concrete cube, core and cylinder compressive strengths that are cast, cured, prepared and tested in laboratory conditions

Core No.	Size	Height			Diameter							l/d ratio	Dimension Factor	Density [kg/m ³]	Weight [g]	Load [kN]	Compressive strength		Standard dev
		1	2	Ave.	1	2	3	4	5	6	Ave.						Measured	Average	
																	[MPa]	[MPa]	
Core 1	150	141.2	141.1	141.2	143.5	143.5	143.7	143.6	143.5	143.5	143.5	1.0	1.0	2453.8	5605.0	760.5	47.0	48.5	2.5
Core 2	150	141.2	142.1	141.6	143.5	143.5	143.6	143.5	143.6	143.2	143.5	1.0	1.0	2443.5	5595.0	852.4	52.7		
Core 3	150	141.9	142.6	142.3	143.5	143.5	143.6	143.2	143.4	143.6	143.5	1.0	1.0	2447.6	5630.0	792.6	49.0		
Core 4	150	141.8	142.5	130.0	143.4	143.6	143.5	143.6	143.4	143.5	143.5	0.9	1.0	2663.1	5600.0	788.2	46.8		
Core 5	150	140.3	142.5	141.4	143.4	143.5	143.6	143.5	143.4	143.5	143.5	1.0	1.0	2438.6	5575.0	763.1	47.2		
Cyl 1	70	70.1	69.2	69.6	70.0	70.4	70.0	70.3	70.4	70.2	70.2	1.0	1.0	2446.9	660.0	203.0	52.4	48.9	3.5
Cyl 2	70	70.3	69.8	70.1	70.2	70.4	70.4	70.3	70.2	70.3	70.3	1.0	1.0	2427.4	660.0	183.0	47.2		
Cyl 3	70	71.4	70.7	71.0	70.2	70.2	70.4	70.3	70.4	70.1	70.3	1.0	1.0	2395.3	660.0	191.5	49.4		
Cyl 4	70	69.5	69.7	69.6	70.4	70.2	70.3	70.2	70.3	70.5	70.3	1.0	1.0	2423.1	655.0	200.5	51.6		
Cyl 5	70	70.0	70.5	70.3	70.2	70.4	70.4	70.3	70.3	70.3	70.3	1.0	1.0	2400.6	655.0	170.5	43.9		
Cyl 1	100	101.8	100.5	101.1	100.2	100.0	100.2	100.0	100.1	99.9	100.1	1.0	1.0	2452.3	1950.0	366.5	46.6	47.6	1.9
Cyl 2	100	100.9	100.5	100.7	100.0	100.0	99.5	99.7	100.2	99.8	99.9	1.0	1.0	2452.6	1935.0	365.8	46.7		
Cyl 3	100	97.7	97.8	97.7	99.6	100.0	99.9	100.0	100.0	100.0	99.9	1.0	1.0	2439.8	1870.0	372.7	47.5		
Cyl 4	100	99.4	98.9	99.2	100.0	100.1	99.5	99.5	100.1	100.2	99.9	1.0	1.0	2444.5	1900.0	362.9	46.3		
Cyl 5	100	99.8	99.8	99.8	100.7	99.6	99.8	99.5	99.5	99.5	99.8	1.0	1.0	2422.1	1890.0	397.5	50.8		
Cyl 1	150	150.6	151.3	150.9	149.7	150.3	149.8	149.9	149.9	149.9	149.9	1.0	1.0	2441.2	6505.0	818.9	46.4	48.0	2.5
Cyl 2	150	151.4	150.7	151.0	149.7	149.8	150.3	150.2	150.1	150.3	150.1	1.0	1.0	2448.7	6540.0	829.5	46.9		
Cyl 3	150	151.6	150.3	151.0	150.3	150.0	149.9	150.2	150.2	150.0	150.1	1.0	1.0	2445.3	6530.0	915.4	51.7		
Cyl 4	150	151.5	151.7	151.6	150.0	150.4	149.2	149.7	150.2	149.7	149.9	1.0	1.0	2457.2	6570.0	873.5	49.5		
Cyl 5	150	151.8	152.8	152.3	150.3	149.6	150.3	150.3	149.5	150.3	150.0	1.0	1.0	2458.7	6620.0	806.2	45.6		

Appendix A

William Smith

Relating concrete cube, core and cylinder compressive strengths that are cast, cured, prepared and tested in laboratory conditions

EBE Faculty: Assessment of Ethics in Research Projects (Rev2)

Any person planning to undertake research in the Faculty of Engineering and the Built Environment at the University of Cape Town is required to complete this form before collecting or analysing data. When completed it should be submitted to the supervisor (where applicable) and from there to the Head of Department. If any of the questions below have been answered YES, and the applicant is NOT a fourth year student, the Head should forward this form for approval by the Faculty EIR committee: submit to Ms Zulpha Geyer (Zulpha.Geyer@uct.ac.za; Chem Eng Building, Ph 021 650 4791). **NB: A copy of this signed form must be included with the thesis/dissertation/report when it is submitted for examination**

This form must only be completed once the most recent revision EBE EIR Handbook has been read.

Name of Principal Researcher/Student: William Summ Department: Civil Engineering
 Preferred email address of the applicant: sumtwi1016@myuct.ac.za
 If a Student: Degree: MSc Eng Supervisor: A. Prof Hans Beushausen

If a Research Contract indicate source of funding/sponsorship:

Research Project Title: Relating cube, cylinder and Core compressive strength
Durability of Reinforced Concrete
~~The influence of surface treatments on the ingress of chloride ions in reinforced concrete~~

Overview of ethics issues in your research project:

Question 1: Is there a possibility that your research could cause harm to a third party (i.e. a person not involved in your project)?	YES	<input checked="" type="radio"/> NO
Question 2: Is your research making use of human subjects as sources of data? If your answer is YES, please complete Addendum 2.	YES	<input checked="" type="radio"/> NO
Question 3: Does your research involve the participation of or provision of services to communities? If your answer is YES, please complete Addendum 3.	YES	<input checked="" type="radio"/> NO
Question 4: If your research is sponsored, is there any potential for conflicts of interest? If your answer is YES, please complete Addendum 4.	YES	<input checked="" type="radio"/> NO

If you have answered YES to any of the above questions, please append a copy of your research proposal, as well as any interview schedules or questionnaires (Addendum 1) and please complete further addenda as appropriate. Ensure that you refer to the EIR Handbook to assist you in completing the documentation requirements for this form.

I hereby undertake to carry out my research in such a way that

- there is no apparent legal objection to the nature or the method of research; and
- the research will not compromise staff or students or the other responsibilities of the University;
- the stated objective will be achieved, and the findings will have a high degree of validity;
- limitations and alternative interpretations will be considered;
- the findings could be subject to peer review and publicly available; and
- I will comply with the conventions of copyright and avoid any practice that would constitute plagiarism.

Signed by:

Principal Researcher/Student:	Date
This application is approved by: Supervisor (if applicable):	<div style="border: 2px solid black; padding: 10px; display: inline-block;">Signed by candidate</div>
HOD (or delegated nominee): <i>Final authority for all assessments with NO to all questions and for all undergraduate research.</i>	01-04-2015
Chair: Faculty EIR Committee For applicants other than undergraduate students who have answered YES to any of the above questions.	

ADDENDUM 1:

Please append a copy of the research proposal here, as well as any interview schedules or questionnaires:

ADDENDUM 2: To be completed if you answered YES to Question 2:

It is assumed that you have read the UCT Code for Research involving Human Subjects (available at <http://web.uct.ac.za/depts/educate/download/uctcodeforresearchinvolvinghumansubjects.pdf>) in order to be able to answer the questions in this addendum.

2.1 Does the research discriminate against participation by individuals, or differentiate between participants, on the grounds of gender, race or ethnic group, age range, religion, income, handicap, illness or any similar classification?	YES	NO
2.2 Does the research require the participation of socially or physically vulnerable people (children, aged, disabled, etc) or legally restricted groups?	YES	NO
2.3 Will you not be able to secure the informed consent of all participants in the research? (In the case of children, will you not be able to obtain the consent of their guardians or parents?)	YES	NO
2.4 Will any confidential data be collected or will identifiable records of individuals be kept?	YES	NO
2.5 In reporting on this research is there any possibility that you will not be able to keep the identities of the individuals involved anonymous?	YES	NO
2.6 Are there any foreseeable risks of physical, psychological or social harm to participants that might occur in the course of the research?	YES	NO
2.7 Does the research include making payments or giving gifts to any participants?	YES	NO

If you have answered YES to any of these questions, please describe below how you plan to address these issues:

ADDENDUM 3: To be completed if you answered YES to Question 3:

3.1 Is the community expected to make decisions for, during or based on the research?	YES	NO
3.2 At the end of the research will any economic or social process be terminated or left unsupported, or equipment or facilities used in the research be recovered from the participants or community?	YES	NO
3.3 Will any service be provided at a level below the generally accepted standards?	YES	NO

If you have answered YES to any of these questions, please describe below how you plan to address these issues:

ADDENDUM 4: To be completed if you answered YES to Question 4

4.1 Is there any existing or potential conflict of interest between a research sponsor, academic supervisor, other researchers or participants?	YES	NO
4.2 Will information that reveals the identity of participants be supplied to a research sponsor, other than with the permission of the individuals?	YES	NO
4.3 Does the proposed research potentially conflict with the research of any other individual or group within the University?	YES	NO

If you have answered YES to any of these questions, please describe below how you plan to address these issues: