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The use of
Construction and Demolition Waste in
Concrete
in Cape Town

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Declaration

I, Kyle Wickins, hereby declare that this dissertation is my own work. The Harvard convention for citation and referencing has been used where extracts, concepts and ideas have been borrowed from other sources.

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Abstract

Incorporating recycled aggregates in concrete, despite the fact that effective technologies are available, is being adopted at a slow rate. These shortcomings have been associated with poor quality recycled aggregate (RA) products, lack of guidelines facilitating the use of RAs in various applications, and little incentive to incorporate these materials into civil engineering projects in Cape Town. In order to promote the use of RAs, a construction and demolition waste (C&DW) recycling culture has to be developed. Analysis of municipal waste data over the past 10 years shows that the commercial aggregate industry and market has not grown. A major contributor to the excess C&DW in the City, is the discarded C&DW once used to manage landfill sites with regard to activities such as cell creation, road building etc. This has resulted in 195 000 tons of the estimated 680 000 tons per annum (2012) of C&DW being disposed in Cape Town.

The approach of the City and the construction industry to waste management is characterised by quality control issues, resource inefficiencies, economic and social burdens and environmental impacts. The realisation of C&DW as a resource and the development of on-site recycling procedures are seen as the key to creating more sustainable C&DW management systems. This is achieved internationally through detailed integrated waste management plans (IWMPs) that require waste generators to identify and separate a variety of C&DWs, as well as specify their proposed uses for these materials. This creates an environment where a specialist waste-processing sector can develop and practices such as the re-use and recycling of multiple C&DWs can flourish.

It is important that the management and handling of C&DWs is carried out in a manner such that the technical requirements of this resource are understood. This study analyses two major C&D materials in clay and concrete masonry (CMA) materials and waste concrete (RCA). Greywacke stone is used as the control coarse aggregate. A 100% replacement ratio of coarse RA is used in all RA concrete mixes. A 50% Klipheiwel and 50% Dune sand mix is used in all concrete mixes respectively.

C&D materials in this study were processed through simulated, on-site procedures to produce 19 mm coarse aggregate for concrete. Increased virgin masonry strength resulted in overall coarser grading distributions. Fines and dust content increased with increased brickwork mortar content and reduced strength in masonry aggregates. Fines and dust content increases with increased concrete mortar content in RCAs, rather than with reduced parent concrete strength. RAs were highly absorptive and absorbed water rapidly. Increased absorption was experienced with lower virgin clay masonry strength, increased brickwork mortar and concrete mortar quantities. Absorption varied in clay masonry aggregate between

The Use of C&DW in Concrete in Cape Town

8 - 15% in high to low strength virgin masonry respectively. Absorption ranged from 4% - 5% in the RCAs.

The clay masonry aggregates varied in dried density from 1780 kg/m^3 to 2120 kg/m^3 . The RCA-45 (45 MPa RCA sample) and RCA-MV (mixed strength RCA sample) had dry densities of 2230 kg/m^3 and 2290 kg/m^3 . The control stone had a dry density of 2690 kg/m^3 . Apparent relative density was low in clay masonry RAs. Compacted bulk density in the masonry aggregates ranged from 980 kg/m^3 to 1200 kg/m^3 . RCA-45 and RCA-MC had bulk densities of 1310 kg/m^3 and 1360 kg/m^3 . These values were lower than the Greywacke stone at 1535 kg/m^3 . Crushing strength in RCAs is defined by the quantity of concrete mortar surrounding the virgin aggregate. Masonry materials performed better in wet crushing tests than the dry tests. Wet ACV and 10% FACT were therefore not good indications of masonry aggregate strength when dry sieving was performed.

A mix water quantity of 180 l/m^3 was used for all mixes. 32% - 56%, 25% and 22% added water quantities were required of the clay brick and RCA mixes to account for absorption properties of the RAs respectively. The multistage mixing procedure used in this study, which made use of a mix and added water quantity, was accurate in its estimation of total water demand and was an effective procedure to achieve a desired slump in recycled aggregate concrete (RAC).

Compressive strength results reveal that the added water quantity does not adversely affect the water/binder ratio of RACs. All of the RACs except for the CMA (concrete masonry) concrete exceeded their mix design compressive strengths of 20, 30 and 40 MPa. However in practice, cement content may need to be increased in the RACs, to achieve compressive strengths similar to those of normal aggregate concrete (NAC). 56-day shrinkage in all the clay masonry aggregate concrete was reduced by an average of 23% when compared to the control concrete. 56-day shrinkage in the CMA and RCA concretes increased when compared to the control Greywacke concrete. RCA concrete shrinkage increased by an average of 48% respectively. The storage of added water within the pores of clay masonry aggregates resulted in the release of this water over time. This replaced the moisture lost to the environment and hydration therefore acting as a self-curing agent that reduced overall shrinkage. Elastic moduli of the RACs were less than NA concrete. The elastic moduli of the clay brick concretes were on average 46% lower, and the RCA concretes were on average 33% lower than the Greywacke concrete at 28 day and 56 day ages.

Masonry and concrete materials should be identified for re-use in intergrated waste management plans. Through separation protocol and simple on-site processing, there is potential for multiple uses of clay masonry, concrete masonry and recycled concrete in low and higher-grade concrete applications.

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Contents

PART A - DEVELOPING A C&D WASTE RECYCLING CULTURE IN CAPE TOWN	1
1 INTRODUCTION	1
1.1 BACKGROUND OF STUDY	2
1.2 AIM OF THIS STUDY	3
1.3 OBJECTIVES OF THIS STUDY	3
1.4 SCOPE AND LIMITATIONS OF THIS STUDY	4
1.5 PLAN OF DEVELOPMENT	5
1.6 REFERENCES	7
2 C&D WASTE IN CAPE TOWN	8
2.1 INTRODUCTION	8
2.2 INDUSTRY ROLE PLAYERS	9
2.2.1 The City of Cape Town	9
2.2.2 The Private C&D Waste Recycling Sector.....	12
2.2.3 Challenges Faced by the Recycling Industry.....	13
2.3 WASTE GENERATION STATISTICS	14
2.3.1 Growth in the Cape	15
2.3.2 C&D Waste Statistics	16
2.3.3 Discussion.....	18
2.4 CURRENT APPROACH TO C&D WASTE MANAGEMENT	21
2.4.1 The Waste Cycle.....	21
2.4.2 Municipal Solid Waste Cycle	22
2.4.3 C&D Waste Cycle	23
2.4.4 Impacts of C&D Waste.....	26
2.4.5 Discussion.....	28
2.5 TOWARDS A SUSTAINABLE C&D MANAGEMENT SYSTEM	28
2.5.1 Resource Efficient C&D Materials Cycle	29
2.5.2 Discussion.....	30
2.6 CONCLUSION	31
2.7 REFERENCES	33
3 OVERVIEW OF NATIONAL AND LOCAL REGULATORY ENVIRONMENT FOR C&DW	34
3.1 INTRODUCTION	34

The Use of C&DW in Concrete in Cape Town

3.2	NATIONAL REGULATORY ENVIRONMENT	35
3.2.1	Overview of National Regulations	35
3.3	REGULATIONS IN THE CITY OF CAPE TOWN	36
3.3.1	The City's IWM Policy	36
3.3.2	IWM By-law of 2009 and IWMPs	36
3.3.3	Concluding Comments	37
3.4	OVERVIEW OF INTERNATIONAL WASTE MANAGEMENT PROGRAMS	38
3.4.1	Australian WasteWise Construction Program	38
3.4.2	CalRecycle Program	39
3.5	MOVING FORWARD IN THE IWMP PROCESS	41
3.5.1	Stakeholder Co-ordination	41
3.5.2	C&D Waste targets and goals	42
3.5.3	Detailed Characterisation of the C&D Waste Stream	43
3.5.4	Further regulatory actions	44
3.6	RECOMMENDATIONS	45
3.7	CONCLUSION	46
3.8	REFERENCES	48
4	PROCESSING AND CLASSIFYING RECYCLED AGGREGATES – A REVIEW	51
4.1	INTRODUCTION	51
4.2	RECYCLING DEFINITIONS	51
4.3	ON-SITE RECYCLING	52
4.3.1	Processing C&D Waste	56
4.3.2	Resource Identification	56
4.3.3	Source Separation	58
4.3.4	Storage	60
4.3.5	Crushing Procedures	61
4.3.6	Classification of Recycled Aggregates	65
4.4	CONCLUSION	69
4.5	REFERENCES	70
PART B	– PROPERTIES OF RECYCLED AGGREGATE MATERIALS	72
5	LITERATURE REVIEW: PROPERTIES OF RECYCLED AGGREGATES AND RECYCLED AGGREGATE CONCRETE	72
5.1	INTRODUCTION	72
5.2	MASONRY MATERIALS	72
5.2.1	Clay Masonry	73

The Use of C&DW in Concrete in Cape Town

5.2.2	Concrete Masonry	77
5.3	PHYSICAL PROPERTIES OF RA MATERIALS	78
5.3.1	Grading of Materials	78
5.3.2	Fines and Dust Content	80
5.3.3	Particle Shape and Texture	80
5.3.4	Absorption and Porosity	81
5.3.5	Relative and Bulk Density	85
5.3.6	Saturated Surface Dry density	89
5.3.7	Contaminants	91
5.3.8	Aggregate Crushing Value and 10% FACT	94
5.3.9	Summary	96
5.4	FRESH PROPERTIES OF RA CONCRETE	97
5.4.1	Effect of RA Materials on the ITZ	98
5.4.2	RA Concrete Mix Design	99
5.4.3	Water Requirement and Workability	102
5.4.4	Summary and Recommendations	104
5.5	HARDENED RA CONCRETE PROPERTIES	104
5.5.1	Compressive Strength	105
5.5.2	Creep and Shrinkage	107
5.5.3	Modulus of Elasticity	108
5.5.4	Summary	110
5.6	CONCLUSION	110
5.7	REFERENCES	111
6	EXPERIMENTAL PROGRAM	114
6.1	INTRODUCTION	114
6.2	MATERIALS	115
6.2.1	Summary of Materials to be Processed into RAs	115
6.2.1	Virgin Masonry Samples	118
6.2.2	Mixed Masonry Materials	120
6.2.3	Waste Concrete Samples	122
6.2.4	Discussion	123
6.2.5	Control Coarse Aggregate	124
6.2.6	Fine Aggregates	124
6.2.7	Binder	126
6.2.8	Water	126
6.3	PHYSICAL PROPERTIES OF RECYCLED AGGREGATES	126

The Use of C&DW in Concrete in Cape Town

6.3.1	Crushing Operation.....	126
6.3.2	Properties of Crushed RA Material	126
6.4	FRESH PROPERTIES OF RECYCLED AGGREGATE CONCRETE	127
6.4.1	Concrete Mix Designs	127
6.4.2	Concrete Mixing Procedure	128
6.4.3	Detailed Composition of Concrete Mix Designs.....	129
6.4.4	Curing	130
6.5	HARDENED PROPERTIES OF RECYCLED AGGREGATE CONCRETE.....	130
6.6	SUMMARY OF TESTING REGIME	130
6.7	REFERENCES	132
7	PHYSICAL PROPERTIES OF RECYCLED AGGREGATES	133
7.1	INTRODUCTION.....	133
7.2	RECYCLED AGGREGATE MATERIALS	134
7.3	PROCESSING - CRUSHING AND SIEVING.....	135
7.3.1	Crushing and Sieving Procedure.....	136
7.3.2	Discussion.....	137
7.3.3	Summary of Aggregate Materials.....	138
7.4	GRADING	141
7.4.1	Test Procedure	141
7.4.2	Results and Discussion	141
7.5	FINES CONTENT	145
7.5.1	Test Procedure	145
7.5.2	Results and Discussion	145
7.6	YIELD RATE & MATERIAL LOSSES	147
7.6.1	Analysis Procedure	147
7.6.2	Results and Discussion	147
7.7	DUST CONTENT	148
7.7.1	Analysis Procedure	148
7.7.2	Results and Discussion	148
7.8	CHLORIDE CONTENT	150
7.8.1	Test Procedure	151
7.8.2	Results and Discussion	151
7.9	PARTICLE SHAPE - FLAKINESS INDEX.....	153
7.9.1	Test Procedures.....	153
7.9.2	Results and Discussion	153
7.10	WATER ABSORPTION.....	155

The Use of C&DW in Concrete in Cape Town

7.10.1 Test Procedure	156
7.10.2 Results and Discussion	156
7.11 SURFACE SATURATED, OVEN DRIED AND APPARENT RELATIVE DENSITY.....	160
7.11.1 Test Procedure	160
7.11.2 Results and Discussion	161
7.12 BULK DENSITY.....	162
7.12.1 Test Procedure	162
7.12.2 Results and Discussion	162
7.13 CRUSHING STRENGTH – 10% FACT AND ACV	164
7.13.1 Test Procedure	164
7.13.2 Results and Discussion	165
7.13.3 Summary of Aggregate Properties.....	169
7.14 CONCLUSIONS	172
8 PROPERTIES OF FRESH CONCRETE MADE WITH RAS	175
8.1 INTRODUCTION.....	175
8.2 CONCRETE MIXING PROCEDURES.....	175
8.2.1 Pre-wetting.....	176
8.2.2 Pre-soaking	176
8.2.3 Multi-stage Mixing	176
8.3 WATER REQUIREMENT	177
8.3.1 Added Water	177
8.3.2 Multi-stage Mixing Procedure.....	178
8.3.3 Discussion.....	179
8.4 WORKABILITY AND WATER CONTENT	180
8.4.1 Test Procedure	180
8.4.2 Trial Mixes.....	180
8.4.3 Results and Discussion	181
8.5 DETAILED MIX DESIGNS	183
8.5.1 Summary	185
8.6 CONCLUSIONS	186
8.7 REFERENCES.....	186
9 PROPERTIES OF HARDENED CONCRETE MADE WITH RAS	187
9.1 INTRODUCTION.....	187
9.1.1 Composition of RA Concrete	187
9.2 COMPRESSIVE STRENGTH	188
9.2.1 Test Procedure	188

The Use of C&DW in Concrete in Cape Town

9.2.2 Results and Discussion	188
9.3 SHRINKAGE	199
9.3.1 Test Procedure	200
9.3.2 Results and Discussion	200
9.4 ELASTIC MODULUS	204
9.4.1 Test Procedure	205
9.4.2 Results and Discussion	206
9.5 CONCLUSIONS	209
10 CONCLUSIONS & RECOMMENDATIONS	212
10.1 LOCAL AND INTERNATIONAL REGULATIONS	213
10.2 PROCESSING C&DW INTO RA	214
10.3 INFLUENCE OF RA MATERIALS	216
10.3.1 Physical Properties.....	216
10.3.2 Fresh Properties	218
10.3.3 Hardened Properties.....	219
10.4 SUMMARY OF MAJOR CONCLUSIONS	220
10.5 THE USE OF RA MATERIALS	221
10.6 DEVELOPING REGULATIONS AND MOVING FORWARD	225
10.7 FURTHER RESEARCH	225
APPENDICES	227
APPENDIX A. OVERVIEW OF GOVERNMENTAL STRUCTURE	227
APPENDIX B. SUMMARY OF NATIONAL ACTS AND POLICIES	228
APPENDIX C. REGULATIONS IN THE CITY OF CAPE TOWN	231
APPENDIX D. INTEGRATED WASTE MANAGEMENT BY-LAW OF 2009232	
APPENDIX E. THE CITY'S C&D WASTE INTEGRATED WASTE	
MANAGEMENT PLAN	234
APPENDIX F. DEVELOPMENT OF THE ANZECC	234
APPENDIX G. CALRECYCLE BACKGROUND	235
APPENDIX H. CUMULATIVE ENERGY DEMAND	236
APPENDIX I. GLOBAL WARMING POTENTIAL	237
APPENDIX J. RAC COMPRESSIVE STRENGTH DEVELOPMENT GRAPHS	238
APPENDIX K. RA CONCRETE SHRINKAGE GRAPHS	241

List of Figures

Figure 2.1: Municipal solid waste history and projection for the City of Cape Town (City of Cape Town 2011).....	16
Figure 2.2: Generation and use of C&D waste 2002/03 in Cape Town	19
Figure 2.3: Generation and use of C&D waste 2008/09 in Cape Town	19
Figure 2.4: The Solid Waste Cycle.....	22
Figure 2.5: Traditional demolition and site activities that generate C&D materials	24
Figure 2.6: Stockpiles of mixed C&D materials in Cape Town	24
Figure 2.7: Current C&D materials waste cycle	25
Figure 2.8: Resource efficient C&D waste cycle	29
Figure 2.9: Location of landfill facilities, aggregate quarries and drop off sites in the Cape Peninsula.....	32
Figure 3.1: IWM Plan - Waste Minimisation Plans for Construction and Demolition projects (Sustainability Victoria 2012).....	39
Figure 3.2: WMP used by San Luis Obispo County in California (California Government 2012)	40
Figure 4.1: On-site recycling vs. Landfilling (Vossberg 2012).....	54
Figure 4.2: Energy contribution of on-site, off-site and landfilling C&D waste (Vossberg 2012)	55
Figure 4.3: Figures show the composition of various C&D waste streams internationally. Labelled are inconsistently showing the importance of characterisation of materials within a waste stream (Kartam et al 2004; Ayers 1999; Chen et. al. 2002)	57
Figure 4.4: Separation schedule created by WasteWise (Australian Standards 1998)	60
Figure 4.5: Various sized mobile jaw crushers (http://miniveyor.org ;http://img.directindustry.com)	62
Figure 4.6: (Top) Gyro crusher opening (http://www.studwise.com.au). (Bottom) Configuration of gyro crusher at AFRISAM plant	62
Figure 4.7: Impact crusher (http://image.made-in-china.com).....	63
Figure 4.8: Vibrating screens used to sieve materials at the AFRISAM plant at Peninsula Quarry. Wire mesh screens with elongated apertures used to remove flaky particles at the AFRISAM plant.....	63
Figure 4.9: Commercial crushing operation at CapeBrick yield coarse aggregate (stone) and fines materials that are discarded.....	64
Figure 5.1: Typical rates of irreversible moisture expansion in bricks and brickwork (Clay Brick Association 2002).....	76

The Use of C&DW in Concrete in Cape Town

Figure 5.2: Particle distribution (Hu et. al. 2011). Masonry A and B are concrete masonry aggregate materials, masonry C and D are crushed burnt clay brick aggregates and IA DOT-C3 and IA DOT- C4 are natural commercial aggregates.....	79
Figure 5.3: Indication of particle shape of BCA and CMA used in Hu et. al. (2011). The top two illustrations are CMA materials and the bottom two clay brick aggregate materials	81
Figure 5.4: Relationship between water absorption and clay brick (referred to as ceramic) content (Padmini et. al. 2009)	84
Figure 5.5: Relationships between water absorption and increased clay brick (BCA) content (referred to as ceramic) in a RCA-BC mix (Agrela et. al. 2011).....	84
Figure 5.6: Relationship between water absorption and mechanical properties of RCA concrete (Eguchi et. al. 2007)	85
Figure 5.7: Relationship between RCA (referred to as concrete) content and SSD density (Agrela et. al. 2011).....	90
Figure 5.8: Relationship between BCA (referred to as ceramic) contents and SSD density (Agrela et. al. 2011)	91
Figure 5.9: Reduction in chloride content in course RA soaked in water (Debieb et. al. 2010). .	93
Figure 5.10: Diagram showing two ITZ in RCA concrete	98
Figure 5.11: Illustration of ITZ in masonry aggregates	99
Figure 5.12: Nomogram by Levy et. al. (2004) for 50% NA/50% BCA. Mix design in Table 5.12 calculated from Nomogram	101
Figure 5.13: Water absorption characteristics of 40 mm RCA (Bento et. al. 2012)	103
Figure 5.14: The sequence of adding the different components of the mix proportion in the mixer (Bento et. al. 2012)	103
Figure 5.15: Compressive strength trends for BCA and CMA (Hu et. al. 2011)	105
Figure 5.16: Deterioration on compressive strength with 100% RCA, BCA 20% and BCA 50% replacement (Yang et. al. 2011)	106
Figure 5.17: Relationship between shrinkage and RCA replacement ratios for 2 RCA sources (Eguchi et. al. 2007)	108
Figure 5.18: (Left) Relationship between MOE and strength of 40 mm RCA concrete (Padmini et. al. 2009). (Right) The relationship between concrete properties elastic modulus, compressive strength and replacement ratio (Eguchi et. al. 2007).....	109
Figure 6.1: Illustrations of the virgin clay masonry materials	118
Figure 6.2: Concrete blocks used to produce concrete masonry aggregate (CMA)	119
Figure 6.3: Construction debris stockpile from which the BCA-MC sample was selected.....	121
Figure 6.4: BCA-MV sample with contaminants	121
Figure 6.5: BCA-MV, illegally dumped rubble sample, sourced from Voortrekker Road, Salt River	122
Figure 6.6: (Left) RCA-45 sample being collected from Concrete Units and being broken down by manual jack hammering before processing (Right).....	122

The Use of C&DW in Concrete in Cape Town

Figure 6.7: (Left) RCA materials being delivered to CapeBrick for storage and use in the manufacture of concrete masonry elements. (Right) Pre-crushed RCA used in this study	123
Figure 6.1: Phillip Dune sand and Klipheuvel crusher sand	124
Figure 6.2: Particle distribution of Klipheuvel and Dune fine aggregates	125
Figure 6.3: Klipheuvel sand (left) and Phillipi Dune sand (right)	125
Figure 6.4: Multi-stage mixing procedure	128
Figure 7.8: Hydraulic splitter (Left). Split and crushed clay brick and concrete materials	136
Figure 7.9: Fixed jaw crusher (Left). Figure showing FBE45 material being fed into jaw crusher mouth (Right)	137
Figure 7.10: The manual sieving procedure. (Top figures) Materials being loaded and shaken to remove fines. (Bottom figures) Coarse aggregate being shaken into a storage bin	137
Figure 7.11: Coarse aggregate particle distribution boundaries as prescribed by SANS 1083: 2006	142
Figure 7.12: Particle distribution of RAs after crushing (vertical line represents 4.75 mm boundary)	143
Figure 7.13: Particle distribution of coarse RAs after sieving (fines removed; vertical line represents 4.75 mm boundary)	144
Figure 7.14: RCA-MC (Left) and RCA-45 (Right) aggregates. The red arrows show the exposed stone faces of the RCA-MC aggregate due to commercial crushing operation.....	146
Figure 7.15: Dust particles of each RA. From left to right (Top) NFP, NFX, FBE45, (Middle) CMA, BCA-MV, BCA-MC, (Bottom) RCA-MC, RCA-45 and Greywacke	150
Figure 7.16: Titration equipment used to test for chlorides by titration	151
Figure 7.17: Splintered, flaky nature of FBE45 and NFX aggregates	154
Figure 7.18: Hollow core clay brick components of BCA-MV sample (Left). ‘Mortar aggregate’ in BCA-MV sample.....	155
Figure 7.19: Flakey, honeycombed and porous surface of the NFX RA compared to FBE45 RA	157
Figure 7.20: Compact, granular surface of CMA	158
Figure 7.21: Rough, cement paste covered RCA-45 sample (Left) compared to the smoother surfaces of the RCA-MC (Right)	159
Figure 7.22: Rate of absorption over a 10-minute period.	159
Figure 7.23: Dry 10% FACT of all masonry elements	166
Figure 7.24: Wet 10% FACT of all masonry elements	167
Figure 7.25: Dry and wet 10% FACT of FBE45, RCA-45, RCA-MC and Greywacke	168
Figure 8.1: Multi-stage mixing procedure	178
Figure 9.1: From Top, Left to Right, NFP, NFX, FBE45, CMA, BCA-MV, BCA-MC, RCA-45, RCA-MC and Greywacke RACs	187

The Use of C&DW in Concrete in Cape Town

Figure 9.2: Compressive strength development w:b = 0.50 (40 MPa target strength shown by red line)	191
Figure 9.3: Compressive strength development w:b = 0.60 (30 MPa target strength shown by red line)	192
Figure 9.4: Compressive strength development w:b = 0.80 (20 MPa target strength shown by red line)	192
Figure 9.5: Variation in 28-day compressive strength between w:b ratios.....	193
Figure 9.6: Variation in 56-day compressive strength between w:b ratio	193
Figure 9.7: 28 Day Density of Hardened Concrete 80 (the bars follow the order of the legend)	195
Figure 9.8: Failure of BCA-MV concrete cube under compression.....	196
Figure 9.9: Photograph of fractures through weak clay masonry and mortar.....	197
Figure 9.10: Photograph of the failure (red lines) in the NFP concrete under compression.....	197
Figure 9.11: Red lines showing failure cracks in RCA-45 (Top) and RCA-MC (Bottom) concrete cubes under compression	198
Figure 9.12: Red lines showing failure of Greywacke concrete cube under compression	199
Figure 9.13: Shrinkage chart showing all RA concretes with w:b 0.50	201
Figure 9.14: Masonry aggregate shrinkage with w:b = 0.50.....	202
Figure 9.15: Masonry aggregate shrinkage graph with w:b = 0.60.....	202
Figure 9.16: Masonry aggregate shrinkage graph with w:b = 0.80.....	202
Figure 9.17: RCA shrinkage graph with w:b = 0.50	203
Figure 9.18: RCA shrinkage graph with w:b = 0.60	203
Figure 9.19: RCA shrinkage graph with w:b = 0.80	203
Figure 9.20: Modulus of elasticity with w:b ratios 0.50, 0.60 and 0.80 (the bars follow the order of the legend).....	206
Figure 9.21: Relationship between static elastic modulus and concrete cube strength at 28 day age	207
Figure 9.22: Relationship between static elastic modulus and concrete cube strength at 56 day age	208
Figure 9.23: Granite virgin aggregate in the RCA-45 concrete (Left) and variable virgin aggregate in the RCA-MC concrete(Right).	209

List of Tables

Table 2.1: Timeline of C&D recycling activity and progress by the City of Cape Town	11
Table 2.2: C&D waste data 2002/03 (City of Cape Town 2005)	17
Table 2.3: C&D waste data 2008/09 (City of Cape Town 2012)	18
Table 2.4: General waste data in Cape Town 2002 and 2009	20
Table 2.5: Comparison on C&D waste quantities from 2002/03 and 2008/09	20
Table 3.1: Appendix information reflected by Chapter 3	34
Table 3.2: Summary of the obligations of waste generators under the IWM-By Law	37
Table 4.1: Pros and cons to on-site and off-site C&D waste recycling.....	53
Table 4.2: Recommended types and uses of C&D Waste (HB 155:2002)	58
Table 4.3: SANS 1083:2006, Table 2 - Requirements for 19 mm coarse aggregate for concrete	65
Table 4.4: Properties of Class 1 RCA materials – HB 155:2002	67
Table 4.5: Recommended mix design parameters for concrete of varying design strength	68
Table 4.6: Comparison of SANS 1083:2006 and HB 155-2002.	68
Table 5.1: Classification of burnt clay masonry units (SANS 227:2007 – Burnt Clay Masonry Units; CSIR 1984)	74
Table 5.2 Absorption values of RA according to various literature sources	83
Table 5.3: Densities of typical 19 mm Western Cape aggregates (Alexander & Heiyantuduwa 2002; Kutugeza 2004; Kleyn 2013)	86
Table 5.4: Comparison of relative densities of RA materials from various authors	87
Table 5.5: Comparison of bulk and absolute densities of RA materials from various authors ..	88
Table 5.6: Comparison of SSD densities of RA materials from various authors.....	89
Table 5.7: Effect of some general contaminants of concrete performance (HB 155-2002).....	91
Table 5.8: Dry 10% FACT values of recognised Cape aggregates (Alexander & Heiyantuduwa 2002)	95
Table 5.9: Comparison of aggregate strength of RA materials from various authors.....	96
Table 5.10: Mix proportions for wet and dry batches of Mixed RA (Alexander & Heiyantuduwa 2002)	100
Table 5.11: Mixed RA concrete mix design used by Kutugeza (2004)	100
Table 5.12: Mix proportions of 50% NA/ 50% BCA concrete as per nomogram by Levy et. al. (2004)	101
Table 5.13: Mix proportions as specified by Padmini et. al. (2009).....	102
Table 5.14: Compressive strength results for various clay brick and RCA replacement levels as found by Yang et. al. (2011) (error in tabulation RCB-80 should be RCB 20. Clay brick is referred to as RCB by author).....	106
Table 6.1: Summary of RA materials	116
Table 6.2: Detailed Concrete Mix Design	129

The Use of C&DW in Concrete in Cape Town

Table 6.3: Summary of testing program	130
Table 7.1: Summary of RA materials	139
Table 7.2: Comparison of Fines and Dust content before and after sieving	145
Table 7.3: Yield rate and material losses to acquire coarse aggregate materials.	148
Table 7.4: Dust content of RAs after crushing and sieving.....	149
Table 7.5: Chloride content of RAs.....	152
Table 7.6: Flakiness Index values of all RAs	154
Table 7.7: 24 Hour water absorption values	156
Table 7.8: SSD, dried and apparent relative density values	161
Table 7.9: Loose and compacted bulk densities	163
Table 7.10: 10% FACT values of recycled aggregates	165
Table 7.11: ACVs of recycled aggregates	165
Table 7.12: Summary of aggregate properties	169
Table 8.1: 24 Hour absorption properties of aggregates.....	177
Table 8.2: Slump and water content results	181
Table 8.3: Concrete Mix Designs for each aggregate material	184
Table 9.1: 28-day compressive strengths of the RA concretes.....	189
Table 9.2: 56-day compressive strengths of the RA concretes.....	190
Table 9.3: Percentage increase binder content required to achieve a 35 MPa target strength .	194
Table 9.4: 56-day shrinkage values in micro-strain	200
Table 9.5: MOE results	206
Table 10.1: Summary of materials analysed in study	215

Abbreviation, Definitions and Terminologies

10% FACT	10% Fines Aggregate Crushing Test
A:C	Ratio of Aggregate to Cement in a concrete mix
ACV	Aggregate Crushing Value
Aggregate	Coarse aggregate (stone) for use in concrete classified as particles in the 4.75 mm up to 37.5 mm range
ANZECC	Australian and New Zealand Environmental Conservation Council
AS	Australian Standards
ASTM	American Society for Testing and Materials
BCA	Burnt Clay Masonry Aggregate. Aggregate consisting of 100% crushed clay fired masonry brick.
BCA - MC	Burnt Clay masonry Aggregate of Mixed origin sourced from CapeBrick.
BCA - MV	Burnt Clay masonry Aggregate of Mixed origin sourced from Voortrekker road, Salt River, Cape Town.
Brickwork Mortar	Cement mortar (binder, sand and water) used to bond brickwork together
C&D	Construction and Demolition
C&DW	Construction and Demolition Waste. Materials resulting from demolishing structures that can no longer serve their purpose. These materials may consist of concrete, masonry, tiles, timber, plastics and papers to name a few components. Also referred to as builder's rubble or builder's waste.
CED	Cumulative energy demand is an energy assessment variable that represents primary energy consumed by an action. This can be described as not a measure of energy such as electricity consumed, but the amount of primary energy needed to produce, use and dispose of an electricity supply (Vossberg 2012).
CMA	Concrete Masonry Aggregate. Aggregate consisting of 100% crushed structural concrete brick or block masonry.
Concrete Mortar	Concrete paste between aggregate particles
DEATH	Department of Environmental Affairs and Tourism

The Use of C&DW in Concrete in Cape Town

Downcycling	Downcycling converts waste materials in to products of lesser quality and reduced functionality. Crushing C&DW into aggregate for varying applications can be described as downcycling. Downcycling should be the last resort to managing waste before disposal.
EN	European Normalization (engineering standard/code reference)
FACT	Fines Aggregate Crushing Test
Added Water	Excess water added, above the mix water, in order to satisfy the absorption requirement of the recycled aggregate.
FI	Flakiness Index
Fines (aggregate) material	Aggregate material less than 4.75 mm in size
G4; G5;	High quality natural gravels used in pavement layer works
G7	Lower quality soil gravel used in selected pavement layer works
GDP	Gross Domestic Product
GWP	Global warming potential is an assessment parameter that measures the global warming potential of the air emissions from an activity over a 100-year period (Vossberg 2012).
Hardcore	Aggregates fill material
IDP	Integrated Development Plan
IP&WM	Integrated Pollution and Waste Management
ITZ	Interfacial Zone. This is the plane of weakness between aggregates and cement paste in hardened concrete.
IWM	Integrated Waste Management
IWMP	Integrated Waste Management Plan
LA	Los Angeles. Referring to the Los Angeles Abrasion Test
Mix Water	Water required to satisfy the w:b and achieve the target strength of the RAC
MOE	Modulus of Elasticity
Mortar	Hardened cement paste. This may be cement paste from RCA or cement-lime-sand combination from plaster and mortar.
MoU	Memorandum of Understanding
MSW	Municipal Solid Waste

The Use of C&DW in Concrete in Cape Town

NA	Natural Aggregate. Aggregate derived from natural sources such as crushed rock from quarries for use in concrete. May also be referred to as virgin aggregate. In the context of this study this usually refers to coarse aggregate (stone).
NAC	Natural aggregate (coarse) concrete
NWMS	National Waste Management Strategy
NEM:WA	National Environmental Management Waste Act
Parent Concrete	Hardened concrete from which RCA is derived
'Processing'	The identification, separation and/or crushing of C&D materials in order to acquire aggregates for use in low-grade applications.
RA	Recycled Aggregate. Coarse aggregate consisting of crushed burnt clay brick masonry (BCA), concrete masonry (CMA), recycled concrete (RCA).
RAC	Recycled Aggregate Concrete. Concrete made with the substitution of natural aggregates for recycled concrete aggregate.
RCA	Recycled Concrete Aggregate. Coarse aggregate that is made up of of 100% crushed waste concrete.
RCA-MC	Recycled Concrete Aggregate of Mixed origin sourced from CapeBrick
Recycling	Recycling is a process of changing waste materials into products that prevent the waste of potentially useful material, reduce the consumption of raw materials and reduce environmental impacts. This could entail reusing precast concrete components or cleaning and reusing clay bricks. This study refers to the recycling C&DW, but strictly speaking processing these materials in this manner described is classified as downcycling.
SANS	South African National Standards
SSD	Saturated Surface Dried
Upcycling	Up-cycling refers to converting waste materials in products of better quality or for better environmental value. This could take place when engineering grade bricks previously used for paving are cleaned and utilised in a structural application.
W:B	Ratio of water to binder (cement) in concrete
WMP	Waste Management Plan

PART A - Developing a C&D Waste Recycling Culture in Cape Town

1 Introduction

Population growth, urbanization, technological choices and their environmental impact are beyond doubt the definitive forces that will shape our world in the future. This growth is directly related to urbanization as an ever-increasing proportion of the population moves to cities. Today, over 52% of the global population lives in cities. This has a prodigious effect on the energy required for manufacturing and transporting products to supply this population. Furthermore, the majority of the resulting unused and discarded material, most of which has its source as natural resources from the earth, is disposed of back into the environment as potentially harmful solids, liquids and gas. This shortsighted mind-set that resources and land are inexhaustible has resulted in the profound environmental and global changes we are facing today.

Consumption of concrete is constantly and rapidly intensifying to support urbanisation. The resulting construction and demolition waste (C&DW) from the upgrading and improvement of structures and infrastructure has major social and environmental impacts. These consist of quarrying and transporting aggregates and concrete products, as well as the impacts resulting from transporting C&DW to landfill sites and the illegal dumping of materials (Marinkovic et. al. 2011). These approaches are the most recognised industry model for handling and disposing of C&D materials. Mitigating the environmental impact of concrete and the construction industry begins with addressing consumption. Resource efficiency is therefore fundamental to achieving a more sustainable industry in the long run.

Cape Town produces approximately 700 000 tons (2009) of C&DW per year. This consists primarily of mixed fractions of demolished concrete and masonry that is derived from buildings, which cannot serve their purpose any longer. This is one of the largest waste constituents on urban sites and their transportation and disposal results in some the largest costs for developers and contractors. Concrete is typically made up of 12 – 15% cement, 8 – 10% water and 75 – 80% aggregate by mass (Mehta 2002). Approximately 2 million tons of virgin aggregate is mined around Cape Town per year. An estimated 1.4 million tons of this aggregate is used in concrete applications (AfriSam 2013). Thus, the use of recycled aggregates (RAs) in concrete presents numerous opportunities for civil engineering concrete

The Use of C&DW in Concrete in Cape Town

applications. Furthermore, it is a vital tool to mitigate environmental, social and municipal waste problems being experienced in Cape Town.

1.1 Background of Study

The use of recycled building materials has been around since Roman times. The concept of recycling modern demolished concrete was formally researched towards the end of World War II after large areas within cities were destroyed during conflict. This resulted in engineers bearing the task of not only rebuilding but also clearing enormous amounts of rubble and debris. The first publications on this subject were written from 1946 -1948 with various Soviet, American and German researches exploring this field post WWII. Research in this field produced no written records of practical uses for this material. The energy crisis combined with the increasing scarcity of natural resources and dumping grounds in the 1970s also generated a renewed interest in this field from America, Europe and Japan (Frick 1987).

Today, research into the use of C&DW for use as aggregate material in concrete is widespread. The utilization of recycled concrete aggregate (RCA) is widely practised with established markets in the EU, USA and Australia achieving C&D recycling rates of over 70% (Ayers 2002). Past researchers in Cape Town have also completed similar studies on the RA industry, which produced positive results and future outlooks. However, over the past 10 years, despite identified economic and practical applications for RCAs, subsequent landfill site closures, increased transportation and disposal costs and the failed development of the commercial C&DW processing industry, have created a large waste management issue in the Cape Town

Incorporating 'green' materials into the industry, despite the fact that effective technologies are available, is being adopted at a slow rate (Mehta 2002). These failures have been associated with poor quality recycled aggregate (RA) products, lack of guidelines facilitating the use of RAs in various applications, and little incentive for the incorporation of these materials into civil engineering projects in the Cape. However, building 'green' structures that are energy and resource efficient is becoming a trend in the engineering and architecture professions and a number of international guidelines and codes are available which present information on the use of RAs. This said industry's failure to recognize and utilise RA s is therefore attributed to RA quality control issues, which are affiliated to the current C&DW management practices. These quality control issues are linked to a mass demolition approach that combines the C&DW stream thereby making the recovery and processing of C&D materials into quality RA s difficult, time consuming and not economically viable. Moreover, research into the use of

The Use of C&DW in Concrete in Cape Town

C&D materials has almost exclusively been linked to recycled concrete with a disregard for other materials such as masonry, which may be of use in the C&DW stream.

Therefore, the key to increasing the use of C&D materials is to create awareness as to potential of various C&D materials on-site. This involves providing information that educates engineers and contractors as to the opportunities in on-site processing and capabilities of multiple C&D materials that can be combined with or substituted for virgin aggregates. This creates awareness as to availability of elements that can be processed into various grades of materials for use in a multitude of low-grade applications, thereby laying the foundation for the development of a recycling culture within the construction industry. With data available on the steps to take to acquire various C&D materials and the performance of these RA s, one can update South African guidelines and codes to promote their utilisation as well take regulatory actions that promote the use of C&D material in concrete in Cape Town.

1.2 Aim of this Study

The aim of this dissertation is to investigate the suitability of various C&D materials, through on-site recycling and concrete mixing procedures, as an alternative source of coarse aggregate for producing concrete in Cape Town. The suitability of these materials is investigated with regard to their physical properties and their effects with 100% substitution as coarse aggregate in concrete. This is done to promote more resource efficient construction practices and may improve the development of the current commercial aggregate recycling market. Furthermore, this addresses current sustainability challenges such as illegal dumping, transportation impacts and landfill airspace availability faced both by the construction industry and the City of Cape Town.

1.3 Objectives of this Study

This investigation focuses on three main objectives. Firstly, a literature review that provides insight into the past and present conditions that define the C&DW sector is presented. This encompasses a review of previous studies and municipal reports from the City of Cape Town that present information on the development of the recycled aggregate industry over the past 10 years. Secondly, a more technical literature review on the processing of C&DWs into RAs, the engineering properties of these individual RAs, and the properties of RA concrete (RAC) is presented and discussed. The third objective entails selecting recognised C&D materials in the Cape Town and investigating, discussing and presenting conclusions on the performance of these materials. This covers their physical properties and performance of the RA s when used as coarse RA s in concrete. This is summarised as follows:

The Use of C&DW in Concrete in Cape Town

- Provide a comprehensive background on C&DW role players, management, generation and regulatory sector.
- Provide a literature review that characterises the physical and RA concrete properties of individual C&D materials.
- Assess the performance of recognised C&D materials that have been processed through on-site methods into RAs with regard to physical and RA concrete properties.
- Provide conclusions that address some of the sustainability challenges faced by the C&DW management and recycling sector.

1.4 Scope and Limitations of this Study

This study provides insight into the C&DW industry in Cape Town. This entails a review of C&DW role players, waste generation, waste management approaches, regulations, material processing and engineering codes that apply to these materials. The technical literature review covers the basic production of the various C&DWs in question as well as aggregate properties of various RA materials that have been utilised by other authors. Aggregate properties reviewed as well as tested in this dissertation include composition, grading, fines content, dust content, chloride content, flakiness index, water absorption, surface saturated, oven dried, apparent relative and bulk densities as well as 10% FACT and ACV testing. Fresh concrete properties cover the concrete mixing procedure, water requirement, workability and water content. The properties of hardened RA concrete scrutinised are the compressive strength, shrinkage and elastic modulus. The results of this testing regime are compared to the performance of a well recognised, control natural aggregate as well as results from other authors.

In the analysis of fresh and hardened concrete, water-binder ratios of 0.50, 0.60 and 0.80 are used. This corresponds roughly to mix design compressive strengths of 40 MPa, 30 MPa and 20 MPa with a SUREBUILD (CEM II/ B-M (L-S) 42.5 N) binder respectively. Greywacke stone is used as the control coarse aggregate. All RA materials are crushed and sieved through simple on-site methods to obtain the coarse aggregate fraction for this study. The coarse RA materials used in this study are limited to recycled concrete, clay masonry and concrete masonry. The 100% substitution of coarse RA is used in all the RA concretes under question. A 50/50 fine aggregate blend of Klipheuwel and Dune sand is used in all the concrete mixes.

1.5 Plan of Development

This body of work is broken down into two parts.

Part A begins with an introductory chapter that gives a brief background to this work. Chapters 2, 3 and 4 of Part A provide a comprehensive background on C&DW in general. Chapter 2 provides the platform for this study and reviews the state of the C&DW recycling industry. This consists of the major C&D role players in the City of Cape Town, the private sector and C&DW generation statistics over the past 10 years. This leads onto a discussion of the solid waste management approaches that have facilitated recycling in other industries. This is used to present an approach to C&DW management that is seen as far more resource efficient and acts as enabler to further the use of C&DWs as RAs in the future. Improving regulations around recycling C&DWs and providing information about the classification and production of RAs are seen as two major drivers to achieving a more resource efficient C&DW management approach. Therefore, Chapters 3 covers the current national and local regulatory environment. Chapter 4 reviews the processing of materials into RAs and compares well known international aggregate standards to the SANS 1083:2006 *Natural aggregates – Aggregates for use in Concrete*. Part A forms the background to this study and lays the foundation for Part B.

Part B covers a more technical approach to using C&D materials with the analysis of their properties when used as coarse aggregates in concrete.

Chapter 5 contains a literature review on the physical, fresh and hardened properties of C&D materials and RAC as found by other authors. These findings and reports provide information and numerical evidence as to the results to be expected by this study.

Chapter 6 provides the experimental program of this dissertation. Details of the various tests, equipment and testing procedures are covered by this chapter. This chapter also contains the basic concrete mix designs used in this study.

Chapter 7 covers the physical properties of the RA s in the grading, fines and dust, particle shape and texture, absorption and porosity, relative and bulk densities, surface saturated dried density and crushing strength in ACV and 10% FACT. These are compared to the control stone aggregate, other author's data, SANS 1083:2006 and the Australian HB 155-2002 aggregate standards, in order to gauge the physical performance of these materials.

Chapter 8 contains information on the properties of the fresh RA concretes. This covers the multi-stage mixing procedure used to reduce the absorptive effects of the RAs, the workability and the total water

The Use of C&DW in Concrete in Cape Town

contents in free and mix water required to achieve the desired workability in the concrete mixes. This chapter also shows the detailed concrete mix design used in this research.

In chapter 9, the performance of hardened concrete made with the 100% substitution of the various coarse RA s over a 56-day period is analysed. Well recognised engineering properties of compressive strength, shrinkage and elastic modulus are tested.

Finally, conclusions and recommendations on the materials, their processing, the influence of them on physical, fresh and hardened concrete properties, recomedations for their use and the development of reglations are summarised in chapter 10. Detailed results, discussions and conclusions can be found at the end of the individual chapters.

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The Use of C&DW in Concrete in Cape Town

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2 C&D Waste in Cape Town

2.1 Introduction

It is estimated that the worldwide production of concrete and masonry rubble is over one billion tons per year (Mehta 2002). As the magnitude of this waste is realised, the recycling and reusing C&DW and the economic and environmental benefits thereof, have gained widespread recognition in the past decade. Internationally, the recycling and reuse of C&DW is a recognised construction industry practice with established markets in the EU, USA and Australia achieving C&D recycling rates of 70%-90% (Ayers 2002; California Government 2012; Sustainability Victoria 2012). The development of a C&DW recycling industry can be driven by a number of economic, environmental and social circumstances. These include:

- Scarcity of quality natural aggregates
- Environmental pressures (from landfill disposal and waste procurement activities)
- Lack of landfill airspace availability
- Increased transportation costs
- Technological developments
- Increased education towards sustainable construction practice

This chapter sheds light on some of these economic, environmental and social circumstances that are present in the C&DW industry in the Cape Town. It begins with an overview of the C&D recycling market role players. This includes the role that City and private sector have played in the development of the C&D recycling industry over the past 10 years. In order to quantify the challenges faced by industry, the next section looks at the available C&DW data in the Cape. This is a numerical analysis of the progression of the C&DW recycling sector and the quantities of materials being generated by the City. The success of C&DW recycling practices is reliant on on-site C&D materials management. Therefore the next section discussed the current approach to waste management in comparing the municipal solid waste (MSW) management and C&DW management cycles. This outline of current waste management practices provides insight into the impacts that large quantities of C&DW are having on the City and the barriers that are impeding the use of recycled C&D materials. Consequently, a resource efficient C&D materials cycle is proposed to mitigate the impacts of the current system.

The Use of C&DW in Concrete in Cape Town

Finally, conclusions are drawn as to the way forwards in promoting the use of C&D materials, developing the C&D recycling market and tackling the waste problems in the Cape Town.

2.2 Industry Role Players

The C&D recycling industry incorporates multiple role players that handle and distribute various materials. This includes two distinct parties in the City of Cape Town and the private C&D recycling sector.

The City manages:

- Municipal transfer and drop-off stations
- Municipal waste collection services
- City contracted C&D waste recyclers
- Municipal landfill facilities

The Private sector includes:

- Construction and demolition contractors
- “Domestic” and “Full-scale” waste transporters
- Private C&D waste recyclers

Within these role players lie complex transitions where C&D materials exit and re-enter the boundary of municipal waste management. This involves a network where materials are generated, serve as inputs (raw materials) in the manufacture of recycled products, are utilised in landfill operation and maintenance, and are disposed of. The following sections discuss these parties briefly in order to develop an overview of this market.

2.2.1 The City of Cape Town

The City generates C&DW from municipal road repair, building activities, housing developments, engineering service and maintenance, upgrades and the clearing of illegal dumping activities. Within these operations, private contractors carry out most of the physical collection, transportation and recycling of the C&D materials. It is estimated that the City only handles 9% of the generated C&DW stream (City of Cape Town 2005). Thus, the role of the City is two-fold as it generates C&DW but more substantially manages the disposal of these wastes at drop-off or landfill sites. It also acts as a regulatory body that manages the generation and separation approach through the National Building Regulations, Building Standards Acts and the recent IWM By-law. This is discussed further in Chapter 3.

The Use of C&DW in Concrete in Cape Town

The City's obligation to physically manage C&D materials, once they are delivered to drop-off and landfill sites by industry, creates a recycling prerogative that is very different to that of the private sector. The City's interest in C&D recycling through the recent legislative actions is due to the following factors:

- The updating of national legislation in NEM:WA, the NWMS and the IWM By-law
- The closure of multiple landfill sites as a result of airspace capacity being reached
- The imminent closure of current landfill sites
- The escalating municipal waste stream including C&D wastes
- Increased illegal dumping by waste transporters, as a result of increases transportation costs and recent tariffs on C&D waste disposal
- Strict environmental and EIA procedures make the procurement of new landfills timely and difficult

The City's primary objectives with regard to C&D recycling and waste management prerogative are therefore to (City of Cape Town 2011):

- Reduce amounts of C&D wastes that end up on landfill sites
- Reduce the amounts of illegally dumped C&D waste

Currently, the City is exploring using recycled materials in the maintenance and construction of road infrastructure. This includes use in sub-base, pavement and kerb elements (MacDonald 2012). In spite of the development of the C&D recycling industry there has been widespread non-acceptance and scepticism towards the quality of recycled sub-base materials, particularly in the production of road base G4 and G5 materials (City of Cape Town 2012; Ayers 1999). This is a result of these RAs not conforming to the specification and standards, in particular the Aggregate¹Crushing Value (ACV) and because of high variability in material batches (Ayers 1999; MacDonald 2012).

Thus, the market for processed C&DW is currently limited with regard to use by the City, as the City's Roads and Stormwater Department do not accept medium to higher grade processed C&DW as a road materials. This has led to City pursuing the development of standard specifications to ensure that recycled materials conform to their requirements as a road building material. This will allow for the

¹ Particular ACVs were not a requirement of the TRH14 specification used by the road construction industry but is a criterion used by council engineers for City funded projects (Ayers 1999)

The Use of C&DW in Concrete in Cape Town

introduction of regulations that allow for the use of recycled G4, G5 material for roads and lower G7 materials for sidewalk layer works, before virgin aggregates are considered (City of Cape Town 2012).

The progress of the City with regard to establishing C&D material regulations, processing plants and standards is overviewed in the following section.

2.2.1.1 C&D Recycling Progress by the City

The summarised progress of the C&D recycling industry from the City's perspective is shown below. As the City's actions are largely related to regulatory decisions it is helpful to show legislative developments in this progression, see Table 2.1 (City of Cape Town 2011; Coetzee 2012; McDonald 2012; Van Vuuren 2012):

Table 2.1: Timeline of C&D recycling activity and progress by the City of Cape Town

Year	C&D Recycling Progress by the City
2000	<ul style="list-style-type: none"> • Large private contractors develop initial C&D waste recycling programs in Cape Town • Integrated Pollution & Waste Management Policy
2001	<ul style="list-style-type: none"> • The City of Cape Town Waste Management department, the Institute of Waste Management and the CSIR Building and Construction Technology jointly hosted a seminar "<i>to bring stakeholders involved in lifecycle of C&D waste to reach a common understanding of C&D waste and its management aspects</i>" in 2001. The seminar identified that: <ul style="list-style-type: none"> • <i>Performance based building specifications need to be created</i> • <i>Legislative support in the form of by-laws on illegal dumping, landfill tax and educational material</i> • <i>Polokwane Declaration - National represented sectors recommitted themselves to the objectives of an integrated pollution and waste management policy.</i>
2004	<ul style="list-style-type: none"> • The City opens crushing operations at the Coastal Park landfill and Gordon's Bay drop-off facility
2006/7	<ul style="list-style-type: none"> • Waste Wise external workshop to facilitate use of recycled materials by industry stakeholders and the City/ This resulted in "<i>a major difference in opinion between City departments with little progress being made.</i>" Differences related to non-conformance of RAs to standards and concern over quality of commercially produced RAs particularly in Roads and Stormwater applications.
2008	<ul style="list-style-type: none"> • National Environmental Management: Waste Act • National Waste Management Strategy
2009	<ul style="list-style-type: none"> • Development of IWM By-law by the City
2010	<ul style="list-style-type: none"> • Solid Waste Management Consultants recommend and pursue C&D waste management solutions • Reduced tariff on uncontaminated C&D waste disposal at landfill • Tender for crushing facilities at current landfill sites filled
2011	<ul style="list-style-type: none"> • Suspension of crushing contractors at landfills due to failures on agreed terms by the contractors

The Use of C&DW in Concrete in Cape Town

	<ul style="list-style-type: none"> • Partial implementation of the IWM By-law to new structures and renovations
2012	<ul style="list-style-type: none"> • Planned Industry workshop on re-use of C&D waste • Increased interest in the development of standards for the use of recycled C&D waste in road construction applications

Detailed information of regulatory developments are discussed in Chapter 3

The City's involvement in C&D recycling is predominantly a waste management prerogative however it does have vested interest in the ability of these materials to be used in road maintenance and construction applications. The City's managerial role is facilitated by private contracts and activities in the private C&D recycling sector. The following section reviews developments in this regard.

2.2.2 The Private C&D Waste Recycling Sector

Ayers (2002) produced one of the first studies on recycled aggregates within the Western Cape. This study recognised three commercial crushing companies that produced recycled aggregate products namely, Malans Quarries, Bradis Demolition and Ross Demolition. In addition to these larger companies, LA Rall and two council C&D recycling pilot projects were established at Gordons Bay and Coastal Park landfill facilities at this time. Four brick manufacturers, namely Cape Brick, Steco Concrete Works, Inca Bricks and Crammix Bricks, were involved in recycling C&D waste for use in various brick products.

During this development stage of the C&D recycling market, the larger aggregate and demolition companies were primarily involved in C&DW recycling initiatives. Recycling activities took place predominantly at these private facilities, which were set up near industrial areas or at designated crushing facilities like Lansdowne and Airport Industria. They were fed by major concrete or rock demolition projects being undertaken by their affiliated concrete or demolition operations, Ross and Bradis Demolition, or through contracts with the City at landfill sites (Ayers 1999; City of Cape Town 2005).

Ayers (2002) comments that the wide variety of products were successfully produced as a result of detailed processing actions and quality controls that limited contamination issues. These include G4 base course, G5 sub-base, G7 materials, 19 mm aggregate, 10 mm aggregate, hardcore and fines materials. These recycled products were found to be 10% - 40% less expensive than virgin materials at this time and a market for these products was developing in the Cape (Ayers 2002).

Currently there are four major recycled aggregate producers in Afrimat, Skye, Ross Demolition and Bradis Demolition (now Cidel) (Vossberg 2012). Cape Brick uses approximately 70% recycled C&DW in their products and purchase around 70 000 tons of C&D materials per year. The rubble is usually

The Use of C&DW in Concrete in Cape Town

delivered from commercial suppliers after primary crushing. One of their major issues is acquiring uncontaminated rubble from waste sources (City of Cape Town 2011; City of Cape Town 2005; Gildenhuis 2012).

Over the past 10 years the industry structure is relatively unchanged with a few more role players in Afrimat and Afrisam joining this sector. Recycling operations still take place predominantly off-site at designated private recycling facilities or at landfill sites by the major demolition and aggregate producing market players. There have been further developments in the use of recycled C&D material within the structural engineering sector. The recycling of C&DW to produce aggregates for use in base slabs, fill and other low-grade concrete applications is increasing. This is to cater for a new market for 'greener' concretes, which earn recognition in the construction industry through tender processes such as the GreenStar rating system (Afrimat 2012).

However, of late it seems that markets have experienced a downturn and C&D recycling endeavours have not realised the market potential of RAs. There are also concerns that the private sector does not always approach C&D recycling operations with the holistic approach of achieving high recycling rates. In cases, recyclers simply select very specific higher-grade concretes or elements of value within structures to be demolished, and then landfill the remaining materials (City of Cape Town 2011). This raises questions as to whether the economic and other challenges faced by these parties have become more substantial over the past decade, resulting in the stagnation of this industry. This direction is discussed in the following section.

2.2.3 Challenges Faced by the Recycling Industry

From literature it is apparent that the recycling industry in the Cape experienced a surge upon its initial development around 2001. Subsequently the market seems to have deteriorated.

At the time of the Ayers (2002) study, multiple recycling operations were exploring C&DW recycling initiatives and the use of recycled materials seemed to be growing, as the construction sector explored new applications for recycled C&D materials. This was mainly in a variety of roadbase and layerwork applications in parking area and access road applications.

Ten years on, growth in the C&D recycling industry in the Cape Town seems to have slowed with the recycled aggregate market described as "small and competitive" (Vossberg 2012). City recycling projects have experienced difficulties, poor markets have resulted in demolisher only identifying very specific elements for recycling, standards are yet to be developed by The City and recycled products are viewed with suspicion. It therefore appears that the C&D recycling industry is inhibited by the same

The Use of C&DW in Concrete in Cape Town

shortfalls it experienced in the past. There are opportunities in the use of RAs in (City of Cape Town 2012; MacDonald 2012; Van Vuuren 2012):

- Council tenders and contracts as G4, G5 and lower grade G7 base layers in road construction projects
- Concrete, low-grade structural concrete, fill and other construction applications

A major criticism has been the lack of available local codes and standards. However, it is questionable that a construction industry, which is notorious in its resistance to change and suspicion towards new materials, will suddenly open its doors to recycled materials if simple provisions are made within the SANS. After all, multiple projects have successfully specified and utilised recycled C&D materials in a variety of applications in the Cape (Ayers 2002; Afrimat 2012). Consequently, it is recognised that the shortfalls are not within the recycled materials but in industry's perceptions and current engineering and construction practices. Failures within the City's and the construction industry's approach to waste management practices has led to quality control issues, whether perceived by engineers or otherwise, within the production of recycled C&D material and therefore a disregard for recycled material use within the engineering sector. These quality control issues are linked to RA products that contain varying amounts of C&D materials that are not understood, such as masonry and concrete, and contaminants such as timber and plastic.

The key to increasing the use of C&D materials is not to facilitate its use in higher-grade concrete applications. It is to educate engineers and contractors as to the opportunities and capabilities of multiple C&D materials that can be used individually or can be combined in place of virgin aggregates. This creates awareness as to availability of elements that can be processed into various grades of materials for use in a multitude of applications. In light of this C&D recycling market overview, the following section reviews the available municipal waste statistics in order to quantify the availability of C&D materials and further develop an understanding of the problems within industry.

2.3 Waste Generation Statistics

Data that characterises the C&DW stream over a long period of time is currently unavailable in the City. This is because there is no formalised waste information system that deals with this waste stream both nationally or locally. It also due to the complex and often strained relationship the private and public sector have in managing this waste stream. This makes data accumulation hard to acquire especially from the private sector. Thus, there are currently only two major C&DW studies that offer data on this waste stream.

The Use of C&DW in Concrete in Cape Town

It has been shown that waste generation correlates to population growth, GDP growth, private consumption and per capita energy consumption (Vossberg 2012). Therefore an outline of growth within the City forms the background to this section.

2.3.1 Growth in the Cape

The City of Cape Town is over 350 years old and is the capital city of the Western Cape province. It has a population of 3.7 million inhabitants with the Cape Town Metropole covering an area of 2461 km². It is 7 times larger than it was in 1945 and has almost exactly doubled in size since 1977 (City of Cape Town 2011; Van Vuuren 2012). It has one of the highest population growth rates in the country at 3% and also a high GDP growth rate of 4.1% when compared the national average of 2.6% (Vossberg 2012).

Waste generation is connected to these economic and population dynamics in the Cape. Prior to 2008, the historical municipal waste growth rate in Cape Town was above 7% per annum. Since then it has slowed to between 2.5% - 4% per annum. Lack of data makes it unclear if this decrease in municipal waste generation is due to the economic downturn or the implementation of waste minimization measures. However, the correlation between GDP growth and waste landfilled has been stronger than between population growth and waste landfilled in the past (City of Cape Town 2011). This is seen in Figure 2.1.

Figure 2.1 shows the disposal of MSW to landfill over a period of 10 years in the City. Landfill data is currently the only available information on the C&DW stream. The impact of economic and social activities on waste quantities can be seen from 2004 to 2009. This was a period of large development prior to the FIFA World Cup in 2010 where waste quantities deviated somewhat from the overall growth trend. The vertical dashed lines in the Figure indicate the years in which the City carried out C&DW studies and hence the data in this body of work. The quantity of data offered by these two studies might be seen as limited, however they are in line with the overall growth trend of the City.

The Use of C&DW in Concrete in Cape Town

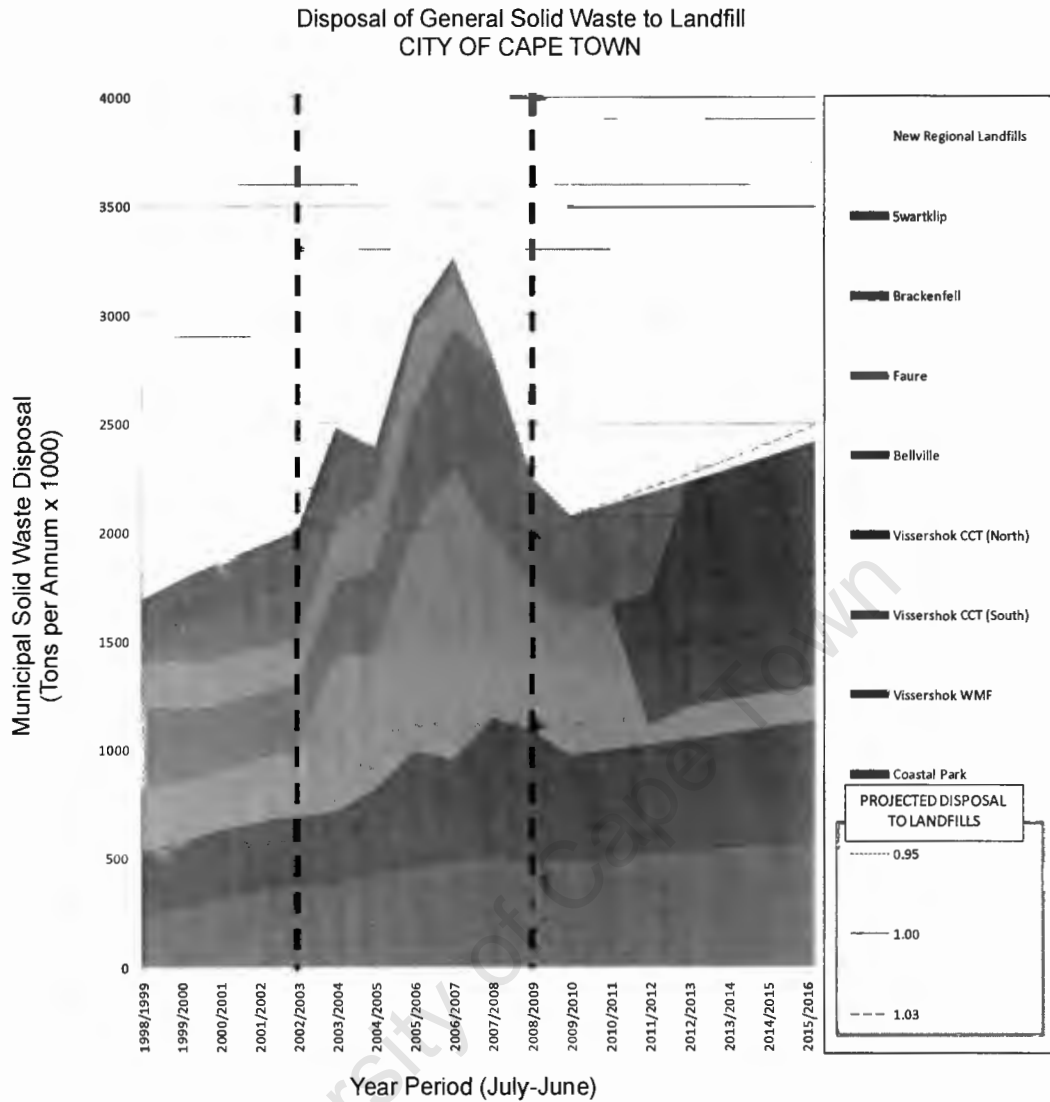


Figure 2.1: Municipal solid waste history and projection for the City of Cape Town (City of Cape Town 2011)

Despite uncertainties around waste growth, the fact is that growth is still significant and is projected to climb higher with the City's strong economic and population growth rates (Vossberg 2012). This data is discussed in further in the following section.

2.3.2 C&D Waste Statistics

There are currently only two major studies on quantities of builder's rubble generated and recycled in the City. The Builder's Rubble Study (City of Cape Town 2005) found that the annual MSW landfilled in the Cape Town Metro was 2 158 000 tons per annum (approximately 5 900 tons/day) in 2002/2003. It was estimated that 15%, or 323 700 tons of the landfilled waste stream, comprised of C&DW.

At this time, 2002/03, 130 000 tonnes of C&D material was being recycled at the City's pilot Gordons Bay and Coastal Park crushing facilities per annum. It was estimated that 530 000 tons of C&DW was being recycled annually at private recycling facilities in the Cape. Therefore, it is estimated that 370 000

The Use of C&DW in Concrete in Cape Town

tons of C&DW was handled by the City (summation of materials recycled by the City, used for landfill management and disposed off, see Table 2.2). This is 17% of the total MSW stream, which is similar to the estimate of 15%, made by the City of Cape Town (2005). This puts the total quantity of C&DW being generated in the metro at approximately 900 000 tons per annum over the 2002/2003 period. An estimated 200 000 tons or 22% of material was needed for landfill management activities. This left about 5% of excess material that was unprocessed and disposed of in landfills. Using this data the total quantity of C&DW being recycled in the Cape was 660 000 tons. The results of this analysis indicate a C&D recycling rate of around 73%. This data is shown in Table 2.2 below:

Table 2.2: C&D waste data 2002/03 (City of Cape Town 2005)

Recycled by City (crushing plants at landfill)	130 000	14%	73%
Recycled by Industry ²	530 000	59%	
Landfill management (cell creation etc.)	200 000	22%	27%
Disposed off	40 000	5%	
Total C&D Waste in Cape Town	900 000	100%	

A more recent study carried out over the period of July 2008 to June 2009 showed that quantities of landfilled municipal waste were approximately 2 212 000 tons per year. This landfilled waste made up 73% of the total 3 030 400 tons of municipal waste in the City (City of Cape Town 2011).

It is estimated that 355 200 tones of C&DW is reused by industry (52%) and 59 800 tonnes crushed by the City (9%). The City uses an estimated 10% of the total C&DW stream to manage the current operational landfill sites (City of Cape Town 2011). This data suggests that 323 100 tons of C&DW was going to landfill sites for recycling, management and disposal in 2008/9. This constitutes 15% of the total quantity of landfilled municipal waste (2 212 000 tons). The City's (2012) estimates are approximately 283 300 tons (13%) at this time. This results in a total of 195 500 tones (29%) of C&D material being disposed of (landfilled) currently. This indicates that 195 500 tons of C&D material is available for reuse or recycling in the Cape. This equates to a C&D recycling rate of 61% in 2008/9. See Table 2.3 below.

² Estimated quantity of recycled C&D waste by industry in Cape Town. Subject to high variability (City of Cape Town 2005; City of Cape Town 2011)

The Use of C&DW in Concrete in Cape Town

Table 2.3: C&D waste data 2008/09 (City of Cape Town 2012)

C&D Waste Statistics 2008/09	Quantity (tons)	Percentage	
Recycled by City (at landfill)	59 800	9%	61%
Recycled by Industry	355 200	52%	
Landfill management (cell creation etc.)	67 800	10%	
Disposed off	195 500	29%	
Total C&D Waste in Cape Town	678 300	100%	

2.3.3 Discussion

Although this data is limited to two studies, it gives an indication of the development of the C&D recycling industry over the past 10 years and verifies the impression one gets from literature on the C&D recycling market.

At the time of the 2002/03 Study, the City had 7 operational landfill facilities, which utilised an estimated 22%, 200 000 tons, of the available C&D materials (900 000 tons) in their operation and management. From literature, it is clear that industry and the City pursued a relatively new technology (in the Cape) through a variety of C&D recycling initiatives from 2001 to 2004. This led to a promising recycling rate of 74%. This competes with current international recycling rates of between 70 - 80% seen in the USA, EU and Australia (Ayers 2002; California Government 2012; Sustainability Victoria 2012). This created a local environment where developing the C&DW recycling industry may not have been considered a prerogative by the City as only 5% of the C&DW stream was unused. This is a possible reason for the delayed research into the creation of new standards and testing regimes that facilitate C&DW use in engineering projects. See Figure 2.2 below:

The Use of C&DW in Concrete in Cape Town

Generation and Use of C&D Waste 2002/03

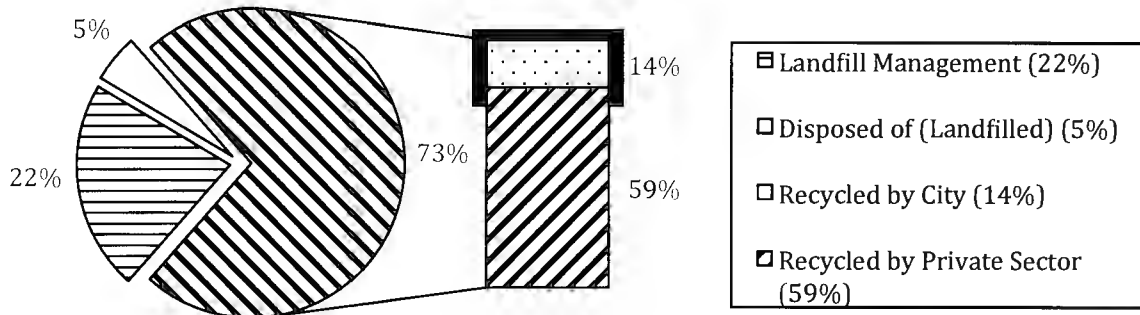


Figure 2.2: Generation and use of C&D waste 2002/03 in Cape Town

Over the next 5 years the C&DW stream decreased to an estimated 678 300 tons per annum. This occurred in conjunction with the closure of the Swartklip, Faure and Brackenfell landfill facilities between 2005 and 2008. Approximately 61% of the available C&DW materials were being recycled over the 2008/09 period. This is compared to 74% over the 2002/03 period. This led to approximately 29% of the C&DW stream or 195 500 tons being disposed of in Cape Town. This is compared to a disposal rate of 5% and quantity of 40 000 tons in the 2002/03 period. This is illustrated in Figure 2.3 below.

Generation and Use of C&D Waste 2008/09

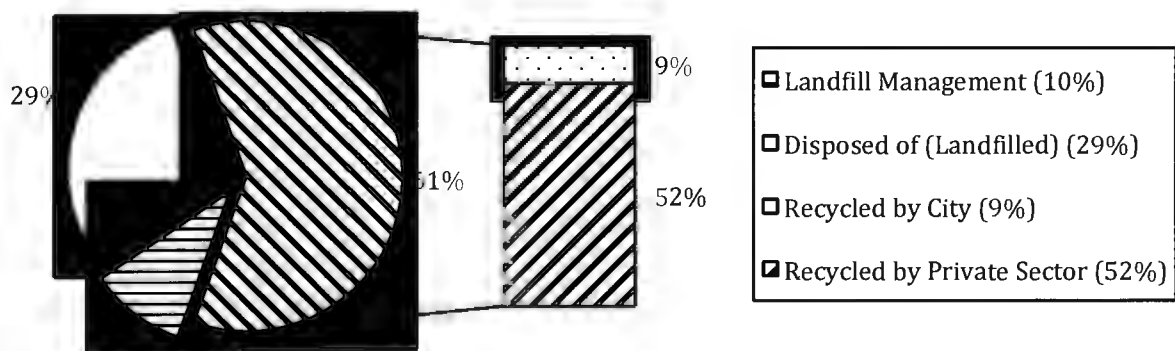


Figure 2.3: Generation and use of C&D waste 2008/09 in Cape Town

The Use of C&DW in Concrete in Cape Town

Table 2.4 shows the quantities of landfilled C&DW, total C&DW and total municipal waste in 2002/3 and 2008/9. These values are similar with a slight downturn in total C&DW produced in 2008/9. This is not seen as irregular as the 2008/09 was a period of low economic activity during the recession. See Figure 2.1.

Table 2.4: General waste data in Cape Town 2002 and 2009

Waste Data in the Cape 2002-2009				
Details	2002/03 ³		2008/09	
	tons	%	tons	%
Total C&D Waste to Landfill site	370000	17	323 100	15
Total C&D Waste in the Cape	900 000	42	678 300	30
Total Municipal Waste	2 158 000	100	2 212 000	100

This presents a relatively stable picture of waste management activities over this period, as the percentage of C&DW to landfill site is 17% in 2002/03 and 15% in 2008/09. However, further analysis of C&DW quantities that were recycled by the City of Cape Town, industry, used to manage landfills, disposed of at landfills and total waste quantities over this period reflects some of the challenges faced in the current C&DW management system.

Table 2.5: Comparison on C&D waste quantities from 2002/03 and 2008/09

C&DW Data in the Cape 2002-2009				
Details	2002/03 ³		2008/09	
	tons	%	tons	%
Recycled by the City	130 000	14	59 800	9
Recycled by Industry	530 000	59	355 200	52
Landfill Management	200 000	22	67 800	10
Disposed off at Landfills	40 000	5	195 500	29
Total C&D Waste in the Cape	900 000	100	678 300	100

From 2002 to 2009 the City's initiatives to recycled C&DW waned from 130 000 tons to approximately 60 000 tones. The recycled aggregate industry operated at a similar level over this period, which demonstrates that the commercial aggregate industry had not taken off and the aggregate market did not

³ City of Cape Town 2005

The Use of C&DW in Concrete in Cape Town

increased over this period. Another contributor to the excess C&DW in the City is the closure of multiple landfill sites and therefore the non use of C&DW to manage landfill sites with regard to activities such as cell creation, road building etc. This has resulted in disposal rates increasing from 5% in 2002/3 to 29% in 2008/9. This is shown in Table 2.5.

In conclusion, literature shows a surge in C&D recycling activity from 2000 – 2004 and the waning of the recycling industry thereafter. Failure of the private recycling sector to establish itself, for markets to grow with the acceptance of RA products, and the closure of multiple landfill facilities has resulted in an estimated 195 500 tons of C&DW being disposed of and therefore being available for reuse and recycling in Cape Town.

The following section attempts to analyse the current approach to C&DW management in order to identify shortfalls that may be responsible for the stunted recycling sector and large quantities of C&DW being disposed of in the Cape, as discussed above.

2.4 Current approach to C&D Waste Management

Failures to recognise RAs and RA quality control issues are linked to the current C&DW management practices. With this in mind, the following section reviews current municipal solid waste management practices and then current C&DW management practices. This allows for parallels to be drawn and shortfalls to be identified within the C&DW management approach. Ultimately this leads to a resource efficient C&D materials cycle being proposed, which has the potential to mitigate some of the difficulties experienced by industry.

2.4.1 The Waste Cycle

Basic municipal waste management activities consist of waste generation, separation, collection, transfer systems, recycling and the disposal of waste products (Weisheng et. al. 2011). Causal loop diagrams can be used to illustrate these management activities in what is known as the waste cycle. Waste cycles allow for the analysis of specific waste streams, the parties involved in handling these waste streams and the waste management practices followed by these parties. This provides an overview of the potential economic, social and environmental impacts that these waste management practices create (Weisheng & Hongping 2011). In the waste cycles shown below, the connectors between waste management components are marked. These connectors show the path of the specific actions undertaken by these parties in the waste management process.

The Use of C&DW in Concrete in Cape Town

The City, private recycling sector and NGOs provide drop-off facilities in the form of drop-off sites, banks and containers at municipal points, schools, businesses and housing complexes (City of Cape Town 2011). The City allows the free delivery of C&D waste to most drop-off sites and transfer stations. These facilities are located within a 5 km to 7 km radius of one another throughout the Cape.

Alternatively, municipal or privately contracted vehicles collect mixed wastes from the kerb side. Waste is then either transported to transfer stations, where a small component is separated (usually by hand) or directly to landfill sites. Some materials at landfill sites may be recovered for recycling, however the recycling of contaminated materials is difficult. The collected materials are then processed into recycled products by their respected industries and the resulting waste follows a similar course through the cycle again. This process can be seen in the Figure 2.4.

This is a basic overview of the municipal solid waste collection cycle. It shows the connection between role players, their activities and flow of materials in the municipal solid waste stream. These connections facilitate the recycling and reuse of specific waste materials, within certain industries in the Cape. These processes are by no means completely efficient but are established practices for the glass, plastic, paper and metal recycling industries in Cape Town. A substantial contributor to the development of these recycling industries in this cycle is the separation of waste materials at source.

2.4.3 C&D Waste Cycle

The current approach to C&DW management has resulted in a number of environmental, social and economic shortfalls within the City. An overview of the current C&DW cycle provides insight into these issues.

C&DW generation is inevitable during construction and demolition activities. The quantity and components of waste might vary from site to site, but the basic on-site activities follow a common course. The process whereby materials are currently generated and handled on-site is illustrated in Figure 2.5.

C&DW is generated from two principal building procedures in the preparation of site and the construction process. These activities consists of site clearing, demolishing, land surface clearing and later in projects, during new construction activities such as removal of construction waste and post construction clean-ups. These practices provide a wide variety of waste material. These on-site materials are generally mixed and stockpiled either on-site or kerb side. Alternatively, materials are gathered (mixed) and loaded into vehicles and transported directly to recyclers or landfill facilities upon their

The Use of C&DW in Concrete in Cape Town

generation. Photos of the general procedure of mixing and stockpiling materials is shown in in Figure 2.5 below.

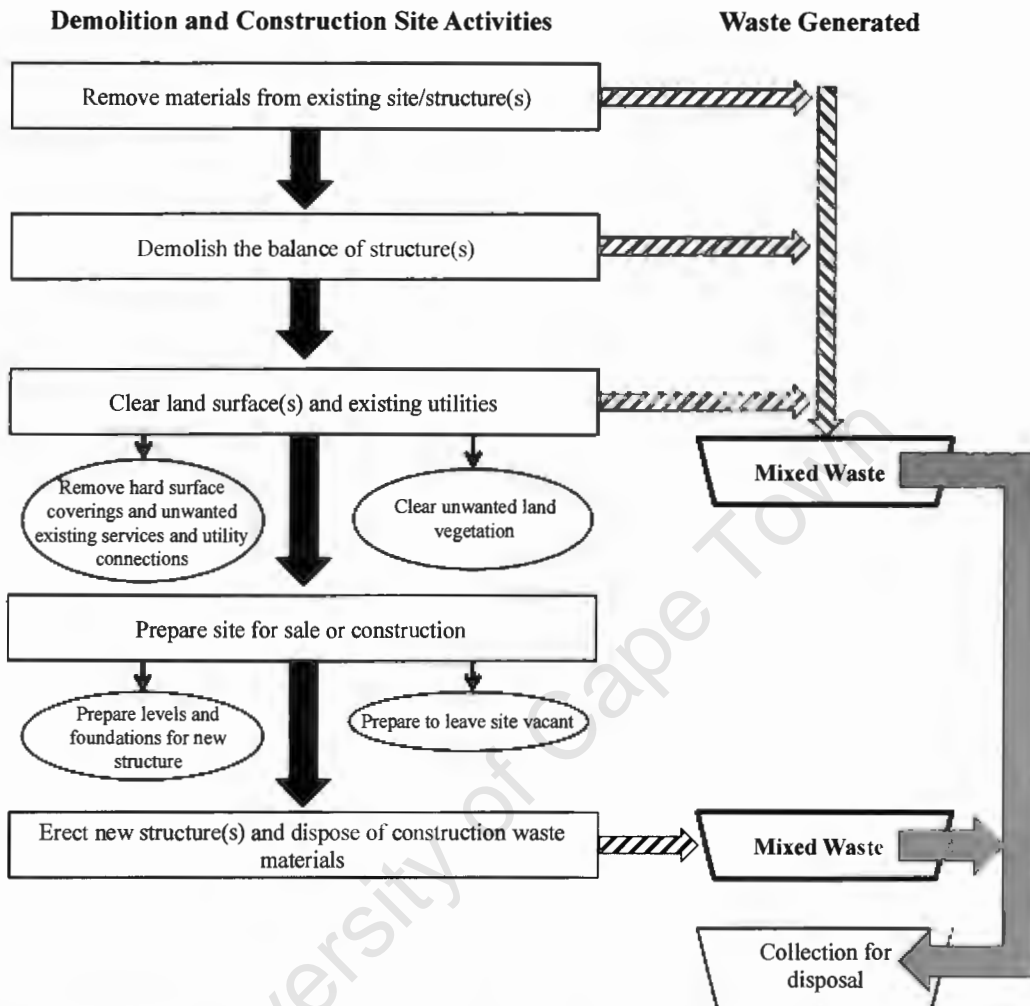


Figure 2.5: Traditional demolition and site activities that generate C&D materials



Figure 2.6: Stockpiles of mixed C&D materials in Cape Town

The Use of C&DW in Concrete in Cape Town

Following the C&DW cycle, Figure 2.7, the collection of mixed C&D materials may be carried out either by municipal parties or private parties. The City estimates that 90% of C&DWs are controlled by private industry. Multiple private demolishing companies, contractors and specialised haulers offer C&DW collection services. Municipal collection services do not collect C&DW unless they are introduced into the municipal solid waste stream. These quantities are not significant but do create issues for the City (City of Cape Town 2005). These waste collectors make use of vehicles ranging from 1 ton small haul 'bakkies', to 10 ton specialised waste vehicles depending on size and volume of waste produced during construction and demolition projects.

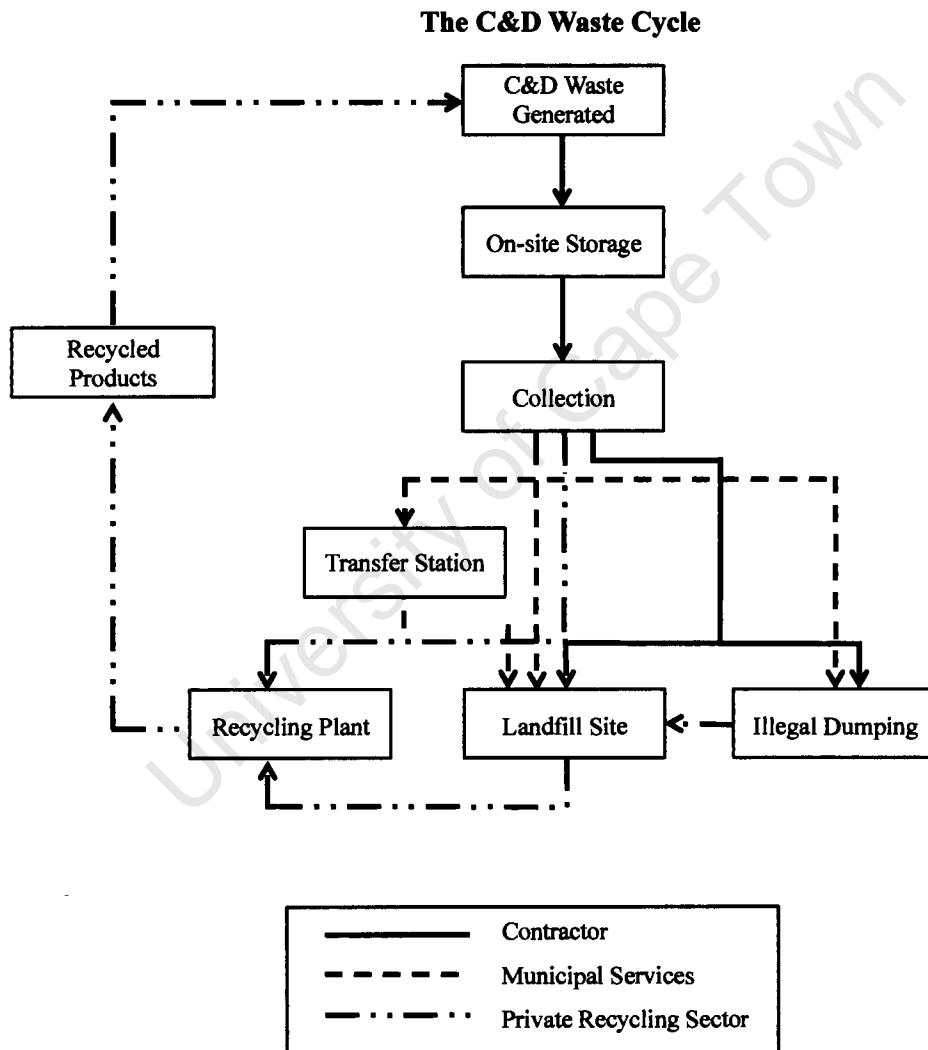


Figure 2.7: Current C&D materials waste cycle

C&DW management and municipal solid waste management are interwoven but separate operations. The City of Cape Town controls traditional MSW management, whereas contractors and parties within construction industry almost exclusively carry out C&DW management actions. These activities then converge in the use of municipal disposal infrastructure.

The Use of C&DW in Concrete in Cape Town

Parties transport C&D materials to transfer stations, recycling plants, landfill sites or illegally dump materials. C&DW transfer facilities in the City consists of a network of 24 drop-off facilities and three dedicated transfer stations. This service is however limited to one free load of 1.3-ton of C&D materials per day. This service is mainly utilised by contractors and small haul operators or what is referred to as the 'bakkie' brigade. The 'bakkie' brigade has been identified as a problem by the City and contributes to the majority of illegal dumping in the City (City of Cape Town 2012; Coetzee, A. 2012).

Larger quantities of C&DW may be delivered directly to landfill facilities. C&DW is currently received in what is referred to as the "domestic scale" and the "full scale" builder's rubble. "Domestic scale" builder's rubble typically results from small-scale renovations. It consists of small loads bought in by trailer or light delivery vehicle. "Full scale" builder's rubble that is generated from large-scale civil works and construction projects is only accepted at landfill facilities. Of the seven landfill sites available in the City, three in the Belville South, Coastal Park and Visserhok are currently fully operational and receive "full scale" C&DWs (City of Cape Town 2011). Studies show that 80% of builder's rubble is disposed of at the Coastal Park and Visserhok facilities (City of Cape Town 2005). A visual inspection is performed at weighbridges to determine the contamination level of the material. Where no weighbridge is available the vehicle is analysed according to its carrying capacity. Materials deemed as "clean" are then directed to C&D recycling stockpiles and all other materials to landfill stockpiles. The City has introduced a disposal fee (Builder Rubble Tariff) of R50/ton excl. VAT for "clean" C&DW at these landfill sites. This classification is carried out by visual inspection. Contaminated builders rubble is charged at the full disposal tariff of R231.90/ton excl. VAT (City of Cape Town 2011).

The MSW cycle and C&DW cycle mainly differ in their on-site separation and their collection protocol. These differences lead to a variety of impacts, which are discussed in the following section.

2.4.4 Impacts of C&D Waste

The largest contributors to the impacts of C&DW management are transportation of materials from site either to recycling plants or landfill sites, illegal dumping which is a result of high transportation costs and distances, and pressure on the City's landfill facilities. These impacts are discussed further below.

⁴ The City of Cape Town defines 'Clean Builders Rubble' as "waste consisting of broken bricks, sand stone, cement, plaster and similar inert materials, but excluding paper, plastic, wood, glass and metals. Clean builder rubble is utilised for constructing temporary roads and disposal sites."

The Use of C&DW in Concrete in Cape Town

2.4.4.1 Transportation

C&DW transportation is the largest contributor to the environmental and economic impacts created by C&DW management (Vossberg 2012). The transportation of natural aggregates from quarries into the City also contributes to the impact of the construction industry. Current vehicle flows are uncoordinated as suppliers and a waste transporter have different fleets of vehicles and schedules that service varying locations. This *ad hoc* system leads to bottlenecks in the road network, noise and air pollution as suppliers and transporters make use of heavy-duty vehicles to make long-haul single-load trips (Bowen et. al. 2008). Furthermore, fossil fuel price increases and landfill tariffs have made it increasingly expensive to deliver C&DWs to the Coastal Park or Visserhok landfill facilities. Additionally, it is estimated that collection distances are set to increase by 40 km with the opening of new landfill facilities (Nahman 2011). This has the potential to further exacerbate this situation and is leading to illegal dumping practices becoming more prevalent. This is discussed next.

2.4.4.2 Illegal Dumping

In spite of these available disposal facilities discussed previously, 80% of illegal dumping is thought to consist of C&DWs (Vossberg 2012). This is a result of C&DW disposal costs increasing with the rising transportation cost, the closure of multiple landfill facilities and the implementation of the C&DW disposal tariff. As a result of these economic challenges, haulers are known to simply discard their waste payloads to avoid drop-off charges or long trips to transfer or landfill facilities (Coetzee 2012; Van Vuuren, 2012). The City estimates that the average cost per tonne of area cleaning, to remove illegally dumped C&DWs, is R1 700/ton (City of Cape Town 2011). The environmental and social burdens created by these activities are also substantial.

C&D hauling operations insist that illegal dumping activities are caused by high landfill charges (City of Cape Town 2011). However, international observations suggest that the determining factor of this behaviour is the expectation and consequences of being caught. Thus, poor policing and limited penalties appear to be more likely to encourage illegal dumping. It has also been shown that once C&D reuse and recycling is realised to have economic potential, these practices decrease (Symonds 1999).

2.4.4.3 Landfilling

There are numerous environmental, economic and social burdens affiliated with the operation and management of landfill sites including (Vossberg 2012):

- The use of large tracts of land that create unsightly mountains of waste that subside extremely slowly due to their anoxic and waterless nature

The Use of C&DW in Concrete in Cape Town

- The release of landfill gas and leachate due the decomposition process. These emissions impact human health and the global climate with the potential to contaminate soil and groundwater
- The attraction of vermin and scavengers which breed diseases
- A social burden in the form of noise, odour, litter, dust and traffic
- The use of large quantities of fuel to operate dump trucks, compactors and digger-loaders which distributing waste, construct cells, apply daily cover, compact waste and constructing access roads

The City is estimated to have sufficient landfill airspace for another 12-14 years (City of Cape Town 2011). International guidelines for airspace provision consider 15 years available landfill airspace the norm. The current C&DW generation quantities, 195 500 tons per annum at a density of ⁵1.5 tons/m³, equate to about 130 300 m³ per year of landfill ⁶airspace being taken up by disposed of C&DW per year. This airspace consumption is not seen as a major issue currently as other wastes such as plastics are know to occupy twice the volume of C&DWs. A certain quantity of C&DW is also needed for the development of waste disposal cells, internal road construction and maintenance and to cover daily waste to deter vermin and bird life at landfill sites (City of Cape Town 2005; City of Cape Town 2011; Vossberg 2012). Therefore the impacts of C&DW on landfill sites are created by the social burdens of landfilling, the transportation and maintenance impacts in the use of fossil fuels and the environmental damage caused by the above operations.

2.4.5 Discussion

The current C&DW cycle is characterised by resource inefficiencies, economic and social burdens and environmental impacts. Developing solutions that reduce or mitigate these impacts through C&DW management is a crucial objective in creating a more sustainable C&DW management system and promoting the use C&D materials. Thus, the following section provides a revised 'resource efficient' C&D materials management strategy and discusses a direction that may be taken in order to mitigate the problems with the current management approach.

2.5 Towards a sustainable C&D Management System

In light of the issues created under the current C&DW cycle, the following section proposes a new approach to C&DW management. These address resource inefficiencies, may mitigate some of the

⁵ Uncrushed rubble (City of Cape Town 2011)

⁶ Airspace is a term used to describe uncompacted volume of materials at landfill facilities

impacts of the current system and has the potential to improve awareness and use of both on-site and commercially produced RA products.

2.5.1 Resource Efficient C&D Materials Cycle

The realisation of C&D materials as a resource and the development of on-site recycling procedures is key to mitigating the issues discussed previously. The resource efficient C&D material cycle diagram in Figure 2.8 below illustrates this ideal.

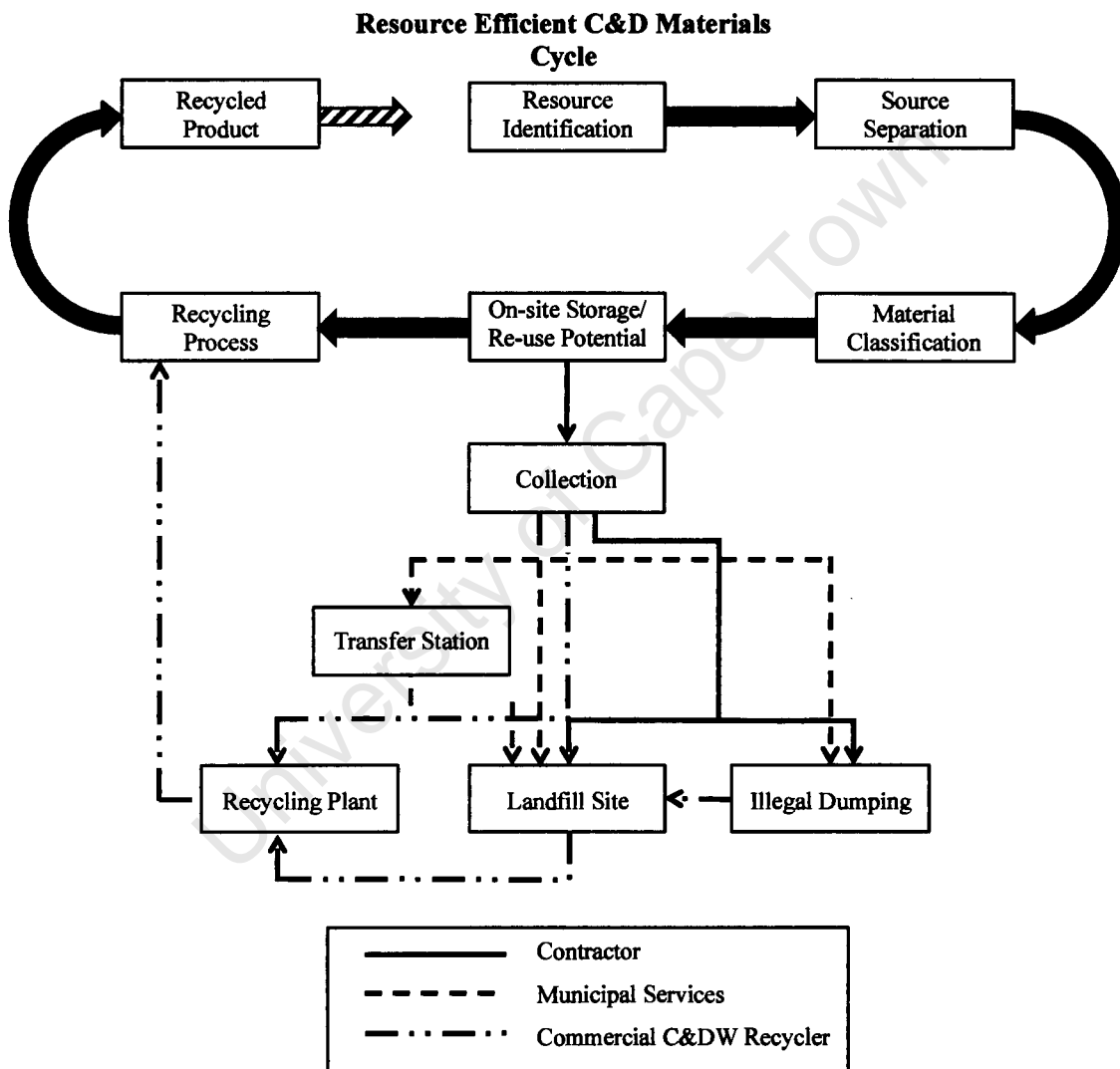


Figure 2.8: Resource efficient C&D waste cycle

The major shift in a resource efficient C&D material cycle when compared to the current C&DW cycle is the implementation of on-site separation practices. This involves the identification of C&DWs as resources, the separation of usable materials during demolition, the classification of materials according to their potential use and the processing of recyclable materials on-site. In this loop the contractor performs the role of the commercial C&D recycler. This has the potential to reduce this waste stream

The Use of C&DW in Concrete in Cape Town

thereby reducing transportation of materials to and from site and reducing the disposal requirements of the current C&DW management system. Furthermore, by simply separating wastes opportunities for off-site recycling increase as higher quality, uncontaminated, classifiable materials are made available to the recycling industry. Development of this system may progress even further if separation practices are widespread. This may offer opportunities for materials from neighbouring sites to be sold or traded in order for the material requirements of other projects to be realised.

2.5.2 Discussion

The development of on-site identification, separation, classification, recycling and re-use protocol relies on two main drivers in:

- Creating an obligation for contractors to identify and separate wastes through updated legislation and legislative enforcement.

For a successful recycling culture to flourish, sound policy and legislative actions have to take place. Governmental structures have to develop initiatives that identify and incorporate specific waste streams. Enforcement and penalties as well as education towards legislative developments are key in creating an environment where a specialist waste-processing sector can develop.

- Providing detailed information to engineers and architects that permits and provides uses for various C&D materials.

This is achieved by tackling the current approach to C&DW management on-site and creating a greater understanding of material properties, contamination issues, processing options, testing requirements and potential uses of multiple C&D materials in various construction applications. This involves promoting the use of C&DW materials within the construction industry by educating engineers and contractors in:

- Identifying C&D waste materials of value
- Identifying contaminants
- Various C&D material properties
- C&D material classification
- Material storage
- Processing options (crushing etc.)
- Basic testing recommendations
- Potential applications for RA materials

The Use of C&DW in Concrete in Cape Town

The development of a more detailed waste classification system is vital if a greater understanding off the potential of elements within the C&DW stream are to be accurately gauged. This allows for key recycling initiatives and industries to be targeted in their waste recycling activities.

2.6 Conclusion

In conclusion, upon closer analysis of the C&D recycling industry, it is clear that C&D recycling activity was high but also aided by landfill management requirements 10 years ago in Cape Town. This is seen in the estimated C&D recycling rate of 73% in 2003 with only 5% of C&D materials being disposed of in the Cape. Recent C&D recycling projections estimated a recycling rate of 61% however, subsequent landfill site closures and the failed development of the commercial C&DW processing sector has created a large C&DW management issue in the Cape. Despite identified economic potential in the C&D recycling sector, an estimated 195 500 tons of C&D waste is available for recycling and reuse in the Cape. This constitutes 29% of the C&DW stream.

The unrealised potential of the C&D recycling industry, despite multiple developed operations in the Cape, is often put down to inadequacies within the current national standards (SANS) that 'do not allow for recycled material use'. There have been concerns about the non-acceptance of particular recycled materials by the civil engineering sector since the initial development stages of this industry. However engineers are not completely bound by these standards. They are in fact a 'guideline' to material use within the engineering profession with other international C&D materials standards being readily available. Consequently it is recognised that there are far larger shortcomings in the construction industry's approach to waste management practices. This has led to quality control issues within the production of recycled C&D material and therefore a disregard for recycled material use within the engineering sector.

The current C&DW cycle is characterised by resource inefficiencies, economic, social and environmental burdens. Some of largest impacts are created by the transportation distances required to get C&DW to landfills, the resultant illegal dumping that arises from these costs, and also the delivery of virgin aggregates to site from quarries. Figure 2.9 below illustrates the magnitude of these distances. This Figure shows the location of the currently operational landfill sites, new landfills to be opened, drop off facilities and major coarse aggregate quarries in the Cape Peninsula.

The Use of C&DW in Concrete in Cape Town



Figure 2.9: Location of landfill facilities, aggregate quarries and drop off sites in the Cape Peninsula

Developing a solution that reduces or mitigates these impacts through C&DW management is a crucial objective in creating a more sustainable C&DW management system, promoting the use C&D materials and moving towards a more resource efficient construction industry. The development of a resource efficient, on-site C&D materials management system that includes identification, separation, classification, recycling and re-use protocol is seen as a solution to reducing these impacts. Furthermore these materials do provide economic opportunities. Achieving these goals relies on two main drivers in:

- Creating an obligation for owners and contractors to identify and separate wastes through updated plan approval regulations and regulation enforcement and;
- Providing detailed information to owners, engineers, architects, quantity surveyors and contractors that classifies and provides uses for various C&D materials.

Therefore these drivers are discussed in detail in the following chapters. These chapters provide details of the current regulatory environment, international waste management protocol, information on the background of C&D processing and classification of C&D materials, both locally and internationally.

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3 OVERVIEW OF NATIONAL AND LOCAL REGULATORY ENVIRONMENT FOR C&DW

3.1 Introduction

Chapter 2 presented a C&DW management direction referred to as a resource efficient C&D materials cycle. In order for this management approach to be successful, positive steps towards developing sound policy and legislative action have to take place. Within this process governmental structures have to develop key initiatives that identify and incorporate specific waste streams. This then creates an environment where a specialist waste-processing sector can develop at local governmental level and practices such as the reuse and recycling of multiple C&D materials can flourish.

The process of developing a ‘recycling culture’ is highly complex as this initiative affects governmental, public and private sector role players. This section looks at the regulatory environment in South Africa. It is a review of updates to policy and legislation level that have an impact on the C&DW stream. Special attention is paid to the National Environmental Management: Waste Act (NEM:WA) and its bearing on the City of Cape Town. It then summarises the City of Cape Town’s approach to developing C&DW reuse and recycling practices. This is led by the amendment of Integrated Waste Management (IWM) By-law and the City’s Integrated Waste Management Plan (IWMP), which has had a phased implementation since 2012. In order to gain an understanding of the potential of the City’s plan, international waste management initiatives in the Australian WasteWise and Californian CalRecycle programs are overviewed. This chapter refers to multiple appendices for more detailed information. The contents of these appendices are reflected in the Table 3.1:

Table 3.1: Appendix information reflected by Chapter 3

Appendix Details	
Appendix	Information
A	Overview of government structure
B	Summary of National Acts and Policies
C	Regulations in the City of Cape Town
D	The City’s Integrated Waste Management By-Law of 2009
E	The City’s C&DW Integrated Waste Management Plan
F	Details behind the development of the ANZECC
G	Details behind the development of the CalRecycle program

This overview is used to provide recommendations as to the directions that might be beneficial for the City to take, as far as updating and tweaking the relatively 'young' Integrated Waste Management By-law and the Integrated Waste Management Plan program.

3.2 National Regulatory Environment

There is an extensive body of national laws, regulations and policies that deal with waste and waste management in South Africa. National legislation covering waste and waste management is fragmented and in most cases outdated with regard to specific waste streams.

It is useful to gain an understanding of the basic governmental structures and institutional arrangements with regard to waste management, before overviewing the national legislative environment. A summary of the responsibilities and legislative protocol in a governmental overview is seen in Appendix A. A more detailed summary of the National Acts and Policies with regard to C&DW can be seen in Appendix B. This is of relevance to solid waste, which currently pertains to the C&DW stream. This review is not exhaustive as there are a myriad of legislative documents of lower level that govern waste arising from mining, nuclear energy, animal/abattoirs etc. Additionally national government is constantly formulating new waste management policies. Discussing all of these in detail exceeds the scope of this national regulatory review.

3.2.1 Overview of National Regulations

National legislation is currently in a transformational phase that seeks to streamline the fragmented, overlapping and out-dated legislation of the past. Waste management was traditionally left to the provincial or local authorities leading to a plethora of by-laws and local regulations covering this topic. This was an ineffective waste management environment in which waste issues were inhibited by clumsy national legislation.

Moving forward, no single national or provincial Act governs waste per se, however with the formulation of the NEM:WA, waste streams can be prioritised through national regulations. This is seen in the creation of waste tyre regulations and the development of gas and motor vehicle regulations. NEM:WA also allows for the realisation of the majority of targets and deadlines set by the early NWMS.

The current national governmental structure and national legislation provides the structures for provincial government and municipalities to construct their own by-laws, regulation and waste management systems under NEM:WA. It is now mandatory for provincial, local and municipal spheres to submit integrated waste management (IWM) plans and therefore identify waste streams and make

The Use of C&DW in Concrete in Cape Town

provision for recycling activities. This development allows for the above shortfall to be addressed within provincial and/or municipal environments. This is discussed in the next section.

3.3 Regulations in The City of Cape Town

As mentioned, the management of waste is traditionally left to local authorities leading to a plethora of by-laws and local regulations covering this topic. This section provides an overview of the development of the IWM By-law and the City's C&DW Integrated Waste Management Plan (IWMP), which is the leading legislation with regard to C&DW in The City. A background and detailed information on Regulations in the City of Cape Town, the IWM By-Law of 2009 and The City's C&DW Integrated Waste Management Plan can be seen in Appendices F, G and H. The following section is a brief overview of these developments.

3.3.1 The City's IWM Policy

NEM:WA requires provincial government to compile IWMPs and review municipal waste management plans (WMPs). The City of Cape Town's Integrated Waste Management (IWM) Policy is a 'response' to NEM:WA. These plans have been formulated to co-ordinate the waste management process in terms of the Cape Town Councils' governance responsibilities. With regard to C&DW, the purpose of this policy is to introduce, facilitate and encourage waste minimisation and management practices as per the waste management hierarchy. This involves the reuse of waste, promotion of waste separation practices, landfill diversion and public-private partnerships (DEAT May 2000). Details of the regulations within the City are seen in Appendix C.

This IWM Policy has led to the passing of the IWM By-law of 2009. This By-law deals with C&DW specifically and gives clear direction to dealing with C&DW management. The details of this management process are discussed in the following section.

3.3.2 IWM By-law of 2009 and IWMPs

The City of Cape Town's IWM By-law of 2009 is the leading legislation that controls C&DW management in Cape Town. The City of Cape Town's approach to waste management has shifted from direct disposal of C&DW at landfill sites, to minimisation and recycling with the implementation of the IWM By-law. It makes reference to *building waste*, which in the context of this study, alludes to C&DW. An overview of the By-Law with obligations and amendments specifically applying to owners/developers generating waste from building and demolition activities is discussed in Appendix D.

Currently the IWM planning approach is in a very early development stage and is therefore very basic. It is aimed at ensuring that C&D materials are not illegally dumped or stored on City property (i.e. the

The Use of C&DW in Concrete in Cape Town

sidewalk). There is an emphasis on separation, however this is limited to *liquids and components for recycling*. In short, the By-Law discloses basic obligations of waste generators (owners/developers) to submit an IWMPs to the City that deal with storing, transporting and disposing of C&DW at a *crushing plant, landfill site or licensed building waste facility*. This is summarised in Table 3.2 below. It is to be implemented in phases to allow system tweaks and optimisations. The first phase targets small residential developments and was implemented in early 2012. The second phase of this process will target business and industry developments (non-residential) and housing developments (high-rise fats, multiple housing etc.). It was envisioned that this process will be compulsory for all building applicants in the 2013 (City of Cape Town 2009). Further details of the City's IWMP is seen in Appendix E.

Table 3.2: Summary of the obligations of waste generators under the IWM-By Law

Obligations under the IWM By-Law	
Mechanism	Details
Separation of industrial waste	Separation into liquids, components and materials for recycling and re-use
Storage of waste	Generated building waste not to be stored in containers provided by the City for residential waste
	Storage is to take place on the owner's property
	Permits are to be obtained to store waste on the City's property where applicable
Disposal of waste	Disposal of waste at licensed crushing plants, landfill sites or any other licensed disposal facility
	Provision of weighbridge certificate to building control officer of full disposal of waste

This marks a shift in construction and demolition practice within the Cape as this By-law requires waste management issues to be addressed during the pre project-planning phase. This allows for a more efficient analysis of waste generation and generation of waste prevention strategies.

3.3.3 Concluding Comments

The requirement of provincial and municipal government to develop plans that cater for specific waste streams has led to the evolution of the IWM By-law which begins to isolate the C&DW stream. This is a positive step in the progression of C&DW management in the Cape. However this extremely young initiative and separation criteria are extremely basic.

The Use of C&DW in Concrete in Cape Town

The requirement of waste generators to separate C&DW at source is key to increasing the use of recycled C&DW in Cape Town. Separating C&DW creates awareness as to the structural elements being demolished and makes contractors conscious of the material components within the C&DW stream. The mixing of C&DW components, as well as other municipal solid waste, is extremely detrimental to the recycling potential of both the C&DW components, as well as other municipal solid waste. Separation practices have enabled other recycling industries to establish sources of uncontaminated waste and then to develop their markets through various recycling initiatives in the Cape. This allows for the identification of materials for reused, to be recycled on-site and/or transported off-site for recycling or for disposal.

This obligation creates a need for detailed pre-construction/demolition planning to cater for the generation and separation processes. The use of IWMPs that promote C&D separation practices are widespread in California, Australia and Japan (California Government 2012; Andrews 1998; Sustainability Victoria 2012; Kasai 2004). It is helpful to overview some of these initiatives to gain a greater understanding of what is required of provincial and municipal government to achieve a more stringent C&DW management approach and gain widespread acceptance of the IWM By-law.

3.4 Overview of international Waste Management Programs

As mentioned the implementation of the IWMP system is very new to the City and the construction industry. It is therefore beneficial to overview some IWMPs that have been adopted by countries in which C&D recycling is a recognised industry.

3.4.1 Australian WasteWise Construction Program

The Australian and New Zealand Environmental Conservation Council (ANZECC) developed the WasteWise Construction Program in 1995. This was facilitated by a waste reduction agreement through negotiations with five of the major Australian construction companies. The agreement utilised a MoU between government and industry to pursue waste reduction initiatives and recycling targets in an effort to reduce the amount of C&DW going to landfill sites (Andrews 1998). Details of this can be seen in Appendix F.

This program has developed into a standard mechanism for dealing with C&DW in Australia. Through this program various documents are provided to facilitate the development of IWMPs. Documents such as the *Guidelines for Preparing Waste Reduction: Strategy for Construction* highlight planning practices in project planning phase, pre-construction phase, off-site and on-site activities (Sustainability Victoria 2012).

The Use of C&DW in Concrete in Cape Town

This project planning phase focuses on educating personnel about the reason for waste recycling and communicating responsibilities to stake holder in order to prepare and facilitate waste analysis, separation and control through out the project. Preconstruction guidelines emphasise building for deconstruction, good dimensioning and designing to standard material sizes and operational waste reduction during the building life cycle. Construction guidelines recommend prefabrication, delivery and storage planning, separation arrangements and disposal management.

Further documents such as the *Waste Minimisation Plans for Construction and Demolition projects* provide checklists and report templates to be completed by the waste generator. These documents contain information such as company details, site details, materials on site, quantities and persons responsible for disposal etc. Extracts from these documents are shown below.

Following the development of this program, Australia has begun to set stricter C&D recycling targets of 80% by 2014 (Australian Bureau of Statistics 2006). They remain one of the leading C&D recycling countries and have published numerous guidelines and standards on the use of C&DW in the construction industry.

Materials On-Site		Re-use and Recycling	
Type of waste materials to be generated	Estimated Quantity (m ³) (Tonnes)	ON-SITE - Specify proposed re-use or on-site recycling method	OFF-SITE - Specify contractor and recycling outlet
Soil			
Rock			
Vegetation greenwaste			
Concrete			
Steel reo			
Structural steel (studs etc)			

Figure 3.1: IWM Plan - Waste Minimisation Plans for Construction and Demolition projects (Sustainability Victoria 2012)

3.4.2 CalRecycle Program

Similar to the WasteWise initiative, legislation was developed by the CalRecycle program through feedback from local government, building industry representatives and C&D recyclers and waste management companies. Development of this program was initially facilitated through workshops that included panels of local government and industry representatives. This was followed up by a forum in which issues surrounding procurement, reuse, marketability and infrastructure for C&DW processing were tackled.

The Use of C&DW in Concrete in Cape Town

Construction and Demolition Recycling Plan and Disposal Report

Permit Number		Job Address				
Owner		Contractor		Phone No		
Construction Type		Square Footage:		Project Est. Cost:		
Recycling Contractor (if applicable)						
MATERIALS	Before Construction (estimated tons)		After Construction (actual tons)			Contractor/Owner to submit all disposal and recycling receipts
	Landfill	Diversion	Disposed	Diversion		
			Landfill	On-site reuse	Off site recycle	Where
Mixed Recyclables						
Land Clearing						
Inerts (Concrete, A/C, etc.)						
Drywall						
Metals						
Lumber						
Cardboard						
Trash		NA		NA	NA	
Total						

Estimated diversion rate: _____ % Actual diversion rate: _____ %

OFFICIAL USE ONLY		For Applicants: To Complete this form see the instructions on the other side	OFFICIAL USE ONLY	
Plan Approved			Goal Achieved	
Information Needed			Substantial Compliance	
Plan Denied			Goal Not Achieved	
Project Value	\$		Penalty Paid	\$
Date			Date	
Reviewed/Approved By:		Reviewed/Approved By:		

Figure 3.2: WMP used by San Luis Obispo County in California (California Government 2012)

Legislation requires that WMPs be completed and submitted prior to the beginning of a project. Essentially this plan estimates how much C&D material will be generated and shows evidence of how the plan is to be achieved, where and how much waste will be diverted. The background and details of this legislation can be found in Appendix G. An example of the WMP used by San Luis Obispo County in California is shown in Figure 3.2.

WMPs are bound by the California Green Building Standard Code (CALGreen). This requires all newly constructed buildings to develop a WMP that diverts a minimum of 50% of the project’s waste. A recycling target of 50% - 75% is encouraged with some jurisdictions specifying recycling rates of 75% for materials such as concrete/asphalt. Incentives are used to ensure compliance with this ordinance. This can be in the form of a deposit that is based on the cost of the project, size of the project, type of project etc. Other incentives used include signed letters of intent to comply with regulations, on-site monitoring and penalties if the contractor does not comply with the ordinance. These deposits are used for administrative costs and program costs including infrastructure improvement (California Government 2012).

3.5 Moving Forward in the IWMP Process

Creating a regulatory environment in which the construction and demolition industries are made aware of the potential of C&DW to be reused and recycled is paramount. The implementation and further development of on-site IWMPs for the construction and demolition industry is seen as the cornerstone of this initiative.

The development of these successful IWMP initiatives internationally are characterised by the following basic procedures:

- Stakeholder co-ordination
- C&D Waste targets and goals
- Detailed characterisation of the C&D waste stream
- Further regulatory actions

These are discussed with reference and to the current IWMPs in the City of Cape Town in an attempt to improve this system in the future.

3.5.1 Stakeholder Co-ordination

The coordination of C&DW recycling schemes affects an extremely wide variety of parties. These include:

- Waste collectors
- Transfer and landfill facilities
- Owners, engineers, architects, quantity surveyors and contractors
- Construction and demolition companies
- Industry organisations
- Government
- Poor, unskilled or unemployed

These parties all have different views and can provide information about the opportunities and difficulties they foresee with the implementation of C&D recycling initiatives.

As discussed in the WasteWise and CalRecycle WMP strategies, the development of C&DW recycling policy is preceded by in depth discussions and pilot studies with key industry role players and stakeholders. This begins with high-level role players such as major contracting companies, industry

The Use of C&DW in Concrete in Cape Town

organisations and government. In the context of the City of Cape Town this would involve companies such as Ross Demolition and Afrimat.

This is seen in the New Zealand Environmental Conservation Council agreement, which bound five major Australian construction companies in a MoU agreement to pursue recycling initiatives and recycling targets for a period of 3 years (Andrews 1998). Germany also followed a similar procedure with the setting of targets of 50% C&D recycling to be reached by 2005, which was initiated in 1996 by the signing of the Voluntary Agreement by several industrial organisations (Macozoma 2006).

Both these agreements showed the construction industries' intentions to support governmental C&DW targets by providing service, information and research and development help. In the case of the WasteWise project, this 'trial' period allowed for the creation of industry wide recycling targets. It resulted in a published guide to achieving bottom line benefits and developing an approach for future companies to coordinate and implement these initiatives.

3.5.2 C&D Waste targets and goals

Creating specific C&DW recycling targets, to assist national landfill reduction targets, is vital in decreasing waste and monitoring progress.

In review of the WasteWise and CalRecycle projects, one of the first steps by government was to create C&DW recycling targets. Through WasteWise, Australia has begun to set strict C&D recycling targets of 80% by 2014 and through the CalRecycle project recycling targets have been increased up to 75% for some materials (Andrews 1998, California Government 2012). In other regions such as the EU, recycling targets of 70% have been set for 2020 (Tojo 2001).

The CalRecycle system is an excellent example of coordinating recycling goals and initiatives through different levels of governance. Through state legislation (Statute AB939 of 1989) each county, within California, was charged with establishing a task force to prepare, adopt and submit a city Source Reduction and Recycling Elements plans by a certain date. This plan was to include waste characterisation, source reduction, recycling, composting, solid waste facility capacity, education and public initiatives, funding provision, special waste and household hazardous waste information at county level. Also included is an IWMP that specified areas for transformation or disposal sites. This was to provide capacity for solid waste generated that cannot be reduced or recycled for a 15-year period. A Waste Diversion Mandate that required each city to show a diversion of 25% of solid waste from landfill was used to enforce this system (California Government 2012).

The Use of C&DW in Concrete in Cape Town

In the South African context, the updating of waste minimisation goals by the NWMS is a positive step towards increasing recycling initiatives. Having said that, these goals are vague and non-specific, not making any reference to any specific waste streams. Furthermore they carry no substance, as they are not substantiated by any penalties. The onus is therefore on The City to create specific C&D recycling goals in the future.

3.5.3 Detailed Characterisation of the C&D Waste Stream

C&DW must be seen as a resource where individual recycled components have specific uses and applications within the building and construction industry. This is seen in the municipal waste stream where components in the plastic, glass and paper are identified, separated and recycled individually. Implementing regulatory actions can enforce this prerogative as has been seen in the recent development of waste tire regulations.

Simply accounting for materials classified as 'building rubble' is inadequate if this material is not sorted into various components. This may include various concrete grades, clay bricks, cement brick, tiles and other C&D materials. This is a result of quality control being one of the defining factors in the ability of C&D materials to be reused in different construction applications. It is important that management and handling of waste is carried out in a manner such that the technical requirements of the waste material are understood (Melton 2004). This makes the collection and recycling of C&DW, to produce high quality, usable materials much more efficient and manageable.

Significant to this is the creation of some sort of pre-construction C&DW identification template. The IWM By-law outlines the responsibilities of waste producers and industry with regard to C&DW minimisation. This is controlled by the submission of IWMPs by waste producers. The current City of Cape Town's IWMP details are rather crude and vague when compared to other WMPs to be completed. Documents such as the Waste Minimisation Plan for Construction and Demolition Projects from WasteWise provide checklists and report templates to be completed by the waste generator. The Japanese Construction Recycling Law is another obligatory C&D separation specification that requires owners to submit a Notification Document for any planned generation of waste in specific projects. This Notification Document includes information such as usage, number of stories, projected floor area, permit numbers, registration numbers and demolition association information in the case of demolition (Kasai 2004).

Most WMP templates make use of waste quantity estimations. Training or guidelines for contractors to submit reasonable estimates of re-use, diversion, disposal and material types as well as how to complete forms of this nature is also important in achieving a sound system. Also, both C&D material quantities

The Use of C&DW in Concrete in Cape Town

and transportation schemes have to be controlled by reliable registration and data collection systems. Contamination is a major factor in determining the economic viability of C&DW recycling (Hansen 2004). In the case of C&DW, quality control of this product is varied and is dependant on incoming waste quality (Schultmann 2001). Detailed registration systems can help control or make provisions for this problem.

This process provides vital data on specific C&DW quantity that is generated in a region. This has a follow on effect for a number of other management initiatives including:

- Monitoring of waste quantities
- The creation of accurate and relevant waste recycling targets
- Management of landfill facilities
- Allowing for relevant updates to legislation

The development of a standard WMP template for the City of Cape Town is therefore also a prerogative for the future. This topic is dealt with in more detail in Chapter 4, section 4.2.3 – Resource Identification.

3.5.4 Further regulatory actions

Once stakeholders have been coordinated and are positive about C&D recycling developments, and an understanding of the waste stream is gauged through detailed WMPs and waste characterisation studies, further regulatory initiatives can be introduced.

Further regulatory actions to be explored within waste management policy that promote the recycling and use of C&DW include (Hansen 2004; Macozoma 2001; Schultmann 2001):

- Discouraging the disposal of large quantities of C&DW with strict landfill pricing mechanisms such as:
 - Pricing per unit quantity of waste generated
 - Two-tier pricing that use a flat fee beyond which a large price increments are incurred
 - Specific waste type pricing schemes
- Taxes on the use of natural aggregates
- Incentives for the use of recycled C&D waste in projects
- Subsidies and grants to C&D waste processors
- Stricter laws and monitoring of illegal dumping

The Use of C&DW in Concrete in Cape Town

- Stricter C&D waste management requirements for waste producers
- Selective demolition being made mandatory
- Local specifications and codes being developed

If policy decisions such as these are utilised, the use of C&DW can become more practical throughout industry. These incentives can engage lower stakeholders such as smaller contractors, waste haulers, architects and designers. This allows the culture across industry to change and commit to minimise waste and explore waste management schemes. Through policy implementation, market drivers can also be activated. Knowledge about the opportunities and technologies available can swing the perceptions that waste minimisation and recycling is a cost factor, rather than an opportunity for saving in industry (Lauritzen 2004; Macozoma 2006). Recycled products must be able to be produced and marketed to compete with comparable raw materials in terms of price and quality. These policy amendments then also have to be supplemented by the modification of the construction standards (SANS) to permit and encourage the use of recycled materials.

3.6 Recommendations

At a national legislative level the first step in facilitating a C&DW recycling culture within South Africa is the recognition of C&DW as a priority resource stream. Initiating this process involves:

- Identifying C&D waste as a priority by the Minister
- Developing a C&D Waste Classification and Management Regulation that:
 - Identifies individual C&D waste components
 - Provides management regulations that control the separation, storage, reuse and recycling of these components

At a provincial and/or municipal level creating legislation/regulations/guidelines in which the construction and demolition industries are made aware of the potential of C&DW to be reused and recycled through IWMPs is key. This involves:

- Stakeholder co-ordination and gain co-operation through initiatives such as an MoU (as discussed in Appendix F and G)
- Develop specific management guidelines and standards that educate industry as to the potential and application of recovered C&D waste. This involves guidelines that specify:

The Use of C&DW in Concrete in Cape Town

- Characteristics and properties of materials
 - Separation
 - Storage
 - Re-use options and;
 - Recycling opportunities for C&D waste
- Develop the IWM By-law by creating a universal pre-construction IWMP document that:
 - Classifies and quantifies individual C&D waste elements on-site
 - Identifies and earmarks the owner and waste management agent
 - Makes provision for the monitoring of C&D waste materials through management procedures such as reuse, collection, weight bridge, recycling and disposal information

3.7 Conclusion

The National legislative environment is currently in a phase of reform. The implementation of the NEM:WA and the validation of the NWMS have created an legislative environment where individual waste streams can be identified and regulation can be promulgated in order to manage these materials. Therefore, the first step in facilitating a C&DW reuse and recycling culture within South Africa is the recognition of C&DW as a priority waste stream at a national level. Currently the simple Waste Classification and Management Regulations confines this prerogative because they regard C&D materials as a combined waste stream. This limits the ability of C&D materials to be reused and recycled, as they become contaminated through the mixing a various municipal waste components.

Further developments within this process warrant the collection of data C&DW in the construction and demolition industry. This allows for the development of valid C&D recycling targets, the monitoring of waste management infrastructure and the development of further legislature, such as a detailed classification and reuse guideline, that promotes reuse and recycling activities in the Cape.

The City of Cape Town has used the national legislative structure to develop a municipal regulation that identifies C&D materials as a priority waste stream. Thus, the IWM By-Law has been created in an attempt to make C&D material separation practices mandatory in the Cape. This creates an environment within industry, where the re-use and recycling of multiple C&DW components becomes increasingly feasible. The IWM By-Law has the potential to promote awareness as to the potential and capabilities of

The Use of C&DW in Concrete in Cape Town

C&D materials as the construction and demolition industry are forced to recognise and manage this waste. However, this By-Law is currently in an early implementation phase and is extremely basic. The creation of 'pre-feasibility' documentation that identifies and quantifies components within the C&DW stream is vital. This process is illustrated in the development of international IWMPs such as the WasteWise and CalRecycle programs. Thus, municipal C&DW management regulations needs to facilitate identification, separation, and on-site processing through clear and standardised guidelines. Therefore, the following section deals with the steps that need to be taken to process C&D materials on-site and the current classification standards recognised in the Cape. This forms the background behind creating IWMPs in the future.

University of Cape Town

The Use of C&DW in Concrete in Cape Town

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University of Cape Town

4 Processing and Classifying Recycled Aggregates – A Review

4.1 Introduction

Chapter 3 reviewed the current regulatory environment, which shows the City's commitment to reducing C&DW through updated waste management legislation. The IWM By-law has set the foundation for changes within municipal government where the separation of C&DW creates an environment where C&D materials are recognised by waste producers. However, the implementation of this by-law does not by any means guarantee that industry will follow recycling initiatives. Separation of C&D waste stream into "*liquids, components and materials that can be recycled*" is a rather vague objective. This warrants the development of guidelines that facilitate C&DW generation, storage, separation and recycling practices in Cape Town.

It is important that the management and handling of waste is carried out in a manner such that the technical requirements of the waste material are understood. This makes the collection and recycling of C&DW, to produce high quality, usable materials much more efficient and realizable. Significant to this is the creation of pre-construction C&DW identification templates and IWMPs as is discussed in the previous sections.

Chapter 4 follows this direction of promoting on-site waste management with a discussion of the benefits of on-site recycling and a recommended processing approach to the on-site separation of C&D materials. This follows the path of the resource efficient C&D materials cycle as presented in Chapter 2, where resource identification, source separation and crushing procedures are discussed. This relates to the development of IWMPs. Finally, international and national recycled aggregate technical standards, for aggregates for use in concrete, are reviewed in order to understand the current requirements of processed C&D materials. This aids in the identification of materials that are of high value within the C&DW stream.

4.2 Recycling Definitions

C&DW can consist of multiple material components including brick, concrete, plaster, mortar, ceramics, stone, asphalt, plastics, woods, paper and soil. An important distinction needs to be made between the upcycling, recycling and downcycling of these components.

The Use of C&DW in Concrete in Cape Town

Upcycling refers to converting waste materials in products of better quality or for better environmental value. This could take place when engineering grade bricks previously used for paving are cleaned and utilised in a structural application.

Recycling is a process of changing waste materials into products that prevent the waste of potentially useful material, reduce the consumption of raw materials and reduce environmental impacts. This could entail reusing precast concrete components or cleaning and reusing clay bricks.

Downcycling converts waste materials in to products of lesser quality and reduced functionality. Downcycling should be the last resort to managing waste before disposal. Crushing C&DW into aggregate for varying applications can be described as downcycling. This study refers to the processing of C&D materials as recycling, but strictly speaking it is classified as downcycling.

4.3 On-site Recycling

C&DW can be processed either on-site or off-site. There are challenges with each of these options and the factors to consider in the choice of either of these directions are complex. These factors include (Macozoma 2006):

- The availability and quality of on-site materials
- The on-site materials requirements
- The space available for storage and operation of mobile processing plants
- The project time constraints
- The availability of processing machinery
- The haul distance between site, the nearest processing facility and other treatment or disposal site

In Cape Town, off-site recycling has been the most widely accepted response to processing recycled C&D materials. Off-site recycling practices takes place at private recycling facilities, brick manufacturers and landfill sites. These facilities are usually large scale, electrically powered, fixed plants that specialise in processing C&DWs (Vossberg 2012). The development and use of recycled C&D materials in Cape Town has been inhibited by, among other things, poor quality control and the production of inferior quality recycled C&DW. This is largely due to the delivery of mixed C&D and municipal waste materials to recycling facilities by waste transportation contractors. This is illustrated by the recent failure of contractors to pursue recycling initiatives at landfill facilities and the continued rejection of these materials, as the construction industry is unwilling to risk utilising inferior materials thereby putting their reputations at stake (Ayers 2002).

The Use of C&DW in Concrete in Cape Town

On-site processing and recycling practices have the potential to improve the quality of commercially produced recycled aggregate materials as well as being the most environmentally beneficial approach to managing C&DW in the Cape (Vossberg 2012). This approach avoids material transportation impacts, virgin material use and can create employment opportunities. On-site separation, crushing and use has a number of advantages over off-site processing however every site is different and will have its own challenges. This is summarised in Table 4.1 (Macozoma 2006, Vossberg 2012):

Table 4.1: Pros and cons to on-site and off-site C&D waste recycling

Lower Costs	<ul style="list-style-type: none"> • Lower material costs: Contractors can supply their own materials for low grade applications
	<ul style="list-style-type: none"> • Lower transport costs: Reduced distanced and material quantity hauls to and from site
	<ul style="list-style-type: none"> • Reduced disposal costs: Reduced distanced to potential recyclers and material quantity hauls from site
Reduced Resources Consumption	<ul style="list-style-type: none"> • Reduced quantities of mined materials needed: Utilising on-site materials reduces the need for commercially produced aggregate materials
Reduced Transportation	<ul style="list-style-type: none"> • Transportation distances may be reduced: Separated materials may be transported to other sites and recyclers reducing long transport distances to landfill facilities
	<ul style="list-style-type: none"> • Reduced virgin materials required: This reduced the need to transport material to site
	<ul style="list-style-type: none"> • Reduced quantities of waste materials: This reduced the need to transport material from site
Lower social burden and infrastructure pressures	<ul style="list-style-type: none"> • Less transport disruption and road infrastructure pressure: Heavy duty vehicles trip delivering virgin materials and collecting waste materials decrease
Increased employment opportunities	<ul style="list-style-type: none"> • Low skilled labour can be used for separation, crushing and stockpiling procedures
Off-site processing	
Detailed site preparation required	<ul style="list-style-type: none"> • Details such as material identification, acquisition, storage, processing and application need to be taken into account from the design phase
Detailed construction programs	<ul style="list-style-type: none"> • Quantities of material needed for project needs to be taken into account • Construction timetable may be effected • Material delivery and storage might be effected
Local noise and dust	<ul style="list-style-type: none"> • Mechanical crushing may increase noise and dust levels on site
Flexibility of materials	<ul style="list-style-type: none"> • Material availability might be limited • Recyclable material availability on site might not have many application in certain projects
Increased education and skills needed	<ul style="list-style-type: none"> • Engineers need to be aware and educated as to the potential of C&D materials and how they can be utilised
	<ul style="list-style-type: none"> • Quality control to ensure adequate materials are utilised is paramount

The Use of C&DW in Concrete in Cape Town

In a recent a life cycle based assessment study by Vossberg (2012), energy assessments in the form of a ⁷cumulative energy demand (CED) and ⁸global warming potential (GWP) was carried out on the crushing, transportation and landfilling of C&DWs in the City of Cape Town. Results of this study are shown in Figure 4.1. The definition of these terms is covered in Appendices N and O.

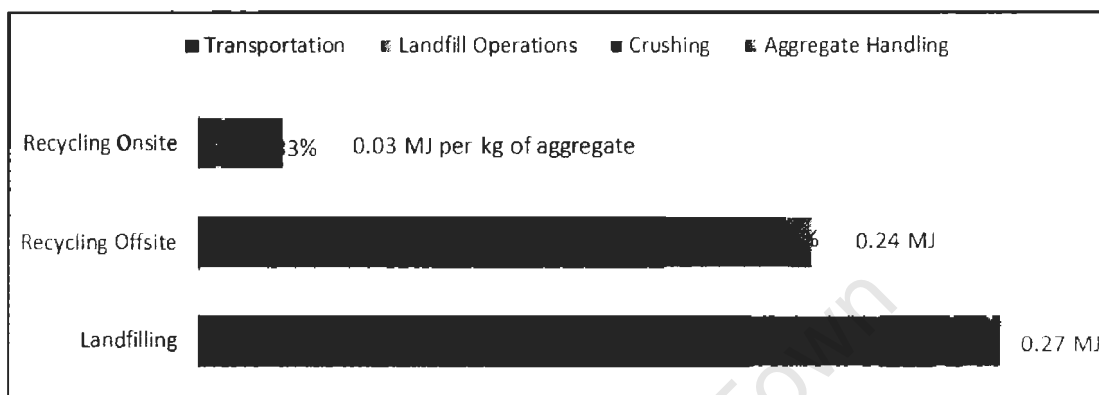


Figure 4.1: On-site recycling vs. Landfilling (Vossberg 2012)

The results from this study show that on-site processing, using mobile crushers uses approximately 90% less energy (CED) than landfilling, and 80% less than off-site recycling. It is clear that the processing of C&D materials on-site is the most favourable approach for reducing the environmental burden, the largest of which is the transportation burden created by current off-site disposal practices.

The above approach can be seen as an ideal case whereby contractors process and utilise all of their available on-site materials (recycling on-site). This energy projection is therefore extremely simplified and in practice a number of other variables will create an increased energy contribution. These contributions may come from materials that are not be able to be processed i.e. crushed with the available machinery, materials that are not utilisable for the projects under question, excess materials and an inevitable component of unusable waste material as a result of processing. Also the increased impact of utilising greater cement quantities in RAC is not quantified.

⁷ CED can be described as a measure of amount of primary energy needed to produce, use and dispose of an electricity supply. See Appendix H.

⁸ GWP measures the air emissions from an activity for a 100 year period. See Appendix I.

The Use of C&DW in Concrete in Cape Town

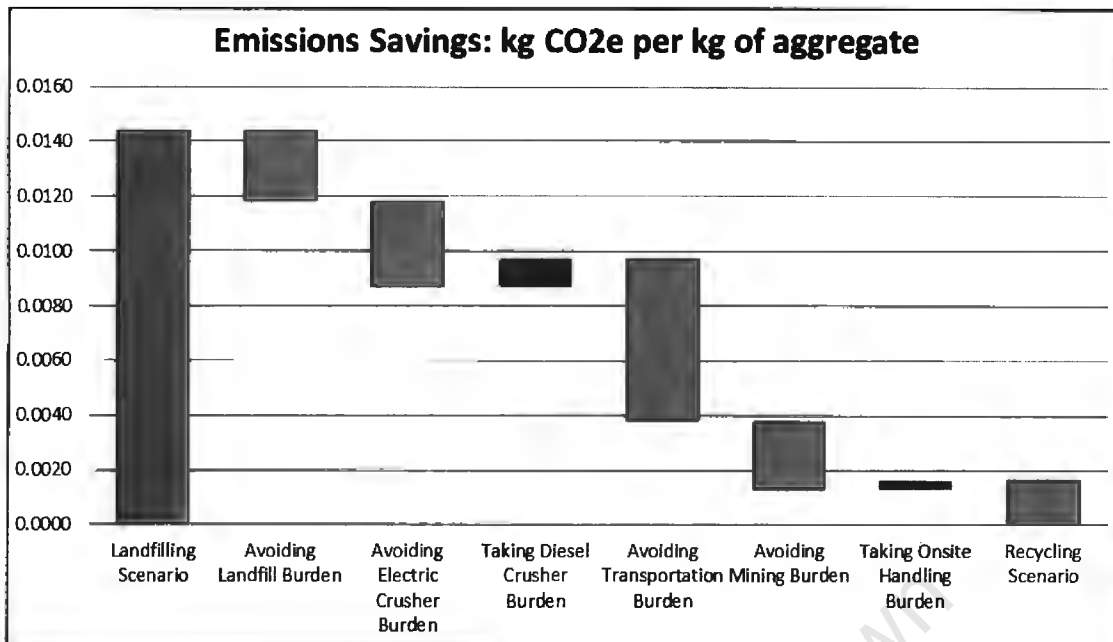


Figure 4.2: Energy contribution of on-site, off-site and landfilling C&D waste (Vossberg 2012)

From Vossberg's (2012) study the transportation of these on-site materials plays the most significant role in establishing the impact of on-site separation and processing practices. This is illustrated in Figure 4.2. The green bars (all axis titles beginning with "Avoiding...") show reduction in GHG due to certain activities with the transportation burden being the largest contributor. The red bars (all axis titles beginning with "Taking...") show additional GHG emissions from on-site processing scenarios (Vossberg 2012). Therefore, the construction industries approach to managing C&DW during separation and processing on-site is also paramount to reducing impacts.

The recycling of C&D material will make use of off-site processing. This practice is seen in all major C&D recycling countries and is a result of the constraints within the on-site approach and the nature of the construction industry's material requirements. One of the major goals is therefore to mitigate the environmental effects of this future response by promoting on-site processing and recycled materials use but also creating an efficient, low energy, off-site C&D recycling management system that merges with on-site classification, storage and collection protocol.

The following section reviews the effects of various processing actions on RA materials. It follows the proposed efficient C&D materials cycle that caters for the issues discussed above and discussed these management actions individually. This is to gain further understanding of an on-site processing approach as well as to link these actions and offer opportunities that may increase off-site RA quality.

4.3.1 Processing C&D Waste

Processing refers to the recycling operation that converts C&D materials into usable aggregate. Depending on the waste stream in question, materials can either be recycled, down-cycled, up-cycled or a combination of these. Materials are down-cycled when a higher-grade structural concrete is processed for use in low-grade concrete applications, this is usually the case for RCA material. Certain masonry, such as engineering bricks, may be up-cycled when it is cleaned and reused for higher-grade applications, recycled when reused and down cycled when it is crushed into aggregate for concrete.

The recycling of C&D materials can consist of various stages of material separation, manual or mechanical crushing and sieving, either off-site or on-site. C&DW is traditionally processed in four general stages namely separation, conveying, crushing and screening. These stages do not necessarily follow this order but may consist of multiple actions where these procedures are repeated to obtain a particular product. In following the resource efficient C&D materials cycle discussed in previous chapters, this chapter separates the C&D recycling operation into 5 stages namely:

- Resource Identification
- Source separation and classification
- Storage
- Processing (crushing or cleaning procedure) and;
- Recycled product classification

Each of these operations is discussed in the following sections.

4.3.2 Resource Identification

The definition of C&DW and characterisation of its components forms an integral part of developing a C&DW management system. This is seen as a major shortfall as the current national characterisation (NEM:WA) defines C&DW as *General Waste - Uncontaminated building and demolition waste* that does not require classification as discussed in Chapter 3, section 3.5.3.

The components of the C&DW stream vary according to location, the type of C&D practices taking place, techniques employed, construction phase, construction sector involved and the social economic conditions. This is illustrated by Figure 4.3, which quantifies the C&DW stream in its various components in various regions including Asia and the Cape Town (Ayers 2002; Chen 2002).

The Use of C&DW in Concrete in Cape Town

Therefore, the development of regulations that characterise the C&DW stream are seen as paramount in furthering separation, storage, reuse and recycling activities in the City. C&D materials need to be identified into components such as:

- Masonry
- Concrete
- Ceramics
- Metals
- Wood
- Plastic
- Other contaminants

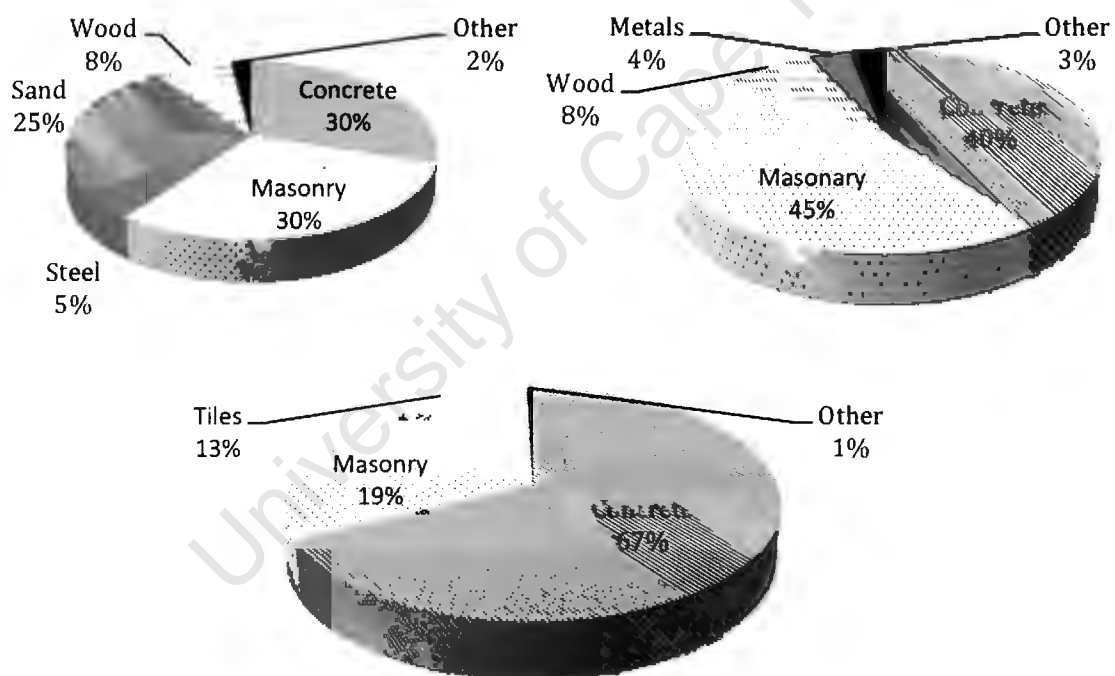


Figure 4.3: Figures show the composition of various C&D waste streams internationally. Labelled are inconsistently showing the importance of characterisation of materials within a waste stream (Kartam et al 2004; Ayers 1999; Chen et. al. 2002)

These materials may then be separated and further classified into materials that may be used in various applications once their technical properties are understood fully. Possible applications are outlined in Table 4.2.

The Use of C&DW in Concrete in Cape Town

Table 4.2: Recommended types and uses of C&D Waste (HB 155:2002)

Summary of types and uses of C&D Waste – HB 155-2002					
Types of C&D Waste	Uses				
	Bulk fill	Drainage/Filter material	Pavement concrete	Road pavement	Structural concrete
Crushed debris	Suitable	Usually suitable	Not suitable	Not suitable	Not suitable
Graded mixed debris	Suitable	Usually suitable	Suitable in some cases	Not suitable	Suitable in some cases
Clean graded brick/concrete	Highly suitable	Suitable	Usually suitable	Suitable in some cases	Usually suitable
Clean graded concrete	Highly suitable	Highly suitable	Usually suitable	Potentially suitable	Usually suitable

4.3.3 Source Separation

A critical component of recycling is acquiring materials and hence a separation protocol. This involves stringent visual inspection and manual separation upon generation. It is generally accepted that the more homogeneous the waste stream, the more easily it can be recycled and reused either as is or as a blend with natural aggregates. Separation therefore aids both off site and on-site recycling operations. Potentially recyclable C&D materials can be separated into the following sub-classes:

- High strength clean reinforced or unreinforced concrete
- Low strength clean reinforced or unreinforced concrete
- Masonry material
 - Burnt clay bricks
 - Engineering brick
 - Paving brick
 - Low strength bricks
 - Concrete masonry
- Mortar
- Plaster
- Ceramics
- Excavated Materials

The Use of C&DW in Concrete in Cape Town

The quality of products generated from C&D materials is largely determined by the quality of the feedstock and on-site separation of materials and contaminants. Contaminants that should be removed from a recycling feedstock are (HB 155-2002):

- Timber
- Asphalt
- Metals
- Gypsum
- Clay and soil
- Glass
- Cardboard and paper
- Plastic
- Organic substances

Education and guidelines are key to promoting and creating a successful on-site separation culture within the demolition and construction industry. Services such as educational programs, brochures and websites containing information outlining C&DW separation and storage procedures all help in facilitating on-site separation practices. This prerogative has been realised in other countries with documents such as the *Guidelines for Preparing Waste Reduction: Strategy for Construction* developed by WasteWise, facilitating the implementation on-site storage and separation programs in the project planning phase, pre-construction phase both on-site and off-site. An extract from this document is shown in Figure 4.4. Websites such as the INFORM, U.S EPA C&D Debris, ACWMA, Builders Australia etc. are also examples of specific educational guidelines available online for waste separation practices.

The Use of C&DW in Concrete in Cape Town

Type of waste materials to be generated	Estimated Quantity (m ³)	Estimated Quantity (Tonnes)	Waste Reduction Technique	Method (On-Site or Off-Site)
Bricks				
Plasterboard				
Timber - ceiling				
Timber - flooring				
Timber - trim				
Timber - wall				
Tiles				
PVC				
Metal - ferrous				
Metal - non ferrous				
Doors & windows (including frames)				
Glass - other				
Carpet				
Carpet underlay				
Fixtures & Fittings - other				
Paper & Cardboard				
Timber pallets				
Cement Bags				

Figure 4.4: Separation schedule created by WasteWise (Australian Standards 1998)

It is imperative that the City develops standard C&DW material identification and quantity estimation documents, as well as a local websites, workshop and educational materials that allow industry to operate within the IWM By-law.

4.3.4 Storage

Generated C&D waste inevitably needs to be stored or stockpiled for a period of time before it can be utilised or collected from site. The storage of generated and separated material, especially if they are recognised as being reused or recyclable C&D material, needs to be done to prevent contamination. This could be contamination by other wastes or as a result of adverse weather conditions. Therefore the most important aspect of on-site storage is the prevention of mixing or contamination of separated C&DW. The development and guidelines in this regard is therefore seen as important to prevent the contamination of separated wastes.

Depending on the amount of C&DW generated, separated and/or processed, materials may take up a significant amount of space on site. This is one of the main arguments put forward to the City by contractors in response to the new By-law that claim that there is no space on site to store separated materials. Looking at current material storage practices, the storage of construction materials such as sand and coarse aggregates on-site, be it kerb-side in some instances, is extremely prevalent. Therefore, the argument of space constraints is regarded as rather weak in most instances.

The Use of C&DW in Concrete in Cape Town

The guide recommends the following mix design parameters for concretes below 25 MPa and below 40 MPa from the classification of the RA. This is summarised in the Table 4.5 below:

Table 4.5: Recommended mix design parameters for concrete of varying design strength

Mix design recommendation based on Grade of parent concrete						
Grade	Use	RCA Class	Substitution level (%)	Cement Content (kg/m ³ min.)	Sand: Aggregate ratio (min.)	Fly Ash content (% min.)
	Compressive Strength (max. MPa)					
Grade 1	40	Class 1A	30	270	0.4	20
Grade 1/2	25	Class 1B	100	225	0.4	20

4.3.6.3 Summary

Material property guidelines for the use of specific recycled masonry and concrete materials in concrete are currently either not available or very basic. This is especially true of recycled masonry materials. The EN and ASTM specifications are difficult to apply and compare to the SANS guidelines as they specify different material testing regimes and material properties. This study therefore makes use of SANS 1083:2006 and HB 155-2002 as they are the most similar in the composition, material property specification and material limits. HB 155 also provides direction for 100% substitution of various RAs as coarse aggregate concrete as is practised in this study.

A summary and comparison of these two guidelines is shown in the Table 4.6 below:

Table 4.6: Comparison of SANS 1083:2006 and HB 155-2002.

Summary of requirements of recycled coarse aggregates			
Property	Requirement		
	SANS 1083:2006	HB 155-2002	
	Nominal size of aggregate mm	Class 1A	Class 1B
Grading	19,0	AS 2758.1	
26,5	100		
19,0	85 – 100		
13,2	0 – 50		
9,5	0 – 25		
6,7	0 – 5		

The Use of C&DW in Concrete in Cape Town

Class 1 RCAs cover the structural use of materials and is separated into two sub-class in 1A and 1B materials. The definition and composition of these sub-classes are described below. Class 2 materials are defined as materials for use in road pavement and road related fill or foundation application. This falls outside the scope of this study.

Class 1A RCA is defined as RCA material with contamination level of less than 1% of bulk mass by other C&D materials. Class 1B RCA is defined as Class 1A RCA blended with no more than 30% crushed clay brick (HB 155-2002). The properties of these classes are shown in the Table below.

Table 4.4: Properties of Class 1 RCA materials – HB 155:2002

Properties and Classification 1 RCA Materials ¹⁰							
Class	Material Property Limits						
	Brick content (% max.)	Stony material <1950 kg/m ³ (%)	Chloride Content (%)	Particle Density SSD (kg/m ³ min.)	Bulk Density (kg/m ³ min)	Water Absorption (% max.)	Aggregate Crushing Value (% max)
Class 1A	0.5	1	0.05	2100	1200	6	30
Class 1B	30	5	-	1800	1000	8	30

Once RA materials are classified into classes, general applications ranging from engineering drainage or bulk-fill materials, granular sub-base materials, cement bound or unbound base coarse, engineering construction materials and coarse aggregate for concrete are prescribed. The guide then prescribes recycled aggregate concrete mix designs for two grades of concrete. These Grade classifications are based on the Class into which the RA is defined as.

Grade 1 RC is unreinforced and reinforced concrete made with a maximum of 30% uniform quality Class 1A RCA with characteristic strength up to and including 40 MPa. Grade 2 RC is unreinforced and reinforced concrete made with up to 100% uniform quality Class 1A or B RCA with characteristic strength up to and including 25 MPa, concrete for use in non structural concrete applications (HB 155-2002).

¹⁰ Properties excluded from Table include friable material, total impurity level, LOI, Loss of substances in washing, soundness and particle size distribution. These properties are excluded as they do not have a reference AS test method or do not have a prescribed limit.

The Use of C&DW in Concrete in Cape Town

Table 4.3 continued: SANS 1083:2006, Table 2 - Requirements for 19 mm coarse aggregate for concrete

10% FACT value, of less than 13,2 mm and more than 9,5 mm fraction (dry), kN, min.	Coarse aggregates for use in concrete subject to surface abrasion, structural elements of reinforced or prestressed nature (or both): 110 Coarse aggregate for use in concrete not subjected to surface abrasion: 70	6.12
Flakiness Index, max.	35	6.13
1) Other gradings are permitted if so required (see Annex A). Such grading shall be specified in terms of the appropriate nominal sizes specified in table. 2) Comply with SANS 3310-1 or SANS 3310-2 3) Optional alternative to the 10% FACT value		

SANS 1083:2006 is compared to the Australian HB155-2002 guide in the following section.

4.3.6.2 HB 155-2002

The HB 155-2002 – *Guide to the use of recycled concrete and masonry materials* gives general specifications on performance, limitations, testing and use of RAs in concrete. This is done in compliance with the Australian Standards (AS) and is recognised by industry in South Africa (AfriMat 2011). This follows a process where RAs are separated into categories or classes. Mix design recommendations for possible concrete compressive strengths with different quantities of RCA materials are also outlined.

This guide recognises that the fundamental properties of recycled aggregates to be tested are:

- Grading, particle shape and surface texture
- Specific gravity
- Moisture absorption
- Aggregate crushing value
- Degree of contamination⁹

The recommendations of this guide define RAs for use as coarse aggregate into two classes, Classification 1 materials (Class 1 RCA) and Classification 2 materials. The physical properties of the RA define which class they conform to.

⁹ Degree of contamination is assessed by visual examination of the > 4.75 mm sieved fraction

4.3.6 Classification of Recycled Aggregates

There are a number of recognised codes that may be used to classify natural and/or recycled aggregate materials. Using all these codes to compare aggregates is not feasible as they use different variables and testing procedures to judge the quality of materials. Consequently the Australian HB guideline and SANS were chosen as the benchmark for this study as they use similar testing regimes and material property variables to gauge quality. These are briefly discussed in the following sections.

4.3.6.1 SANS 1083:2002

SANS 1083:2006 is the South African standard for *Aggregates from natural sources – Aggregate for concrete*. This Standard has yet to recognise a distinction between RAs and NAs. This is limiting the use of RAs in the Cape as natural aggregates may differ substantially from RAs making it difficult to validate the use of these materials in concrete. *Table 2* in SANS 1083 outlines the requirements of course aggregates. This is shown below:

Table 4.3: SANS 1083:2006, Table 2 - Requirements for 19 mm coarse aggregate for concrete

Property	Requirement				Test Method sub clause
	Nominal size of aggregate				
	mm				
Grading ¹⁾	19,0	13,2	9,5	6,7	6.2
26,5	100				
19,0	85 – 100	100			
13,2	0 – 50	85 – 100	100		
9,5	0 – 25	0 – 50	85 – 100	100	
6,7	0 – 5	0 – 25	0 – 50	85 – 100	
4,75		0 – 5	0 – 25	0 – 50	
2,36			0 – 5	0 – 25	
1,18				0 – 5	
Dust content, material that passes a 75 um sieve ²⁾ , mass percentage, max.	2				6.3
ACV ³⁾ , of less than 13,2 mm and more than 9,5 mm fraction (dry), mass percentage, max.	29				6.11

The Use of C&DW in Concrete in Cape Town

Screening is vital if one is to produce a material of a certain size and particle distribution. Commercially, particle shape is also controlled through elongated screens that sieve out materials that are flaky or elongated in nature, as seen in Figure 4.8.

4.3.5.2 Yield of Aggregate

The scale of the operation plays a significant role in the fraction of the recycled aggregate produced. Larger crushing operations have the tendency to pulverise weaker masonry or concrete paste and create a lot of fines and dust that is generally discarded but may be recycled. Putting concrete waste through these crushing processes removes the majority of this old mortar leaving what is essentially the virgin aggregate after processing. Weaker materials that are fed into large machinery may result in a very low yield of usable coarse aggregate. This is illustrated in Figure 4.9 below which shows processed coarse aggregate and a waste fines stockpile. These photos were taken at the recycled aggregates processing plant at CapeBrick in Cape Town. Smaller on-site processing can consist of only a primary crushing procedure with the use of mobile jaw crushers or manual processing with the use of manual labour. Smaller operations produce far more variable materials but produce less waste fines materials.

There is not much literature on the yield and economy of aggregate recycling operations. Japanese methods that involve multiple processing actions to remove the majority of mortar from the RCA, show low RCA recovery rates of only 20-30%. Simpler methods such as basic crushing and sieving are known to have recovery rates of between 55-77%. One of the considerations of multiple processing actions is the production of large quantities of fine material as result of large quantities of mortar being removed from these RAs (Eguchi et. al. 2007).

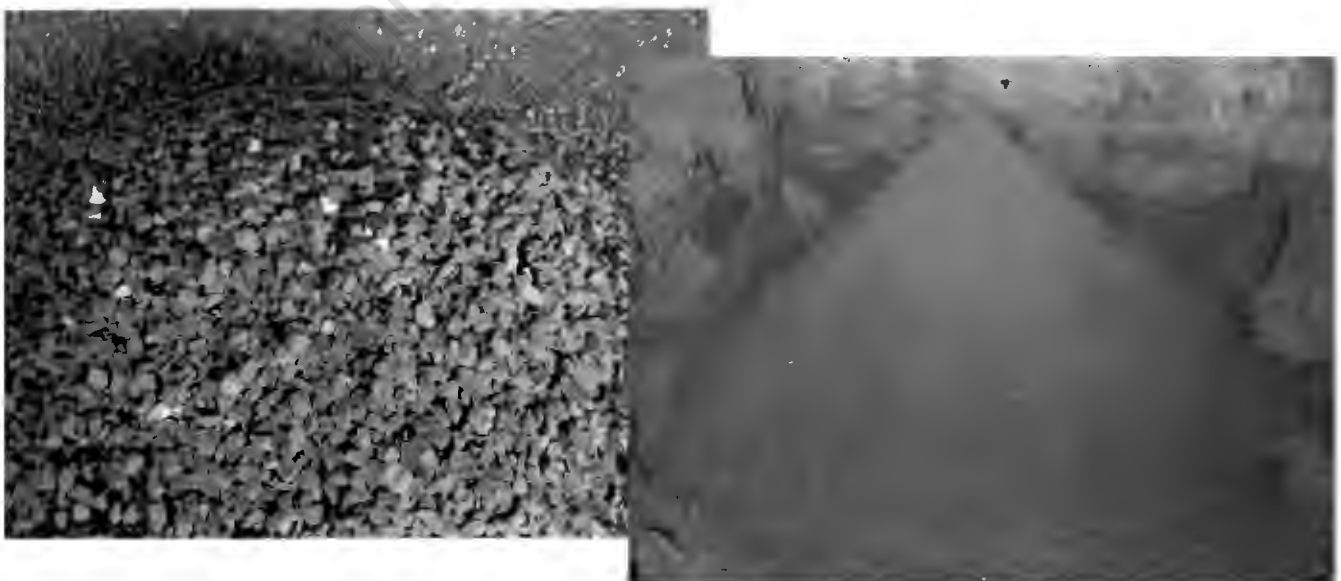


Figure 4.9: Commercial crushing operation at CapeBrick yield coarse aggregate (stone) and fines materials that are discarded

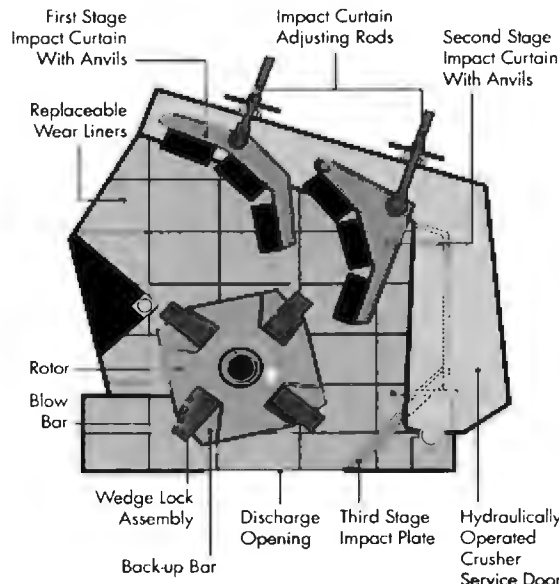


Figure 4.7: Impact crusher (<http://image.made-in-china.com>)

4.3.5.1 Screening

Material generally moves onto the screening equipment after the various crushing actions. Screening consists of different vibrated wire mesh or rubber screens that are used to separate material types and grades. Crushed particles that are of required size pass through the screens and larger particles are re-routed to the crushing process. Various screens may also remove fines and any contaminants like steel, wood and plastics.



Figure 4.8: Vibrating screens used to sieve materials at the AFRISAM plant at Peninsula Quarry. Wire mesh screens with elongated apertures used to remove flaky particles at the AFRISAM plant

The Use of C&DW in Concrete in Cape Town



Figure 4.5: Various sized mobile jaw crushers (<http://miniveyor.org> ;<http://img.directindustry.com>)

Gyratory or cone crushers generally consist of an inner cone and a conical head. The inner cone has a circular movement on an eccentric axis, similar to the mechanism used to drive the wheels on a steam engine, but does not rotate. The materials travel down the head and between the two surfaces and are progressively ground down. Generally gyratory crushers are used for primary crushing and cone crushers for secondary or tertiary crushing. These crushers produce a consistent aggregate often with more rounded edges and/or cubic shape, they also tend to break micro-fractures resulting in more stable aggregates (Guimaraes et. al. 2006).

Impact Crushers make use of a high-speed rotor on which mounted 'hammer plates' or 'blow bars' break down material against 'face plates' or 'impact curtains'. This process is similar to that of a lawnmower and the grade of material is adjusted by varying the distance of the hammer plates to the faceplates. Aggregates are slung against the hammer plates, which tend to chip off sharp edges. Impact crushers produce a smaller, more consistent aggregate with rounded edges. Consequently they are often used for the final crushing stage or as tertiary crushers in commercial operations (Clayton 2013).

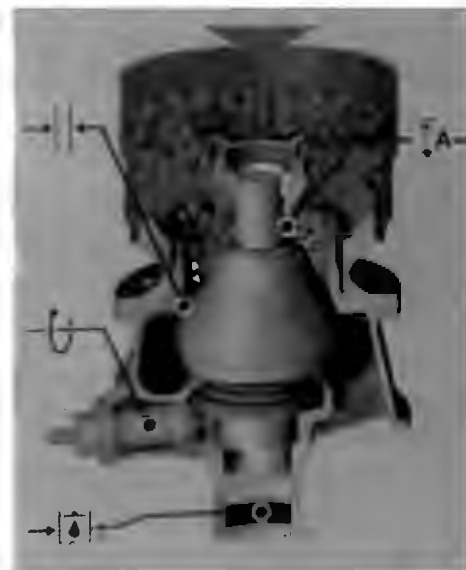


Figure 4.6: (Top) Gyro crusher opening (<http://www.studwise.com.au>). (Bottom) Configuration of gyro crusher at AFRISAM plant

4.3.5 Crushing Procedures

Crushing operations can have a significant effect on the properties of the RAs and can produce very different samples even from homogeneous materials (Padmini et. al. 2009; Eguchi et. al. 2007). The crushing procedure and the output of materials is also very much determined by the material's strength and hence the components within the C&DW stream.

Crushing operations can include:

- Manual crushing with the use hydraulic jacking or manual hammering
- Primary mechanical crushing usually by jaw or gyro crusher
- Secondary and further tertiary mechanical crushing usually by gyro or impact crusher

Crushing operations can be performed by smaller mobile crushing units or 'mobile crushers' (usually jaw crushers), or by complex crushing units that may use a combination of crushers, sieves and contamination removal procedures to acquire a certain quality of material. The type of crushing equipment used dictates RA properties.

Large-scale crushing plants usually make use of primary, secondary and/or tertiary crushers. The primary crusher is used to break down larger pieces of waste into manageable sizes (fist size), and the secondary crusher processes this waste into finer materials and control particle shape. Both primary and secondary crusher types can consist of Jaw Crushers, Impact Crushers, Gyro Crushers or a combination thereof.

Jaw Crushers consist of a wedge shaped crusher in which one face moves creating a 'chewing' action. Material is fed into the top of the machine and the motion adjusted to achieve different grades of materials. Jaw crushers are often used for primary crushing operations to break down larger pieces of materials into manageable sizes. Mobile crushers, which can range from the size of a bus to the size of a generator, generally utilise jaw-crushing machinery. These crushers can be used for soft and hard materials and generally produce angular particles with sharp edges (Symonds et. al. 1999). This is because jaw crushing essentially mimics point-loading conditions on an aggregate surface, which is known result in a high degree of flakiness and rod shaped aggregates (Guimaraes et. al 2006).

The Use of C&DW in Concrete in Cape Town

Table 4.6 continued: Comparison of SANS 1083:2006 and HB 155-2002.

Dust content, material that passes a 75 um sieve ²⁾ , mass percentage, max.	2	2	
ACV ³⁾ , of less than 13,2 mm and more than 9,5 mm fraction (dry), mass percentage, max.	29	30	
10% FACT value, of less than 13,2 mm and more than 9,5 mm fraction (dry), kN, min.	100 or 70	-	
Flakiness Index, max.	35	-	
Particle Density SSD (kg/m ³) min.	-	2100	1800
Bulk Density (kg/m ³) min.	-	1200	1000
Water Absorption (%)	-	6	8
Chloride Content (%)	-	0.05	-

4.4 Conclusion

The current C&D waste cycle is seen as a major cause of the stunted secondary recycled market and poor quality recycled aggregate products in Cape Town. The mixing of various C&D wastes upon generation contaminates reusable materials and stifles the potential of materials to be recycled. The identification, separation and classification of potentially recyclable materials are therefore paramount to promoting a C&DW recycling culture. This has the potential to follow a path where materials are generated, separated and processed on-site for use in various construction. Following this approach may use substantially less energy than landfilling and off-site recycling in Cape Town. The potential to utilise low skilled labour and create job opportunities in the separation and storage procedures involved in on-site recycling are also substantial.

Guidance in this approach is currently not available in South Africa and thus, the potential of C&D waste materials for reuse is unrealised. This direction can only be explored through the provision of information regarding the physical and RAC performance of these materials. This can then be used to update the current SANS to recognise and classify RAs for use in concrete.

Therefore this argument forms the background for Part B of this study. The following chapters discuss the physical properties of processed RAs and the effects these materials have on RAC. It begins with a literature review compiled from other researchers who have explored separation, simple primary crushing and sieving operations that promote the on-site recycling.

The Use of C&DW in Concrete in Cape Town

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PART B – Properties of Recycled Aggregate Materials

5 LITERATURE REVIEW: Properties of Recycled Aggregates and Recycled Aggregate Concrete

5.1 Introduction

Previous chapters have provided a background on the regulations, management and processing of C&DW. This chapter presents literature on the properties of C&D materials that have been used as RAs in concrete by other authors. This provides a more technical background on the performance of C&DWs. This includes an assessment of literature on the physical, fresh and hardened properties of RA materials and recycled aggregate concretes (RACs). Physical properties include the grading, dust, particle shape, absorption, density and crushing characteristics. RA mix designs and fresh properties include RAC water requirements and hardened properties in compressive strength, shrinkage and modulus of elasticity (MOE) are reviewed. This provides an indication of the characteristics of these RAs when compared to commonly used natural stone aggregates. They also provide insight into the potential and feasibility of 100% substitution of these RAs in concrete before the proposed experimental program is implemented.

5.2 Masonry Materials

Masonry material refers to brick or blocks that may be stacked, or laid using various kinds of mortar to construct a permanent masonry structure. They are typically produced in standard sizes in bulk quantities. They may be made from clay, shale, calcium silicate or concrete materials. Brick products vary greatly and the classification and use of masonry as aggregate can be precarious if the properties of these products are not fully understood. This section therefore overviews the basic brick production process, the SANS 227:2007 classification of clay masonry and then the relevance of the production process to classification for reuse as aggregate.

5.2.1 Clay Masonry

5.2.1.1 Clay Brick Production

Typical brick production follows a process where various clay materials are crushed and mixed with water and other additives. This mixture is then extruded into a continuous strip, cut by wires and pressed into moulds (forming). The bricks are either then open air-dried, dried in sheds or by kilns (drying) to produce green bricks. These bricks may then be fired at high temperatures in gas or coal fired kilns to produce 'fired' bricks.

Firing is divided into five stages; final drying (evaporation of free water), dehydration, oxidation, vitrification and flashing or reduction firing. All except flashing are associated with rising temperatures within a kiln. Generally final drying occurs at about 200°C, dehydration from about 150°C – 980°C, oxidation from 540°C – 980°C and vitrification from 870°C to 1320°C.

This melting takes place in three stages; incipient fusion, where clay particles become soft and stick together in a mass; vitrification when extensive fluxing occurs and the mass becomes tight and increasingly solid; and viscous fusion where the mass breaks down and becomes molten. The key to the firing process is to control the temperature in the kiln so that the incipient fusion and partial vitrification occur but fusion is avoided. This process is characterised by three stable crystalline compounds forming, namely silica (SiO_2), corundum (Al_2O_3) and mullite ($2 \text{Al}_2\text{O}_3 \cdot 2 \text{SiO}_2$) in the clay brick (The Brick Industry Association 2006). This temperature control marks the progression of a typical NFP brick, fired to between 700- 800°C, to a higher quality NFX fired to between 800- 900°C. Kiln type and firing temperature play a large role in defining clay brick quality. There is often a 'zone' of bricks that may fall close to or on either side of the vitrification 'line'. This zone may mark the line between NFP and NFX bricks and therefore results in very different material properties and opportunities for these products (Collis 2013).

Durability, compressive strength and absorption values of brick are achieved as a result of the fusion and vitrification process during firing. These properties together are taken as the predictors of durability in brick specifications. For a given clay mix, higher compressive strength and lower porosity are typically achieved by higher firing temperatures. Properties also dependent on raw material selection (The Brick Industry Association 2006). Clay type, increased feldspar, iron and/or manganese contents produce a darker colour and higher brick strength (Corobrik 2012). This can be seen in facing, paving and engineering bricks, when compared to the NFP and NFX bricks.

The Use of C&DW in Concrete in Cape Town

5.2.1.1 Clay Masonry Classification

SANS 227:2007 classifies virgin burnt clay bricks into three categories for varying masonry purposes. This classification is summarised in the Table below:

Table 5.1: Classification of burnt clay masonry units (SANS 227:2007 – Burnt Clay Masonry Units; CSIR 1984)

Classification of Clay Brick Masonry				
Material	Category	Description	Classification	Description
Burnt Clay Masonry	Facing Brick	Bricks require no decorative treatment such as plastering or painting	FBS (Standard)	Clay bricks selected/ produced for their durability, uniform size & shape
			FBX (Extra)	Clay bricks selected/ produced for their durability and high uniformity in size, shape and colour
			FBA (Aesthetic)	Clay bricks selected/ produced for their durability and aesthetic effect of non-uniformity, size, shape and colour
	Stock or General Purpose (Non facing)	Bricks usually receive coat of plaster/ other decorative treatment after laying	NFP (Plastered)	Clay bricks suitable for general building work that is to be plastered
			NFX (Extra)	Clay bricks suitable plastered or unplastered use, general building work below damp-proof course, under damp conditions or below ground level where durability rather than aesthetics is the criterion for selection
	Engineering	Brick of high compressive strength and durability	E (Designated by E followed by nominal compressive strength in MPa i.e. FBE21)	Masonry units produced for structural or load bearing purposes in face or non-face work (manufacturer supplies bricks to agreed compressive strength)

The Use of C&DW in Concrete in Cape Town

This classification table considers both aesthetic as well as strength qualities of clay brick products. The quality of clay bricks with regard to potential for reuse is more easily gauged by understanding the production of clay bricks. As discussed in *clay brick production*, vitrification is key process whereby clay masonries obtain their strength and durability. It is therefore of use to classify clay bricks into categories that are defined by this process.

Clay masonry can be grouped into sun-baked, also known as green or clinker bricks, 'under-fired' and 'over-fired' bricks. This classification distinguishes clay bricks into the level of vitrification that they have achieved and therefore their durability, which is of more importance than aesthetic quality for aggregate production. Sun baked bricks are not suitable for use as aggregates as they are known to deteriorate when exposed to water. Placing sun baked brick particles in water for a period of time illustrates this property. These bricks are also known to produce high quantities of dust and disintegrate when physically broken down (crushed or hammered) (Collis 2013).

'Under-baked' clay bricks have reached a point of vitrification that produces brick strengths of up to approximately 7 MPa, such as the NFP bricks. These bricks are generally used for partitioning walling, non-load bearing walls and internal walls that are to be plastered. These bricks are covered under stock or general purpose classification by SANS 227:2007. NFX bricks also fall under the stock or general purpose classification in SANS. These bricks are characterised as higher quality, 'over-fired' bricks. NFX products have undergone a higher state of vitrification to the extent that they can be used under damp conditions or below ground level where durability is the important criterion for use. These bricks are used extensively in structures for external, load bearing walling (Collis 2013; Corobrik 2013).

'Over-fired' bricks also consist of higher quality facing (FBX, FBS and FBA), paving and engineering bricks (FBE21, FBE45 etc.). SANS 227:2007 classifies these bricks as being exceptionally uniform in shape and of higher strength and durability than general-purpose or stock bricks. These products have been fired at high temperatures, with higher quality clays to achieve extensive fusion and vitrification within their matrices. This results in high strength and allows for the use of these bricks in large structures, in highly impact applications (paving) and to support concrete structural systems (Collis 2013; Corobrik 2013).

5.2.1.2 Moisture Expansion

Clay bricks undergo an irreversible, 3-dimensional moisture expansion due to absorption of moisture from the atmosphere as soon as bricks leave the kiln. There is no difference in expansion between perforated and solid bricks. Bricks stored in air expand in the same manner as bricks from a kiln or drier (Clay Brick Association 2002). This expansion continues at a decreasing rate for some years. This

The Use of C&DW in Concrete in Cape Town

affects joint work and requires that vertical and horizontal control joints are created in brick walls. Each brick has a different rate of expansion therefore spacing depends on the brick type (Taylor 2009).

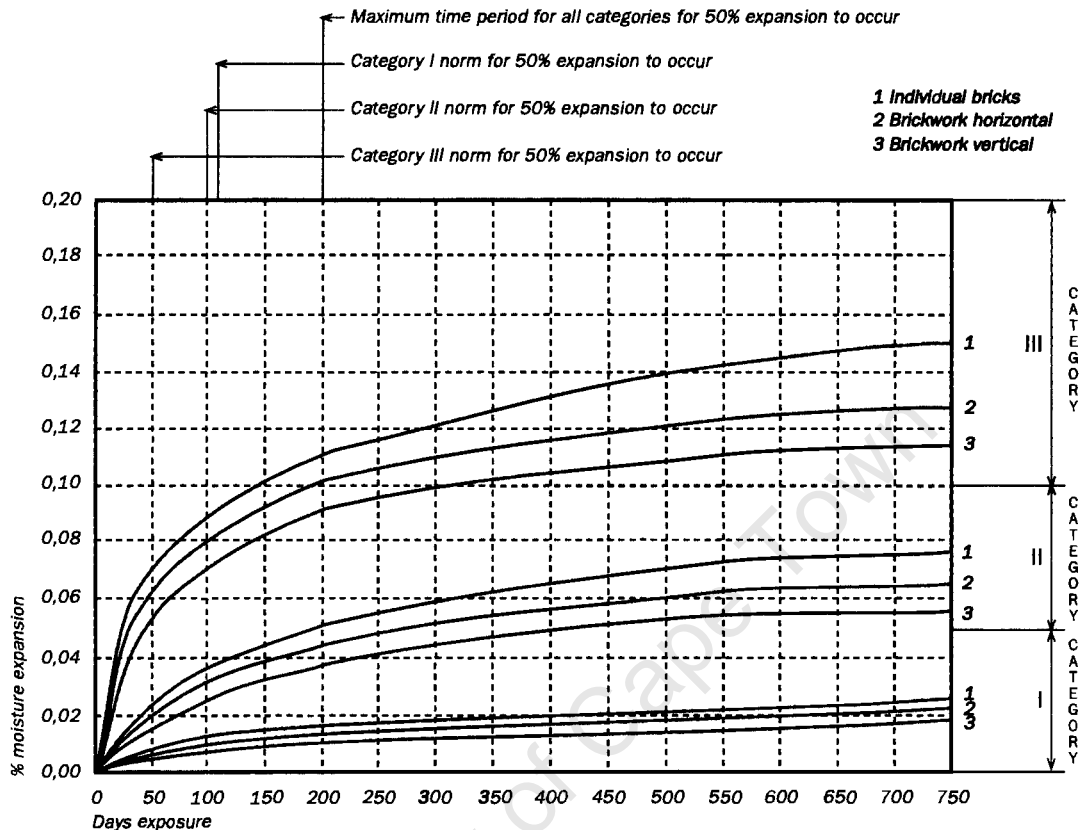


Figure 5.1: Typical rates of irreversible moisture expansion in bricks and brickwork (Clay Brick Association 2002)

There is a high early age expansion rate of expansion during the first month followed by an almost constant rate. Generally expansion usually takes place in the first 6 months after manufacture and it is recommended that bricks are stockpiled for as long as possible and kept damp before use (CSIR 1984). This trend is shown in Figure 5.1. Average moisture expansion rates may range from less than 0.04% (12 mm per 30 m) to 0.12% (36 mm per 30 m) and higher (CSIR 1984). Average measured rates of expansion are 0.006% per annum (Taylor 2009). SANS 10249 classifies potential moisture expansion of clay bricks into three categories; 0.00-0.05% for category I bricks, < 0.05-0.10% for category II bricks, < 0.10-0.20% for category III bricks. These provisions allow for limits on maximum spacing of joints in horizontal walling and parapets. No burnt clay masonry units having a characteristic moisture expansion exceeding 0.2% may be used in any reinforced or prestressed masonry walling designed in accordance with this part of SANS 10164 (SANS 227:2002).

This expansion is irreversible and is not linked to dimensional movement due to wetting and drying. The magnitude of total expansion of a brick wall depends on the (Taylor 2009):

- Characteristic coefficient of expansion of the bricks

The Use of C&DW in Concrete in Cape Town

- Length of time that the bricks were exposed to atmospheric moisture before laying
- Degree of exposure after laying (exposure to sun increased expansion, sealing with mortar or paint reduces expansion)
- Elapsed time after laying
- Length and height of the brick between control joints

Moisture expansion is of particular importance if newly produced bricks are used for aggregate in concrete. This expansion inside the concrete matrix may cause cracking and other problems.

5.2.2 Concrete Masonry

Concrete masonry is made of Portland cement, fine aggregate, coarse aggregate, water and admixtures. Concrete masonry is generally grey in colour due to the use of Portland cement as a raw material. The concrete masonry industry is well known for its use of recycled aggregate derived from a variety of C&D wastes such as waste concrete and masonry. These materials are usually selected from C&D waste sources and then follow a multiple crushing, contaminant removal and grading operations (Cape Brick 2012).

Generally, concrete blocks contain a higher percentage of finer aggregate (coarse sand) and lower quantity of coarse aggregate and water than concrete mixes used for construction purposes. These units are normally less dense than conventional concrete due to the manufacturing processes. Typical cement: aggregate ratio by mass is between 5 - 20%. Typical water: cement ratio is about 0.3. This produces a dry, stiff mixture that holds its shape during extrusion from moulds. Drier mixes are usually more difficult to compact because of high internal friction. This results in higher porosity and low ¹¹green and compressive strength. Unit weight generally gives an indication of denser compaction and greater compressive strength (Fultons Concrete Technology 2009; WHD Microanalysis Consultants Ltd. 2012; CSIR 1984).

The manufacture process of concrete blocks consists of four basic processes: mixing, moulding, curing and cubing. The curing process speeds up strength development with increased temperature and pressure applied by a kiln. Where strength development is a result of the hydration process in concrete, compaction plays a larger role in final strength in concrete masonry (Cairns 2009).

¹¹ Green strength refers to strength before masonry is fired or cured

5.3 Physical Properties of RA Materials

Single component RAs are rarely produced in the Western Cape as recyclers generally receive mixed C&D wastes and separating this material is a time consuming and costly procedure. These products are extremely variable in composition and the potential for their use is often stifled by the varying quantities of very poor materials present in their make up (Ayers 2003; Alexander & Heiyantuduwa 2002; Kutugeza 2004). Furthermore, literature describing the properties of various C&DWs that have been used as RAs is not extensive and often unclear upon reading. This is because RAs vary according to their source, waste management approach and the processing (crushing) actions from which the materials are acquired.

Depending on the definitions adopted, RAs can consist of a single C&D material, such as clay brick or recycled concrete, or a mixture of C&D materials such as plaster, mortar, wood, plastic and concrete brick. A high proportion of conventional demolition waste, in particular materials such as concrete, masonry and tiles, are well suited to being crushed and recycled however, the use of these materials in new concrete is technically more demanding and is less common. These materials can be substituted for natural aggregates and have been utilised successfully in lower grade applications, most notably as engineering fill and road sub-base applications (HB 155 – 2002). The majority of literature does not present data on 100% substitution of RAs into concrete. This chapter provides a background as to the performance of single material RAs where possible, in order to get an understanding of their individual components.

This section analyses burnt clay brick, concrete masonry and recycled concrete that has been processed into coarse aggregate for use in concrete. Typical physical tests include grading analysis, fines and dust content, particle shape and texture, absorption and porosity, relative density, bulk density and surface saturated dry density, sulphate content and chloride content. These tests give an indication of the physical characteristics of these RAs when compared to commonly used natural stone aggregates.

5.3.1 Grading of Materials

The grading of an aggregate refers to the proportions of material that pass through sieves of different aperture sizes. It is usually described by means of a particle size distribution diagram. Continuously (well-graded) stone is said to produce a more workable concrete mixes. This has led to a recent shift in commercial aggregate production from single sized 26 mm, 19 mm or 13 mm stone, to a more continuously graded '22.4 mm' stone (Kleyn 2013).

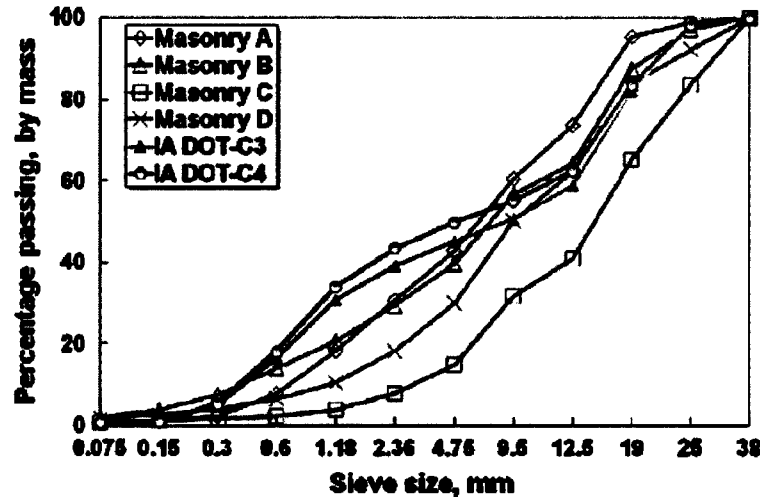


Figure 5.2: Particle distribution (Hu et. al. 2011). Masonry A and B are concrete masonry aggregate materials, masonry C and D are crushed burnt clay brick aggregates and IA DOT-C3 and IA DOT- C4 are natural commercial aggregates.

As mentioned, particle distribution properties are closely related to the crushing operation and crushing machinery used to process C&D materials. Hu et. al. (2011) performed simple primary crushing on clay and concrete masonry units with the use of a small chipmunk jaw crusher. The jaw width was set to 19 mm and no re-sieving or recombining was performed to obtain a prescribed particle distribution. Hu et. al's (2011) study shows that the masonry aggregate is generally coarser, particularly the concrete masonry aggregate, than natural aggregate materials. Basic primary crushing yields a wide band of particle sizes. The quantity of finer particles, particles below 4.75 mm, increase substantially with the presence of attached mortar in masonry aggregates. Results of Hu et. al's (2011) are shown in Figure 5.2.

In studies by Poon et. al. (2006) clay brick material, sourced from a demolished masonry wall in Hong Kong, was crushed manually with a hammer and sieved to produce single sized, 10 mm and 20 mm coarse aggregates. These materials achieved the required grading limits set by BS 882. Yang et. al. (2011) also achieved this outcome from processed bricks sized between 2.36 mm and 20 mm. Both these grading requirements are similar to what is prescribed by SANS 1083:2006.

Zhang and Ingham (2010) performed a grading analysis on laboratory cast 20, 40 and 60 MPa concrete slabs. These slabs were processed into coarse 20 mm aggregate by an impact crusher at a mining quarry. 19 mm and 13 mm grading curves showed that the 40 and 60 MPa RCA fell within the required envelope set by NZS 3121:1986. The 20 MPa RCA fell outside the 19 mm range and the 13 mm inside the 13 mm limits. This indicates that impact crusher may pulverised weak concrete mortar and that coarse aggregate recovery ratios might be low for certain crushing procedures.

The Use of C&DW in Concrete in Cape Town

Most studies find that RCAs conform well to coarse aggregate grading standards and existing NA gradings when fines are removed (Tabsh et. al. 2009; Padmini et. al. 2009; Debieb et. al. 2010; Zhang et. al. 2010). The following section discussed the impact of fines and dust quantities on coarse RAs.

5.3.2 Fines and Dust Content

The use of recycled concrete fines in concrete is generally not recommended by most authors due to the increased water requirement of fresh RAC as a result of the increased surface area of this material (Eguchi, K et. al. 2005; Yasuhiro, D. 2007; Tam, V. 2005).

Some authors have found that alkalis from the residual paste of RCA help activate the pozzolanic reaction of supplementary concrete materials (Achtemichuk et. al. 2011). However, this fines content is restricted. Dhir et. al. (1999) found that limiting replacement of below 20% RC fines did not significantly affect the compressive strength of RCA concrete. As this study is concerned with the use of coarse aggregates, the majority of fines material below 4.75 mm will be removed through sieving after crushing has taken place. It is thought that fines content increases with reduced parent concrete and masonry strength, as the weak mortar is pulverised by crushers, as well as increased plaster and/or mortar content in masonry materials (Zhang and Ingham 2010).

5.3.3 Particle Shape and Texture

It is recognised that particle shape is one of the most important factors that determine the performance of aggregates in fresh concrete. Aggregates that are less spherical or cubical in shape and have a rougher surface texture are affiliated with increased water requirements, due to the increased surface area, and reduced workability, due to increased friction and mechanical interlock between particles (Grieve 2009). Elongated, 'slab particles' are also known to break more easily and tend to lie in the horizontal plane under which air and water can accumulate affecting the aggregate paste interface (ITZ) (Martin-Moralez et. al. 2011).

Generally the shape of RAs is irregular and studies from Spanish recycling plants shows that concrete tends to break into rounder shaped particles rather than elongated shaped pieces (Martin-Moralez et. al. 2011). The residual paste attached to the surface of RCA particles makes them more rounded. This paste also gives them a rough, coarse and cracked surface that has been shown to result in increased bond strength between the RCA and new cement paste in some cases (Tabsh et. al. 2009). Masonry aggregates have a more planar, angular aggregate shape when compared to a smoother surface for NA (Hu et. al. 2011; Padmini et. al. 2009). The angularity of burnt clay aggregate (BCA) particles can be seen in the lower blocks in Figure 5.3.

The Use of C&DW in Concrete in Cape Town

The parameter used to determine the particle shape of aggregates is known as flakiness index. Some authors comment that RCAs have a lower flakiness index, 5-9%, than that of NAs. Local tests on commercial recycled aggregates for use in a ground slab in the Western Cape for AFRIMAT (2012), resulted in a flakiness index value of 13%.

Crusher type and processing actions are known to contribute to aggregate shape considerably (Martin-Moralez et. al. 2011; Ayers 2002). Chen et. al. (2011) found that RCA particle shape was similar to that of NA after two stage crushing and a variety of screening procedures. Impact crushers are known to produce a smaller, more consistent aggregate with sharper edges. Jaw crushers are known to produce more variable sized aggregates with sharper edges (Ayers 2002). In a literature review by Tabsh et. al. (2009), it was found that complex commercial processing produced smoother more spherical particles than laboratory processing.

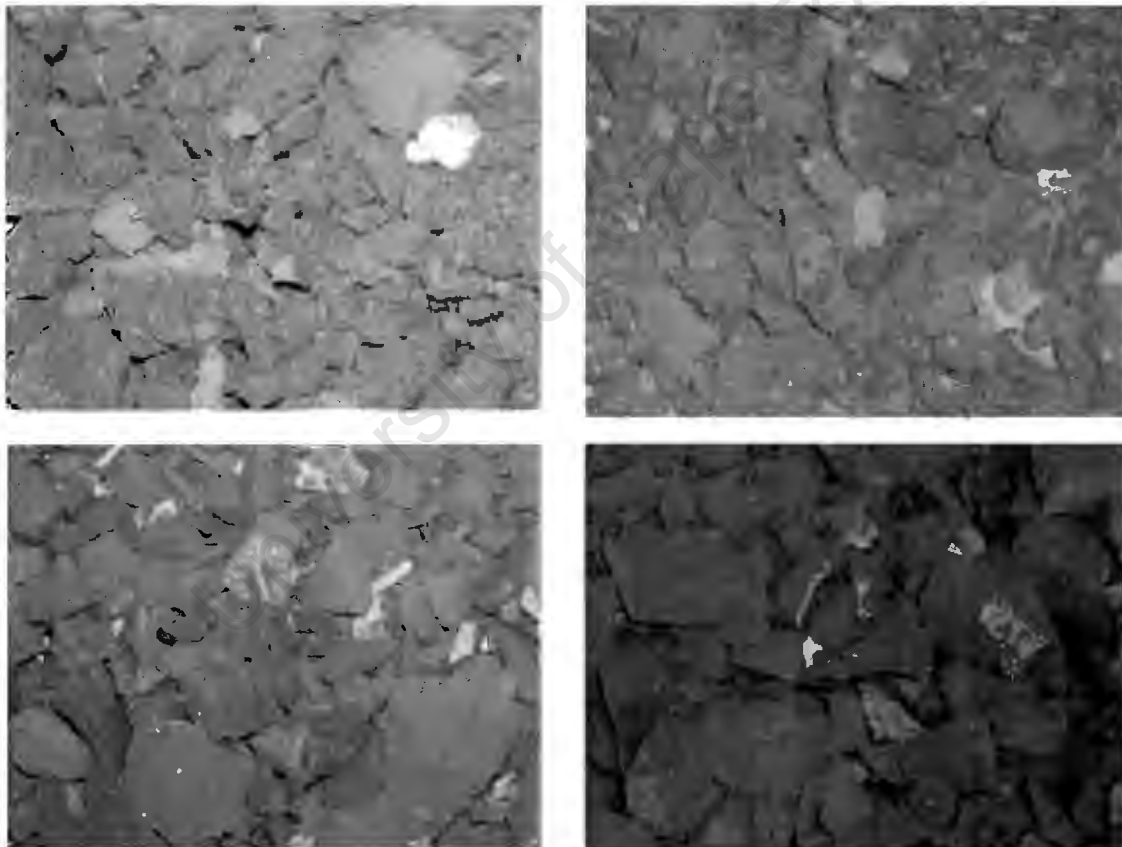


Figure 5.3: Indication of particle shape of BCA and CMA used in Hu et. al. (2011). The top two illustrations are CMA materials and the bottom two clay brick aggregate materials

5.3.4 Absorption and Porosity

Studies show that one of the most distinctive differences between NAs and RAs is the porosity and water absorption characteristics of RA materials (Yang et. al. 2011). Porosity in bricks is attributed to fine capillaries that form during firing. These pores serve a purpose as the capillary effect, whereby

The Use of C&DW in Concrete in Cape Town

water is absorbed and released, helps regulate temperature and humidity in normal masonry wall applications. However, this property also makes these materials susceptible to chemical attack through water during this capillary action. Bricks with water absorption of 8% are 10 times more durable in resisting salt attack than that with water absorption at 20%. Well-burnt brick normally has a water absorption rate of less than 10%. This is in contrast to that of cement mortar that may exceed 15%. To mitigate chemical attack, the rate of water absorption for facing bricks should be maintained around 10%. Absorption in concrete bricks is generally lower than that of clay bricks (Claybricks & Tiles 2010).

RCAs have absorption values within a range of 4.4% - 7.7% (Egutchi et. al. 2007; Hu et. al. 2011; Zhang & Ingham 2010). Some authors present absorption values of up to 19.5% for masonry aggregates. These are thought to be a result of extremely high masonry mortar contents (Poon 2006). SANS does not put limitation on absorption for masonry materials. The limits prescribed are such that they are agreed between the supplier and purchaser. This is however an important property that effects efflorescence, mortar, plaster, expansion and durability of the clay brick unit. Typical Southern African NAs have absorption values below 0.5% revealing that RAs are over 10 times more absorptive than NAs (Grieve 2009)

Diebeb et. al. (2010) comments that water absorption is similar in NA concrete and RCA concrete however, the initial absorption rate of RCA concrete is 10 times that of NA concrete. This largely due to excess mortar material that has a more porous structure. The high absorption of RAs must be accounted for due to the fact that part of the water added to a concrete mix may fill the accessible pores of the RA affecting workability and w:b, especially near the ITZ. Porosity is also known to affect particle density, compressive strength and resistance to aggressive environments (chemical attack) (Grieve 2009).

Some literature suggests that absorption values decrease with increased strength of the parent concrete (Hu et. al. 2011; Zhang & Ingham 2010; Eguchi et. al. 2007). Conversely, Padmini et. al. (2009) reported that the water absorption increases with increased strength of parent concrete due to the higher quantity of porous attached mortar that is not broken down during crushing. These contradictory results are thought to be a result of varied RA processing actions by the authors, which are not discussed in their studies.

The Use of C&DW in Concrete in Cape Town

Table 5.2 Absorption values of RA according to various literature sources

Absorption Values of RA Materials						
RA Description	Material Components		Material Size (max.)	Parent Material Strength	Absorption	Reference
	%	%	mm	MPa	(%)	
Laboratory cast concrete beams	RCA (13 mm NA)		13	20	7,6	Zhang & Ingham 2010
				40	7,4	
				60	7,2	
	RCA (19 mm NA)		19	20	4,6	
				40	4,6	
				60	4,4	
Laboratory cast cubes	RCA		20	25	6,4	Eguchi et. al. 2007
				39	6,9	
				52	6,3	
			25	27	7,3	
			40	30	7,7	
			40	41	6,2	
Mixed Sources	RCA	BCA			-	Agrela et. al. 2011
	98	2		5,2		
	94	3		5,1		
	92	7		7,3		
	91	4		5,9		
Lead Painted Masonry	CMA		19		7,7	Hu et. al. 2011
				5,9		
	BCA			6,5		
				5,1		
Clay Brick Partition	BCA		10		19,5	Poon et. al. 2006
			20		18,4	
100% medium weight brick	BCA				11,2	Yang et. al. 2011
Various Clay Brick	BCA				10,2	Poon & Chan 2006

Increased absorption is reported when aggregate size decreases, as a higher surface area is available for mortar to adhere to (Padmini et. al. 2009; Zhang & Ingham 2010). The impact of size on absorption

The Use of C&DW in Concrete in Cape Town

properties is seen in the increased absorption from 4.4% in 19 mm RCA to 7.6% in 13 mm RCA in Table 5.2 above (Zhang & Ingham 2010).

The effects of attached mortar content and the increased absorption capacity of RCAs is seen in Figure 5.4 below. Padmini et. al.'s (2009) experimental results verify that increased mortar results in increased absorption levels in RAs. BCA and concrete masonry aggregate (CMA) materials show higher absorptive properties than RCAs. Absorption properties are a defining factor of virgin masonry materials and brick manufacturers usually specify the absorption potential of their products.

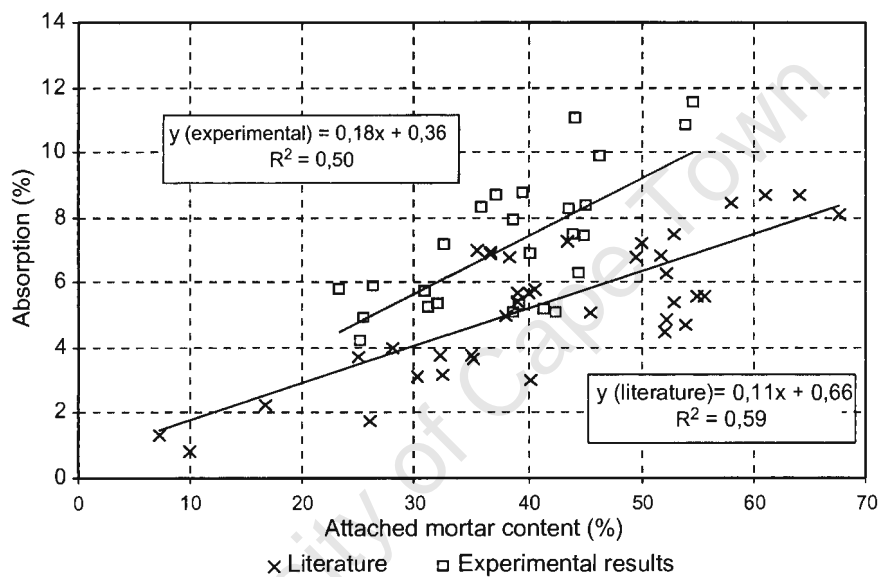


Figure 5.4: Relationship between water absorption and clay brick (referred to as ceramic) content (Padmini et. al. 2009)

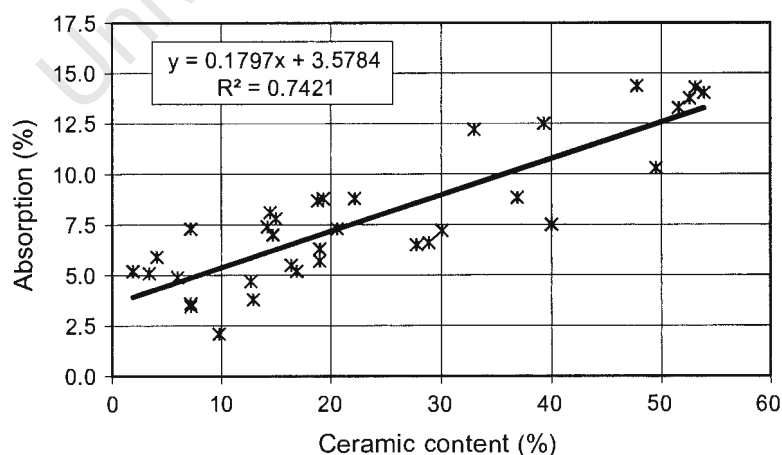


Figure 5.5: Relationships between water absorption and increased clay brick (BCA) content (referred to as ceramic) in a RCA-BC mix (Agrela et. al. 2011)

In a study by Agrela et. al. (2011) two RCAs, one containing less than 10% ceramic (BCA) content and the other containing between 40% and 50% BCA were analysed to find a correlation between these

quantities and the absorption properties of these RAs. From the Figure 5.5 it is clear that a higher BCA and lower RCA contents contribute to increased absorption potential of the RA material.

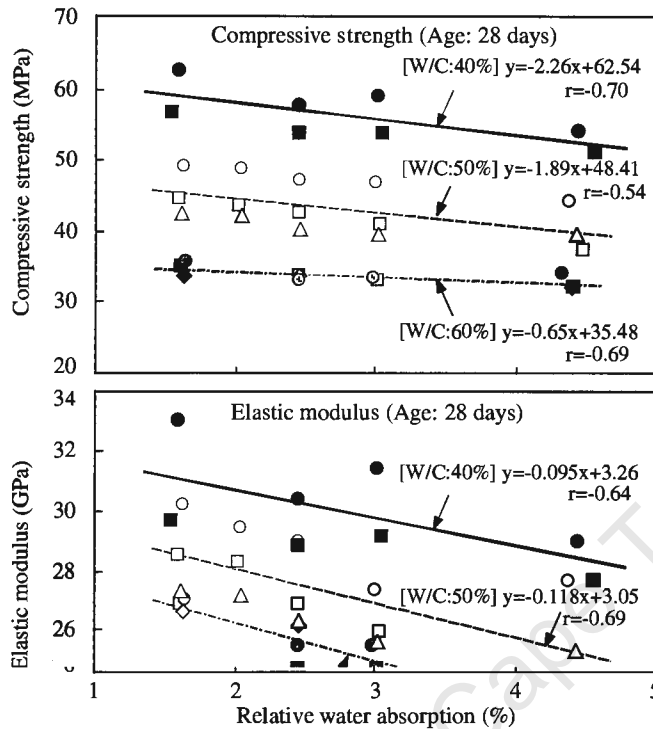


Figure 5.6: Relationship between water absorption and mechanical properties of RCA concrete (Eguchi et. al. 2007)

Eguchi et. al. (2007) attempted to estimate the effects on compressive strength, drying shrinkage and elastic modulus of RCA concrete by analysing the quality of RCA according to its absorption potential. The correlations between these mechanical properties with varying w:b ratio, replacement ratio and water absorption potential can be seen in Figure 5.6. With increased relative water absorption, elastic modulus and compressive strength decrease. This data illustrates the consequences of utilising RAs that show high absorption properties.

5.3.5 Relative and Bulk Density

Relative density is also referred to as specific gravity. This is the ratio of the density of a substance to the density of a reference material (usually water). NA relative densities are usually in the range of 2.5 to 3.0. Aggregates that fall outside this range are believed to create mixing, transportation, placing, compacting and finishing issues for concrete mixes (Grieve 2009). The presence of low-density mortars results in lower relative and bulk densities in RAs (Padmini et. al. 2009).

Kutugeza (2004) provides literature that compares densities of Western Cape aggregates shown in Table 5.2 below. The relative densities of typical Cape coarse aggregate Granite, Greywacke and Quartzite are

The Use of C&DW in Concrete in Cape Town

between 2.63 and 2.65, loose bulk densities between 1365 and 1400 kg/m³ and compacted bulk densities between 1460 and 1525 kg/m³. More recent data acquired from AfriSam in March 2013, shows that 13 mm, 19 mm and 25 mm Greywacke stone has a relative density of 2.72 and a loose and compacted density of 1370 kg/m³ and 1490 kg/m³ (Clayton 2013).

Table 5.3: Densities of typical 19 mm Western Cape aggregates (Alexander & Heiyantuduwa 2002; Kutugeza 2004; Kleyn 2013)

Densities of Western Cape NA Materials				
Rock Type	Source	Relative Density	Loose Bulk Density (kg/m ³)	Compacted Bulk Density (kg/m ³)
Granite	Malmesbury (Rheebok Quarry)	2.63	1365	1460
Greywacke (Malmesbury Shale)	Contermanskloof (Peninsula Quarry)	2.64	1360	1480
		2.72	1370	1490
		2.65	1400	1525
Quartzite	Mossel Bay Quarry	2.65		1480
Dolomite	Blydskap Dolomites	2.72	1380	1500

Reviewing various literature sources, Table 5.4, shows that the relative densities of RCAs are lower than typical Cape NAs. Literature values range from 2.20 – 2.52. Specific gravity of RCAs is known to be about 5% - 10% lower than the parent aggregate mainly due to the less dense and porous residual mortar content (HB155-2002). Some literature suggests that there might be an increase in relative density with an increase in parent concrete strength and maximum aggregate size (Zhang & Ingham 2010; Padmini et. al. 2009). Relative densities of masonry aggregates with high parent strength compare well with RCA materials. These densities range from 2.33-2.39 (Hu et. al. 2011; Poon & Chan 2006). Some BCAs display densities as low as 1.93 and 1.86 (Yang et. al. 2011, Poon & Chan 2006). This is thought to be from materials of very low parent strength, as is the case in the 6 MPa BCA analysed by Poon & Chan (2006).

The Use of C&DW in Concrete in Cape Town

Table 5.4: Comparison of relative densities of RA materials from various authors

Relative Densities of Various RA Materials					
RA Description	Material	Material Size (max)	Parent Material Strength	Relative Density (Specific Gravity)	Reference
		mm	MPa		
Laboratory Cast Concrete Beams	RCA (13 mm NA)	13 (NA)	20	2,28	Zhang & Ingham 2010
			40	2,32	
			60	2,33	
	RCA (19 mm NA)	19 (NA)	20	2,51	
			40	2,52	
			60	2,53	
Laboratory Cast Cubes	RCA	20	25	2,28	Eguchi et. al. 2007
			38	2,27	
			52	2,20	
Concrete Recovered from a Turbine Power Plant	RCA	25	27	2,23	
			40	2,21	
			40	2,31	
Laboratory cast cubes (Granite and Riversand NAs)	RCA	10	35	2,46	Padmini et. al. 2009
			49	2,40	
			56	2,38	
	RCA	20	37	2,52	
			50	2,51	
			58	2,48	
Lead Painted Masonry	CMA	19	21	2,34	Hu et. al. 2011
			33	2,39	
	BCA		74	2,37	
			102	2,39	
100% Medium Weight Brick	BCA	-	-	1,93	Yang et. al. 2011
Various Clay Brick	BCA	-	6	1,86	Poon & Chan 2006
			13	2,33	

Loose bulk densities range from 1022 - 1432 kg/m³ and compacted bulk density from 1427-1568 kg/m³ in RCAs respectively. Loose and compacted bulk densities of RCA compare relatively well to typical Cape aggregates (Table 5.3) in some cases but the overall trend is that these properties are lower than

The Use of C&DW in Concrete in Cape Town

that of NAs. Aggregate size and source of RCA seem to affect these results. A tabulated summary of density values as found by various authors is shown below in Table 5.5.

Table 5.5: Comparison of bulk and absolute densities of RA materials from various authors

Bulk and Absolute Densities of Various RA Materials							
RA Description	Material	Material Size (max)	Parent Material Strength	Bulk Density Loose	Bulk Density Compacted	Absolute Density	Reference
		mm	MPa	kg/m^3			
Laboratory Cast Concrete	RCA	14 (min 4)	64	1164		2329	Debieb et. al. 2010
		20 (min 14)		1022		2319	
Laboratory cast cubes (Granite and River sand)	RCA	10	35	1338	1468		Padmini et. al. 2009
			49	1327	1438		
			56	1324	1427		
	RCA	20	37	1432	1568		
			50	1421	1536		
		58	1394	1498			
Commercial Source (Mixed RA)	70% RCA 20% BCA	20		1241			Chen et. al. 2003
				1252			
Commercial Source (Mixed RA)	RCA	10				2523	Poon et. al. 2006
		20		2493			
Clay Brick Partition	BCA	10				1797	
		20		1618			
Commercial Source (Mixed RA)	RCA	20				2546	Sanchez de Juan et. al. 2009
	Mortar	-		1665			
Commercial Recycling Facility	RCA	10				2523	Poon & Chan 2006
Clay Brick Partition	BCA	10				1797	

Obtaining bulk density values for BCAs is difficult, as research on individual masonry aggregate is not well covered. The impact of a 20% inclusion of BCA materials can be seen in Chen et. al's (2003) study where loose bulk density decreases to 1241 kg/m^3 . A comparison of the absolute densities of BCA materials found by Poon et. al. (2006), Debieb et. al. (2010) and Sanchez de Juan et. al. (2009), show that the average value of absolute density is 2442 kg/m^3 .

The Use of C&DW in Concrete in Cape Town

Sanchez de Juan et. al. (2009) sought to identify the impacts of mortar on BCA materials by projecting a trend line in the relationship between the absolute density of mortar and BCA content. It was estimated that mortar has an absolute density of 1665 kg/m^3 . It is thought that the BCA material analysed by Poon et. al. (2006), was not cleaned and the clay brick partition simply crushed and analysed. The result of this is a very low BCA absolute density of 1618 kg/m^3 .

5.3.6 Saturated Surface Dry density

Water absorption and saturated surface dry (SSD) density are two related parameters that often define the quality of RAs. As mentioned, the high absorption of RAs must be accounted for due to the fact that part of the water added to the mix will fill the accessible pores of porous RA materials. To reduce the impact of high absorption, pre-soaking is often used to fill (saturate) these pores and limit the impact of water absorption. The parameter of SSD density must therefore be taken into account as this density value is often used in the mix design of RA concrete.

Local tests on commercial recycled aggregates for use in a ground slab in the Western Cape for AFRIMAT, revealed a dry density of 2360 kg/m^3 and SSD density of 2460 kg/m^3 . Reviewing SSD values of RCAs from various sources shows that relative density values increase from around 2.20 to 2.40 with pre-soaking (Chen et. al. 2003). SSD absolute densities also increase to between $2546 - 2580 \text{ kg/m}^3$ in RCAs and from 1916 and 2147 kg/m^3 in BCAs (Eguchi et. al. 2007; Poon et. al, 2006; Sanchez de Juan 2009; Poon & Chan 2006).

A comparison of SSD and other density values is shown in Table 5.6 below:

Table 5.6: Comparison of SSD densities of RA materials from various authors

Saturated Surface Dry Densities of Various RA Materials								
RA Description	Material	Material Size (max)	Parent Material Strength	Relative Density	Absolute Density	SSD Relative Density	SSD Density	Reference
		mm	MPa	kg/m^3				
Laboratory cast cubes	RCA	20	25	2,28		2,42		Eguchi et. al. 2007
			39	2,27		2,38		
			52	2,20		2,41		
Turbine Power Plant Concrete	RCA	40	27	2,23		2,40		
			30	2,21		2,38		
			41	2,31		2,46		

The Use of C&DW in Concrete in Cape Town

Table 5.6 continued: Comparison of SSD densities of RA materials from various authors

Commercial Source	RCA	10		2523		2580	Poon et. al. 2006
		20		2493		2546	
Clay Brick Partition	BCA	10		1797		2147	
		20		1618		1916	
Commercial Source	RCA	20		2546		2579	Sanchez de Juan et. al. 2009
	Mortar	-		1665		2000	
Commercial Recycling Source	RCA	10		2523		2580	Poon & Chan 2006
Clay Brick Partition	BCA	10		1797		2147	

BCAs are known to reduce the density of mixed RA materials due to their porous nature. Agrela et. al. (2011) sought to find relationships between RCA (referred to as concrete) and BCA (referred to as ceramic) content of RA materials and their SSD densities. Their results concur with literature and show an increased in SSD density with increased RCA content (Figure 5.7) and a reduced SSD density with increased BCA material content (Figure 5.8).

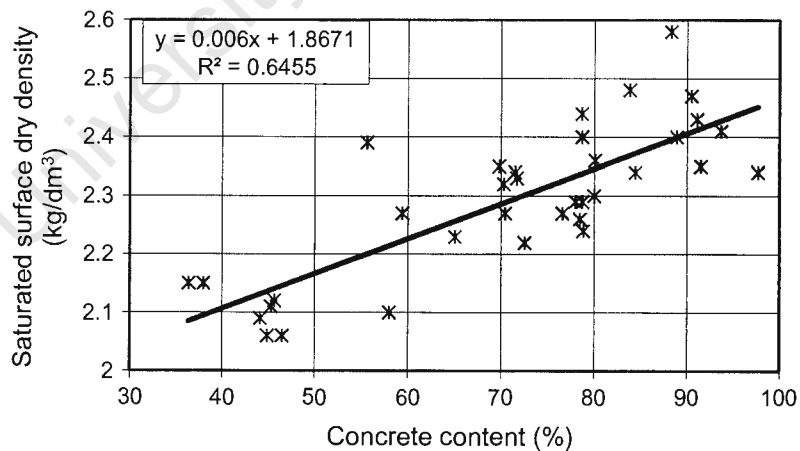


Figure 5.7: Relationship between RCA (referred to as concrete) content and SSD density (Agrela et. al. 2011)

The Use of C&DW in Concrete in Cape Town

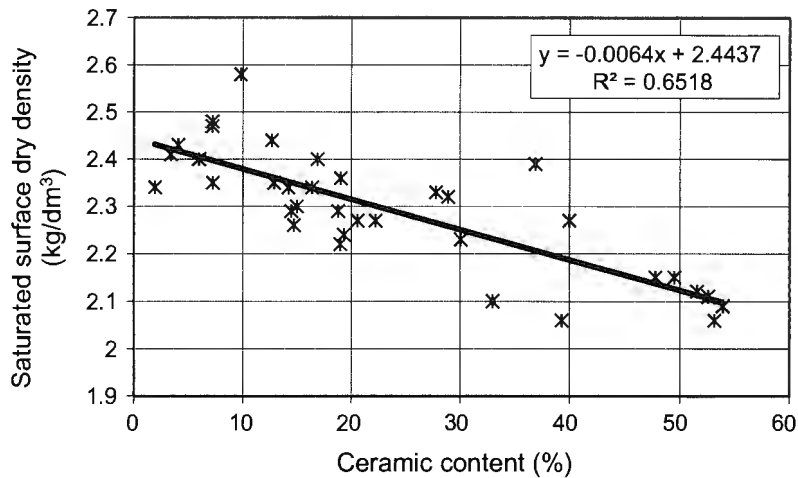


Figure 5.8: Relationship between BCA (referred to as ceramic) contents and SSD density (Agrela et. al. 2011)

5.3.7 Contaminants

The purpose of identifying and separating C&D waste on-site is to reduce the impact of inherent contaminants that are associated with mixed RA materials. This approach not only produces better quality RAs but also reduces operational costs associated with producing RA products commercially. Even with the separation of C&D waste into BCA, CMA and RCA groups, there are a few contaminant concerns in the Western Cape. These may include sulphates, chlorides, wood, plastics, paper, textiles and paint products. The key contaminants that have potential adverse effects on concrete properties and general comments are shown in Table 5.7.

Table 5.7: Effect of some general contaminants of concrete performance (HB 155-2002)

Effects of contaminants on concrete performance	
Magnesium Oxide	Low concentrations ($\approx 0.01\%$) of MgO (periclase) from refractory bricks can cause localised expansion in concrete
Stony material	Marginal effect at less than 5% concentrations
Gypsum	May induce ettringite formation and lead to expansion
Wood	May decompose or swell in moist condition. Potential for pop-outs in finished concrete
Clay lumps	Undesirable in concrete
Plate glass	Reactive with cement paste leading to alkali-silica reactions

5.3.7.1 Sulphates

The presence of sulphate ions is known to promote spalling in concrete. Sulphates may stem from masonry, especially when masonry has been used in chimney applications, or from the presence of gypsum plaster (HB 155-2002). This process is initiated by a reaction between the sulphate ion (SO_4^{2-}) and calcium hydroxide ($\text{Ca}(\text{OH})_2$) on the hardened cement paste. This is known as 'gypsum corrosion' and is associated with an increase in volume in the cement paste. This expansion is said to only be significant when sulphate levels reach concentrations of 3000 ppm (Grieve 2009). HB 155-2002 recommends a sulphate contamination level of less than 0.5% for RAs.

Gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) plastering is largely responsible for the leaching of sulphates into RAs. Gypsum plasters are unusual in external work and usually used for internal finishing. However, if internal brick walling is used for to produce BCA or CMA, there may be large quantities of plaster material present on their surfaces. It is noted that this reaction is less prevalent in coastal environments due to gypsum being more soluble in solutions containing chloride ions. This reduces expansion in the sulphate reaction. Fly-ash cement blends have also been known to mitigate sulphate reactions (Alexander & Heiyantuduwa 2002).

Debieb et. al. (2010) remarks that RCA containing 0.3-0.8% of sulphates (by mass of SO_3) of which the greater part is bound in the hydrated microstructure of the cement and does not produce significant expansion. Martin-Moralez et. al. (2011) comments that sulphate contamination of RAs is common. These are usually removed by manual picking for larger fragments however percentage of sulphates in small, crushed particles was in the range of 1.5% in his study.

The correlation between gypsum content and soluble sulphates has been studied by Agrela et. al. (2011). He recommends rejecting recycled aggregates with a gypsum content higher than 1.7%. This is due to the fact that Spanish and European specification for soluble sulphates are 0.8% for aggregates used in the production of concrete. From literature Agrela et. al. (2011) comments that larger pieces of gypsum plaster soften and weaken when saturated. Hansen (1992) found that 3% contamination of gypsum plaster in concrete resulted in a 15-50% reduction in strength depending on the curing approach used (Kutugeza 2004).

5.3.7.2 Chlorides

The presence of chlorides on the surface of steel reinforcement can lead to depassivation and result in corrosion of steel. Chloride content limit are usually only prescribed for fine aggregates. This is because sands, such as Dune Sand, may be derived from coastal regions where they come into contact with

The Use of C&DW in Concrete in Cape Town

seawater. The limits prescribed for chloride content in fine aggregates are 0.08% for normal concrete and 0.03% for reinforced steel concrete in South Africa (Grieve 2009).

Given the porosity of RAs and the exposure of these materials to coastal weather conditions in the Cape, chloride penetration is a concern. Alexander & Heiyantuduwa (2002) found that chloride content of mixed RCAs to be 0.152% by mass of aggregate in the Cape. This was reduced to 0.042%, just above the allowable limit of 0.03%, after being soaked in water for seven days.

Martin-Moralez et. al. (2011) reports that most mixed recycled aggregates in Spain show chloride content of under 0.05% (the EU limit for chloride content for reinforced concrete) however, samples taken from coastal regions show slightly higher averages of 0.053%.

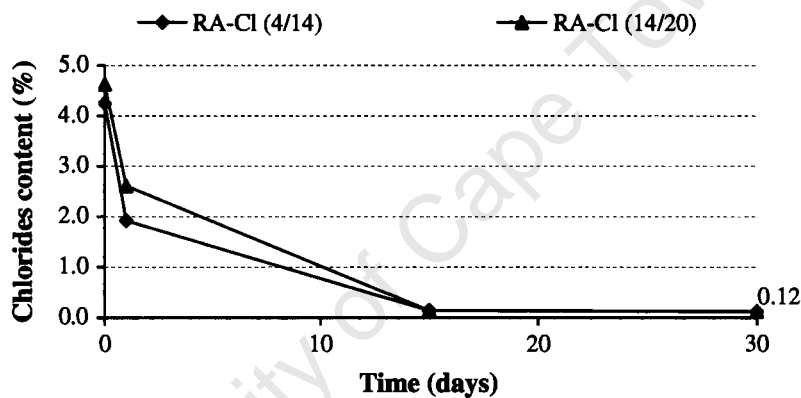


Figure 5.9: Reduction in chloride content in coarse RA soaked in water (Debieb et. al. 2010)

Debieb et. al. (2010) states that 15 days of immersion in water has resulted in coarse aggregates losing up to 96% of their chloride content, making RAs comparable to NAs (Figure 5.9). The leaching actions of chlorides lead to the conclusion that soaking of RAs can leave them clean and usable in any concrete without any risk of corrosion. Martin-Morales et. al. (2011) and Alexander (2006) reported similar results when RAs are immersed soaked or washed.

5.3.7.3 Lead Based Paints

Hu et. al. (2011) crushed a used lead based paint coated concrete and clay bricks. It was found that even when these materials failed classification parameters due to high (up to 2.2%) leachable lead content, the high alkalinity of cement resulted in concrete mixes that showed no toxicity characteristic for lead with Pb content less than 1 mg/l. This is lower than the limit of 5 mg/l set by the Resource Conservation and Recovery Act (USA).

5.3.7.4 Organic Substances

Organic substances such as polymeric materials, wood, paper and soft friable substance may become unstable when wetted and dried. A limit of 0.15% by weight of materials lighter than 1200 kg/m³ is recommended (HB 155-2002).

Organic matter including paints, bitumen, insulation material, textile and sugars can have an influence of the setting and compressive strength of concrete. Commercially graded and separated aggregates usually relatively low amounts of this material. When possible, using aggregate materials contaminated with industrial chemical should be avoided since no single specification caters for potential of specific contaminants (HB 155-2002).

5.3.8 Aggregate Crushing Value and 10% FACT

Particle interaction during crushing plays an important role in the results achieved by these tests. The degree of crushing will increase when particles are packed together with increasing confining pressure, particle size, particle angularity and decreased uniformity, density and interaction (Guimares et. al. 2006). Aggregate crushing value (ACV) and 10% fines aggregate crushing test (FACT) values are an indication of resistance to crushing under gradually applied load. These are useful indications of overall aggregate quality. Grieve (2009) comments that crushing parameters do not necessarily give a complete indication of an aggregate's performance in concrete. SANS recommends a 10% FACT value of 110kN for coarse aggregates for use in concrete exposed to abrasive environments. A 10% FACT of 70 kN is recommended otherwise (SANS 1083:2006).

Alexander (2006) reports that where the density of the ITZ is improved, aggregate strength can have a significant effect on concrete strength. This may also be true of particles with a rough surface texture, a defining characteristic of RA materials. NAs are usually well above the range of most concrete crushing strengths. RA materials are far more variable with some masonry aggregates having strengths as low as 5 MPa. This makes these parameters important to indicate the ability of RAs to give dimensional stability to concrete.

As observed by several researchers, the resistance against mechanical crushing of RAs is lower than that of NA. This is due to the separation and crushing of porous mortar coating from RCAs and masonry aggregates, as well as the inherent weaker strength of masonries when compared to stone (Hu et. al. 2011; Eguchi et. al. 2007; Padmini et. al. 2009). The resistance against mechanical actions also decreases with the reduction in maximum size of aggregate. This can be attributed to the larger surface area of smaller sized aggregates with higher mortar coating, when compared to larger size aggregate (Poon & Chan 2006; Padmini et. al. 2009).

The Use of C&DW in Concrete in Cape Town

Alexander & Heiyantuduwa (2002) found that dry RCA sample crushing values were greater than the limits set by SANS1083:2006. Their results show values of 150 kN and 190 kN for wet and dry 10% FACT tests on local RCAs from Malans Quarry in the Western Cape. When comparing 10% FACT values of RAs to those of recognised Western Cape aggregates, the NAs values far exceed those of the RAs results. This may not be critical as NA crushing values usually far exceed the strength requirement of normal concretes. This is taken into account by SANS 1083:2006, which prescribes a comparatively low 10% FACT value of 110kN, when compared to the values achieved by NAs in Table 5.8.

Table 5.8: Dry 10% FACT values of recognised Cape aggregates (Alexander & Heiyantuduwa 2002)

Densities of Western Cape NA Materials		
Rock Type	Source	10% FACT
Granite	Malmesbury (Rheebok Quarry)	280
Greywacke (Malmesbury Shale)	Contermanskloof (Peninsula Quarry)	299
Quartzite	Mossel Bay Quarry	244
Recycled Aggregate	Malans Quarry	190

Data on other local tested commercial recycled aggregates revealed the following results. RCA for use in a ground slab in the Western Cape for AFRIMAT, revealed dry 10% FACT values of 153 kN and also wet and dry ACVs of 28.3% and 30.2% respectively. Kutugeza's (2004) results on commercially produced RCAs produced dry 10% FACT values of between 175 kN and 188 kN respectively.

A comparison of various crushing strength from authors is shown in Table 5.9.

Poon & Chan studied (2006) individual and blended RCAs and BCAs. The replacement levels (by weight) were 0%, 25%, 50% and 75%. The results indicate that the RCA had a better resistance to crushing, 146 kN, when compared to the BCAs, 49 kN. Strengths of the RCA and BCA decreased after soaking from 146 to 109 kN and from 49 to 35 kN respectively. The corresponding reductions were approximately 25% and 28% for recycled concrete aggregate and crushed clay brick. These reduced values are of interest as soaked RA are sometimes used to reduce water absorption in RA concrete mix design. A comparison of the strength characteristics of RCA, BCA and blended RCA and BCA, shows that increasing the use of crushed clay brick reduced the 10% FACT values in both the dry and soaked

The Use of C&DW in Concrete in Cape Town

conditions. As the crushed clay brick content increased from 0% to 75%, the 10% FACT values reduced by 51% and 56% in the dry and soaked conditions (Poon & Chan 2006).

Table 5.9: Comparison of aggregate strength of RA materials from various authors

10% FACT Values Various RA Materials						
RA Description	Material		Material Size (max)	Aggregate Strength 10% FACT		Reference
			mm	kN		
				Dry	Soaked	
Malans Quarry	RCA			190	150	Alexander & Heiyantuduwa 2002
AFRIMAT	RCA		19	153		Klein 2013
Commercial recycling facility	RCA		10	146	109	Poon & Chan 2006
Clay Brick Partition	BCA			49	35	
Blended RA	75% RCA	25% BCA		107	77	
	50% RCA	50% BCA		86	60	
	25% RCA	75% BCA	72	48		

Tabsh et. al. (2009) found that RCAs show a 30% reduction in crushing strength when compared to NAs. The strength of the parent concrete is said to affect these results with increased parent concrete strength resulting in increased mechanical capabilities. The importance of the source of these concrete was emphasised as inferior sourced concrete may perform extremely badly. This is often the case with BCAs as the strength of these materials can vary considerably.

5.3.9 Summary

Literature on the physical and mechanical properties of recycled concrete (RCA), clay brick (BCA) and concrete masonry (CMA) materials that have been used as coarse aggregate in concrete have been covered in the above sections.

The use of simple procedures such as manual or jaw crushing has shown to produce particle distribution curves that conform to various standards. BCA materials are thought to be coarser than CMAs and RCAs. Fines materials increase with decreased parent concrete strength in RCAs and with increased mortar content and decrease strength in BCAs. Mortar content in coarse RCA may increase with

The Use of C&DW in Concrete in Cape Town

increased parent concrete strength. Sieving is important as a wide band of material sizes are produced during crushing.

RCAs have rough, coarse and cracked surfaces with a particle shape that is similar to the parent aggregate. BCAs have a more planar, angular aggregate shape. This contributes to RCA, clay brick aggregates and CMA having high absorption values within a range of 4.4% - 7.7%. Some authors present absorption values of up to 19.5% for BCAs with extremely high masonry mortar content. Increased mortar content results in increased absorption levels in RAs.

The presence of low-density mortars results in lower relative and bulk densities in RAs. Relative densities of RAs are lower than typical Cape NAs. RCA values range from 2.20 – 2.52. Relative densities of BCAs with high parent material strength compare well with RCA material with densities ranging from 2.33-2.39. Loose bulk density ranges from 1022 - 1432 kg/m³ and compacted bulk density from 1427-1568 kg/m³ in RCAs, compare relatively well to typical Cape aggregates.

High mortar content and lower parent material strength contribute higher absorption and lower densities in RA materials. It is therefore important to get an indication of these parameters prior to the use of RA materials in concrete. These properties will give an indication of the procedures to be taken to achieve desired workability, stability and cohesiveness in concrete mix design and in fresh concrete.

The mechanical properties ACV and 10% FACT value can have a significant affect on concrete strength. RA materials are highly variable with some masonry having compressive strengths as low as 1 MPa. These parameters are therefore important to indicate the ability of RAs to give dimensional stability to a concrete mix. The importance of the source of these RAs is emphasised as inferior sourced RAs may perform extremely badly.

Literature indicates that the RCAs have a better resistance to crushing when compared to the clay brick aggregates. Strengths of the RCA and BCA decrease after soaking. These reduced values are important as soaked RA in an SSD are sometimes used to reduce water absorption in RA concrete mix design.

5.4 Fresh Properties of RA Concrete

The highly absorptive and angular nature of RAs contributes to increased water requirements in RA concrete. Due to these uncertainties various approaches are taken in RA concrete mix design to achieve a required workability in a fresh concrete mix. This section provides information on the effects that these properties have on the aggregate paste interface, mix designs and approaches various authors have taken to reduce these characteristics of RAs.

5.4.1 Effect of RA Materials on the ITZ

RCAs are typically made up of stone with hardened concrete paste on their surfaces. BCA and CMA materials are generally composed of crushed masonry particles that may or may not have brickwork mortar (mortar or plaster) on their surfaces. The structure of RCA is different to that of BCA however, the performance of these materials, when used as aggregate for concrete, is thought to be a result of similar interface actions and physical properties. The variations in concrete structure between NAs, RCAs and masonry RA are therefore discussed below.

In fresh concrete made with NA, the presence of a water film results in the w:b immediately around the aggregate particle being significantly higher than that of the cement paste. This is because most NAs essentially do not absorb water. This interfacial zone (ITZ) is regarded as the weakest link in the concrete matrix inhibiting the achievement a composite action between the cement paste and NAs (Alexander 1996).

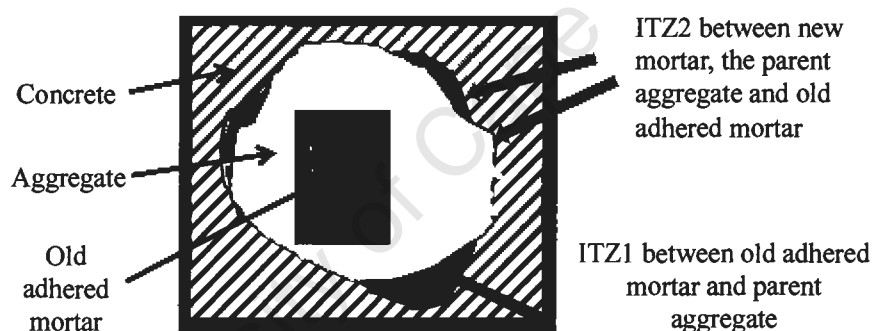


Figure 5.10: Diagram showing two ITZ in RCA concrete

The structure of RCA concrete is more complex than that of NA concrete. This is thought to be a consequence of two planes of weakness or interfacial transition zones (ITZs): one located between the RCA parent aggregate and the old adhered mortar (Figure 5.10. - ITZ1), the other between the new cement paste, the RCA virgin aggregate and RCA old concrete paste (Figure 5.10. – ITZ2). The strength of RA concrete, particularly RCA concrete, may therefore be determined by the weaker of these two ITZs (Alexander 1996).

This structure increases in complexity in masonry aggregate concrete. This is thought to be a result of two ITZs but also the highly porous structure of masonry when compared to RCAs and NAs. As with RCA concrete two ITZs exist, one between masonry aggregate, old attached brickwork mortar and the new concrete and also between the masonry mortar and the new concrete. The old brickwork mortar in masonry aggregates is substantially weaker and more variable than the mortar on RCAs as it is not concrete mortar but plaster or cement mortar. Also, the large pores and absorptivity characteristics of

masonry materials may affect the ITZ in those regions in a number of ways. This ITZ in masonry aggregates is illustrated in Figure 5.11 and discussed further below.

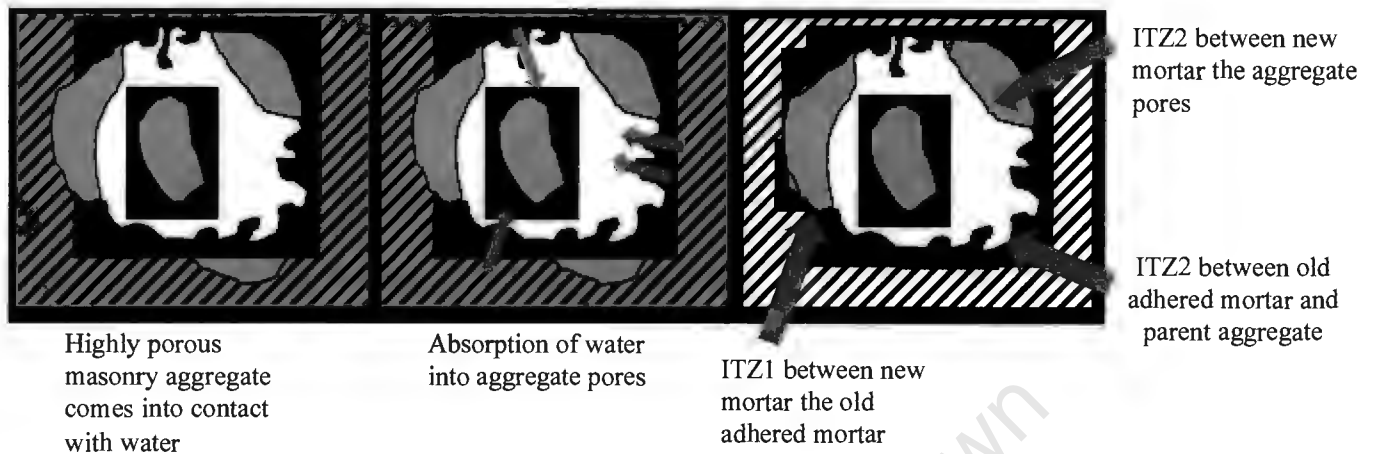


Figure 5.11: Illustration of ITZ in masonry aggregates

Dry masonry aggregates are extremely absorptive and therefore water may be removed from the fresh concrete paste effectively decreasing the w:b in the ITZ region. This could potentially increase the strength of the concrete around the ITZ but leads to decreased workability and w:b in the fresh concrete mix. RAs are typically pre-wetted to mitigate absorptive properties before use. When wet RAs are exposed to fresh cement paste, Barra et. al. (1998) states that there are two directions this free water on the wetted aggregates can take. Water can either increase the w:b at the ITZ, thus reducing the strength of the bond between aggregate and cement paste, or migrate towards the paste after setting thus improving the microstructure of the concrete (Kutugeza 2004). This release of the stored water from within the RA pores over a period of time may be aided by the capillary effect in which moisture is absorbed and released in masonry materials. This may aid long-term hydration and reduce shrinkage.

5.4.2 RA Concrete Mix Design

Variations in the physical properties of RAs make it extremely difficult to predict the water requirement needed to produce a concrete mix of specific workability. To overcome this, authors typically have make use of trial mixes to achieve the desired slump and w:b needed to achieve the specified strength (Kutugeza 2004). Literature on the mix design of RA concrete made with single RA components is not well covered. Therefore, this section makes use of resources from both mixed RA and single RA sources.

The Use of C&DW in Concrete in Cape Town

Table 5.10: Mix proportions for wet and dry batches of Mixed RA (Alexander & Heiyantuduwa 2002)

Mixed RAC Mix Design by Alexander & Heiyantuduwa (2002)		
Material	SSD	Dry
W:C	0.72	0.72
Water (l/m ³)	165	165+32
50CEM I: 50GGBS (kg/ m ³)	229	229
RCA (kg/m ³)	1009	1009
Fine Aggregate (kg/ m ³)	888	888
Slump (mm)	90	80

Table 5.11: Mixed RA concrete mix design used by Kutugeza (2004)

Mixed RAC Mix Design by Kutugeza (2004)						
Mix	W:C	CEM I 42.5	Corex Slag	RA	NA (fine)	Water
XRC	0.50	200	200	1060	700	180
	0.60	150	150	1060	785	180
	0.75	120	120	1060	840	180
	0.90	100	100	1060	875	180

Reviewing local studies by Kutugeza (2004) and Alexander & Heiyantuduwa (2002), they used the mix design method proposed by the Cement and Concrete Institute as a guide to estimate concrete mix proportions. Alexander & Heiyantuduwa (2002) carried out multiple trial mixes until the required concrete workability was achieved. Mix designs made use of both surface saturated and dry batches of aggregates. The final mix designs are shown in Table 5.10 above. It shows that the dry batches needed 32 l/m³ of extra water to achieve a similar slump and cater for the absorptive properties of the RAs. Kutugeza (2004) saturated mixed RAs prior to mixing but reserved a portion of the 180 l/m³ of free water to adjust workability to the required 80 mm slump. Multistage mixing, where various concrete components were introduced at different times, was also used. The quantity of water added to achieve SSD conditions in both studies is unknown. The water recorded in the SSD mix design in Alexander &

The Use of C&DW in Concrete in Cape Town

Heiyantuduwa (2002) work is simply the water added, 165 l/m^3 , to achieve the concrete mix design strength. Unknown added quantities of water to achieve SSD conditions when pre-wetting RAs is seen as a shortfall within these procedures.

Levy et. al. (2004) compares the properties of BCAs, RCAs and their RA concrete mixes with 28 day design compressive strengths of 20, 30 and 40 MPa. This data is used to produce mix design nomograms for various RA mixes. The nomogram for a 50% NA/50% BCA mix in SSD conditions and the corresponding material quantities are shown below in Figure 5.12.

Table 5.12: Mix proportions of 50% NA/ 50% BCA concrete as per nomogram by Levy et. al. (2004)

Mix Design for 30 and 40 MPa RAC						
28-Day strength	Aggregate	Slump	W:C	A:C	Cement (65% CEM I 39 35% GGBS)	Water Content
MPa		mm			kg/m ³	litres
30	50% NA/ 50% BCA	70	0.72	5.90	300	216
40			0.56	4.25	420	235

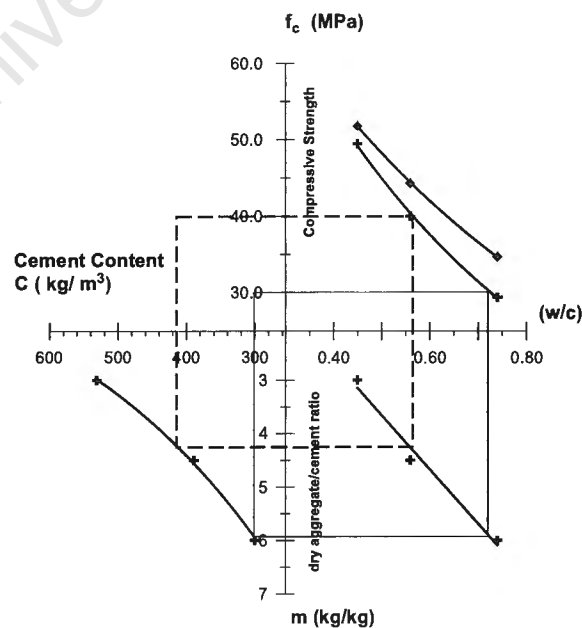


Figure 5.12: Nomogram by Levy et. al. (2004) for 50% NA/50% BCA. Mix design in Table 5.12 calculated from Nomogram

The Use of C&DW in Concrete in Cape Town

Using mix proportion data that took into account desired workability, actual workability and compressive strengths of parent concrete of 35, 49 and 56 MPa. Padmini et. al. (2009) found the relationship between w:b, compressive strength, A:C ratio and cement content. This was plotted in the nomogram. Using this nomogram, a mix design for 30, 35 and 40 MPa concrete made with 20 mm RCA can be established. This is shown by the dashed lines in Figure 5.12.

Table 5.13: Mix proportions as specified by Padmini et. al. (2009)

Mix Design for RAC from 20 mm Coarse RCA						
28-Day strength	Aggregate	Slump	W:C	A:C	Cement (CEM I)	Water Content
MPa		mm			kg/m ³	
30	Coarse 20 mm RCA	50	0.6	3.2	380	217
35			0.5	4.3	430	206
40			0.38	5.1	525	200

5.4.3 Water Requirement and Workability

RAs are characterized by higher water absorption properties. This may not only cause harsh, uncohesive and high bleeding mixes but also effect concrete durability and strength (Bento et. al. 2012; Kutugeza 2004).

Researchers agree that RCAs require 5 - 10% or 10 – 20 l/m³ more water than NAs to achieve a comparable workability (slump) (Yang et. al. 2011, Tabsh et. al. 2009, Kutugeza 2004). Slump losses might also be rapid as a result of high rates of absorption by RAs (Alexander & Heiyantuduwa 2002; Debieb et. al. 2010, Kutugeza 2004).

As a result of the absorptive properties of RAs, admixtures such as plasticizers are often used in fresh concrete to combat these effects. Some studies have addressed this problem with other techniques.

The Use of C&DW in Concrete in Cape Town

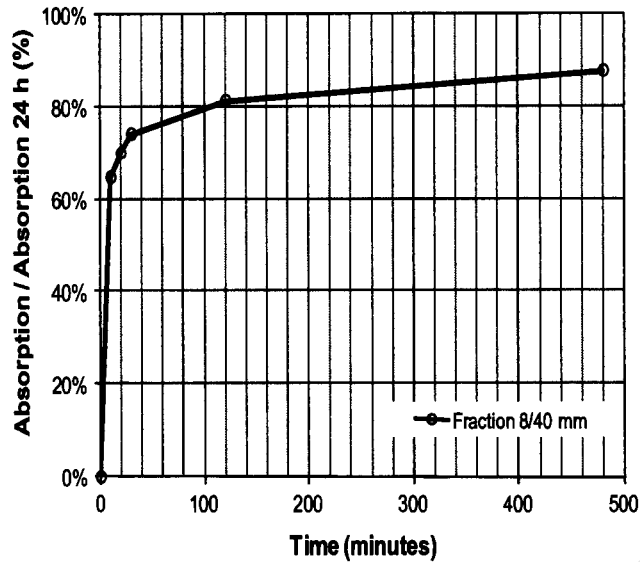


Figure 5.13: Water absorption characteristics of 40 mm RCA (Bento et. al. 2012)

RAs can be pre-wetted or soaked before mixing. Reference to this technique is discussed in Bento et. al. (2012) where RCAs were wetted by a sprinkler system and covered by a plastic sheet in order to maintain their humidity the day before they were used. Humidity around 80% is recommended. Various authors recommend different pre-soaking durations. This is not only to cater for the absorption potential but also reduce potential segregation of fresh concrete due to the high absorption rate of RCAs during the mixing of fresh concrete. Bento et. al. (2012) found that 75% of the total absorption of RCA material took place within the first 30 minutes of soaking. See Figure 5.13. He refers to other authors having found 50% water absorption takes place within a 10 – 30 minutes mixing period. This resulted in the pre-soaking of aggregate for 2 hours prior to use in his study. This can be compared to Hansen (1992), who recommends 1 hours soaking and Padmini et. al. (2009) who found that 10 minute water absorption value satisfied workability requirements.

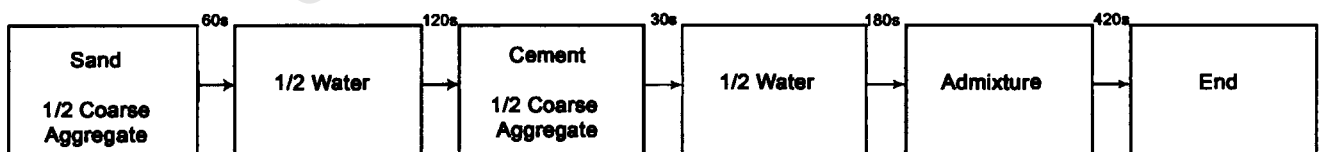


Figure 5.14: The sequence of adding the different components of the mix proportion in the mixer (Bento et. al. 2012)

Introducing water and other concrete materials into the concrete mixing process in stages is another technique. This is also known as a multiple step mixing procedure or two-stage-mixing (Hu et. al. 2011; Tam et. al. 2005; Zhang & Ingham 2010). Tam et. al's (2005) two-stage mixing involves half the water being mixed with the RAs for 60 seconds and the rest of the ingredients added and mixed for a further 120 seconds. It is suggested that for larger w:b ratios this process improves concrete strength substantially (Zhang & Ingham 2010). This is similar to Debieb et. al.'s (2010) multistage mixing

process that consists of combining coarse aggregate, fine aggregates and half the mix water, then the cement and finally the rest of the mix water in equal intervals over 5 minutes. This also relates to the mixing procedure used by Bento et. al. (2012) as illustrated in Figure 5.14. Adverse absorption properties are corrected by pre-wetting aggregate inside the concrete mixer and then by 'sealing' the RA with cement paste.

Barra et. al. (1998) comments that by mixing aggregates with water and cement first (or a prepared mortar), the pores and micro-cracks of the aggregates are coated (sealed) with cement paste. This reduced the high absorption properties displayed by RAs if they are mixed solely with water first. Tam et. al. (2005) and Bento et. al. (2012) verify this 'sealing' process and therefore use multistage mixing to achieve this outcome.

5.4.4 Summary and Recommendations

The fresh properties of concrete have practical implications for construction and determine the ease of handling. They also have bearing on compactability and the distribution of particles within a concrete mix that affect hardened concrete properties.

Normal mix design methods can be used to calculate material proportions for RA concrete. However, variations in the physical properties of RAs make it difficult to predict the water requirement needed to produce a concrete mix of specific workability. To overcome this, authors typically create trial mixes to achieve the desired slump and w:b needed to achieve the specified strength. Researchers agree that RAs require more water than NAs to achieve a comparable workability. This is especially true of BCA materials. Slump losses might also be rapid in these aggregates as a result of high rates of absorption. In order to mitigate absorption effects, RAs are usually pre-wetted or soaked before used in concrete mixes. Otherwise multi-step or two-stage mixing that pre-wets and then seals aggregates with cement paste inside a concrete mixer is also said to improve workability in fresh concrete.

5.5 Hardened RA Concrete Properties

The hardened properties of concrete are affected by the strength of the aggregates, the strengths of the concrete matrix and the interfacial bond between aggregates and concrete matrix. The porosity of RAs in hardened concrete may affect the concrete matrix by increasing or decreasing w:b. These pores also introduce flaws that may create localised areas of stress. Therefore increased porosity may result in decreased hardened concrete strength (Grieve 2009). Hardened RA concrete properties of compressive strength, shrinkage and elastic modulus are reviewed in this section.

5.5.1 Compressive Strength

Many researchers agree that compressive strength of RAC decreases with increased RA substitution. However, authors have reported contrasting trends in the magnitude of this strength decrease.

Poon et. al. (2006) conducted studies on different RCA materials and reported that replacement levels of 25% and 50% had little effect on compressive strength. Another study by Poon (2006) states that coarse BCAs decrease 28 day concrete strengths by 30 – 40%. Also, Chen et. al. (2003) reported that the greater the brick and tile content in mixed RCAs the lower the compressive strength by 75-85%.

Hu et. al. (2011) tested the compressive strength of various clay and concrete masonry concrete at 2, 7 and 28 days. The trends were similar to that of normal concrete with strength decreasing with increased w:b. Masonry A, B, C and Ds virgin compressive strengths were 21, 33, 74 and 102 MPa respectively. Aggregate B and D resulted in the highest compressive strengths of 46.0 and 40.6 MPa when Portland cement with w:b of 0.34 and 0.43 were used. Strengths as low as 5.4 MPa and 5.6 MPa were recorded for mixes with higher aggregate contents (a:c = 6). Improved strength is thought to relate to higher aggregate strength and concrete workability by the author. It is noted that the concrete in this study had a relatively low w:b as an air entrainer was used to achieve the desired workability. The trends are shown in Figure 5.15 below.

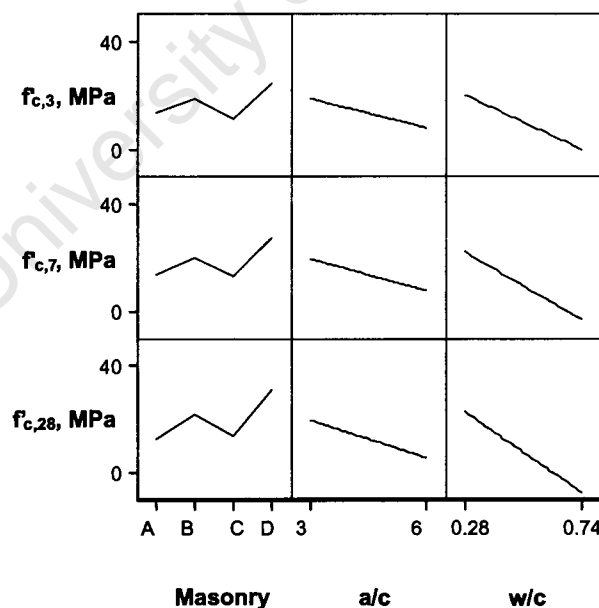
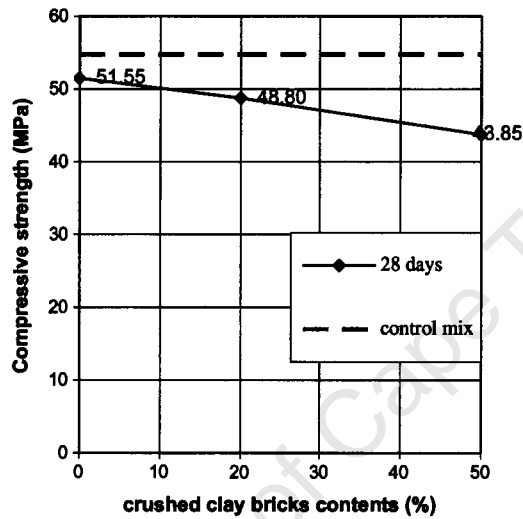


Figure 5.15: Compressive strength trends for BCA and CMA (Hu et. al. 2011)

Yang et. al. (2011) analysed compressive strength results for four mixes at 7 and 28 days with the same w:b's and a design strength of 38 MPa. Pre wetting and complete removal of fine aggregate was carried out in this study. Compressive strength values and the corresponding trend in reduction of compressive

The Use of C&DW in Concrete in Cape Town

strength that were found, with increased RA replacement, are shown in Figure 5.16 and Table 5.14. 100% RCA replacement yielded good strength results with a strength reduction of only 6.7% and 5.7% respectively from the 41.6 MPa and 54.7 MPa benchmark set by the NAC. These mixes were comparable to the NA mixes at similar w:bs. It is seen that as BCA content (referred to as RCB in Table 5.14) increases from 20% to 50%, there is a relative 28 day strength reduction of 10.7% to 19.8% (Yang et. al. 2011). Figure 5.15 illustrates the deterioration of compressive strength with 20% and 50% BCA replacement.



(b) 28 days strength

Figure 5.16: Deterioration on compressive strength with 100% RCA, BCA 20% and BCA 50% replacement (Yang et. al. 2011)

Table 5.14: Compressive strength results for various clay brick and RCA replacement levels as found by Yang et. al. (2011) (error in tabulation RCB-80 should be RCB 20. Clay brick is referred to as RCB by author)

Results of cube compressive strength test.

Mixtures	Specimen age (day)	Compressive strength (N/mm ²)			Relative strength reduction (%)
		Cube 1	Cube 2	Average	
NA-100 (control)	7	41.9	41.2	41.55	0
	28	54.7	54.6	54.65	0
RCB-80	7	38.1	38.3	38.2	8.1
	28	49.3	48.3	48.8	10.7
RCB-50	7	35.5	35.8	35.65	14.2
	28	44.3	43.4	43.85	19.8
RC-100	7	38.8	38.7	38.75	6.7
	28	51.2	51.9	51.55	5.7

Limbachiya et. al. (2010) state that there is no effect on final strength with a 30% replacement of RCA. In a literature review by Yang et. al. (2011), it was found that RCA concrete strength was comparable to NAC, at 100% replacement, but w:b needed to be at a ratio higher than 0.60. If w:b decreased to 0.40, RCA concrete only reached 75% strength of control mix.

The Use of C&DW in Concrete in Cape Town

Zhang & Ingham's (2010) study acquired coarse RCA from 20, 40 and 60 MPa laboratory cast slabs. These were then used to produce concrete with 5% more cement content, to account for loss of strength reported by previous researchers, and with 28 day strengths of 20, 40 and 60 MPa. The results showed that all RCAs produced higher strengths than that of the 20 MPa NAC. The 20, 40 and 60 MPa RCA concrete led to a 28 compressive strengths of 40, 48 and 52 MPa for the 40 MPa mix design. The mean strength of this mix was 47.5 MPa. Only the concrete made with 60 MPa RCA, reached 60 MPa strength after 28 days with a target mean strength of 69 MPa. It was concluded that RCA concrete showed a delayed strength gain when compared to NAC. RCAs derived from higher strength parent concrete may be used in lower strength concretes but, RCA derived from parent concrete with a lower strength than that of the design strength of RCA concrete, should not be used.

Tabsh et. al. (2009) also found that the stronger the parent concrete the better the RCA concrete performed. Of the RCA concretes made with 50 MPa, 30 MPa and an unknown parent concrete, the 50 MPa performed the closest to concrete with NA, even with an increase in water content of 10% to achieve desired workability. He stresses the importance of the sourced parent concrete strength.

Padmini et. al. (2009) comments that the difference in strength between parent concrete and RCA concrete increases with higher concrete strength requirements. This reduction is between 10-35% for different mixes. The reduction between RCA concrete and NA concrete is 20-35% for 10 mm, 14-35% for 20 mm and 10-25% for 40 mm RCAs. This shows the effect of increased mortar quantity as aggregate size decreases. Padmini et. al (2009) concludes that a given RCA concrete strength increases with an increase in strength of RCA.

5.5.2 Creep and Shrinkage

Drying shrinkage and creep may be a particular concern for concrete made with porous aggregates. Mansur et. al. (1999) used different grades of clay brick as coarse aggregate in concrete. Results showed comparable compressive strength with a lower drying shrinkage and identical creep with that of NA concrete. This was in conjunction with a drastically reduced elastic modulus and workability. Yang et. al. (2011) quote literature that found creep of coarse RCA concrete to be 30-60% higher than conventional concrete. Shrinkage was between 0.30 mm/m and 0.80 mm/m at 90-day age.

A relationship between shrinkage and replacement ratio for two sources of RCA in concrete, $w:b = 0.6$, was found by Eguchi et. al. (2007). As the replacement ratio of two RCA samples increases from 30% to 100%, shrinkage increases. This is expressed in Figure 5.17.

The Use of C&DW in Concrete in Cape Town

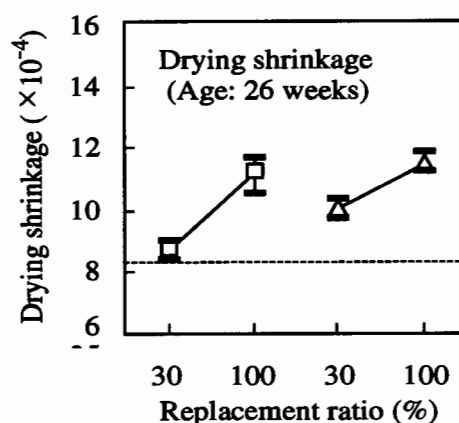


Figure 5.17: Relationship between shrinkage and RCA replacement ratios for 2 RCA sources (Eguchi et. al. 2007)

One of the purposes of Bektas et. al.'s (2009) study is to investigate the effect of BCA on drying shrinkage of concrete. The mixture proportions had a w:b = 0.5. The mortar containing 10% crushed brick showed the highest shrinkage whereas the 20% crushed brick replacement resulted in the lowest shrinkage value. Bektas et. al. (2009) reports that other authors such as Mansur et. al. (1999) have also found decreased shrinkage with increased brick content. It is thought that the brick particles may be acting as a self-curing agent by holding the initially absorbed mixing water in its pores for longer periods and releasing it slowly as the concrete ages. Therefore, drying shrinkage is delayed since the hydration continues due to the presence of internal moisture (Kutugeza 2004; Bektas et. al. 2009). This concurs with the description of free water movement by Barra et. al. (2009).

Masonry materials are known to expand and contract throughout their use. In general clay bricks are dimensionally stable. Shrinkage on drying and expansion on wetting are in the range of 0.015 per cent. Literature comments that upon wetting, expansion can vary between 0.04% and 0.12%. This expansion is irreversible and is not linked to dimensional movement due to wetting and drying. The amount of expansion depends on the raw material components, the degree of firing and degree of moisture exposure prior to being used. Generally expansion usually takes place in the first 6 months after manufacture and it is recommended that bricks are stockpiled for as long as possible and kept damp before use. SANS allows for expansion not exceeding 0.02% when concrete bricks are wetted. (CSIR 1984).

5.5.3 Modulus of Elasticity

Generally, RA concretes exhibit lower moduli of elasticity (MOE) than those of NA concretes (Padmini et. al 2009). Agrela et. al (2011) found that RA concrete MOE values were 70-80% of NA concrete and

The Use of C&DW in Concrete in Cape Town

comments that this shows that ceramic (BCA) content does not significantly affect MOE values of RA concrete.

Poon & Chan (2000) report that MOE decreases by 30% - 50% with BCA substitution in concrete. Their findings recommend a limited substitution of 25% for coarse and 50% for fine aggregates. Also applications should be limited to low performance concrete.

The relationship between concrete properties, elastic modulus, compressive strength and replacement ratio for two sources of RCA in concrete, w:b = 0.6, is expressed in Figure 5.18 produced by Eguchi et. al. (2007). One can see that as the RCA replacement ratio increases from 30% to 100% in each of the RA concrete mixes, compressive strength and MOE decrease. The difference in quality between samples is thought to be a result of variation in the parent concrete's NA components. River gravel was used in Series D and crushed stone in Series E.

Padmini et. al. (2009) finds that for a given strength of concrete, the MOE of RCA concrete is lower than that of parent concrete. MOE is reduced when RCA concrete is made with smaller sized aggregates. This is illustrated in Figure 5.18. The presence of relatively porous parent mortar affects the ability of RCA to restrain the concrete matrix, which affects MOE. Finally, for a given strength of RCA concrete, RA derived from parent concrete of different strengths, is not thought to affect MOE.

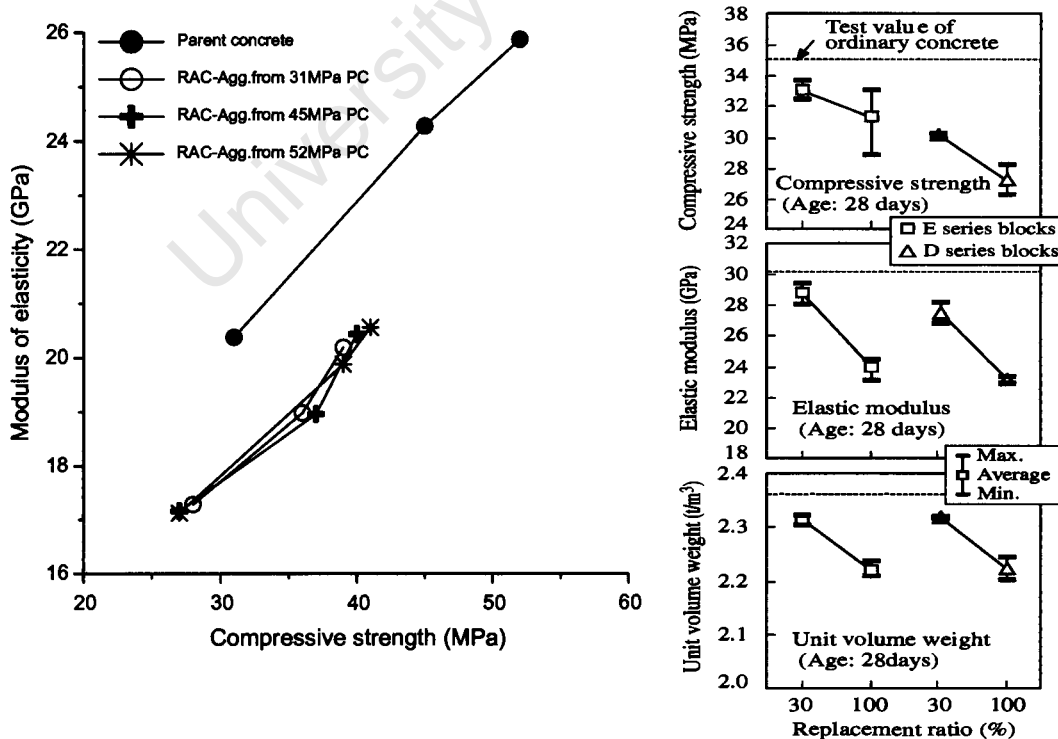


Figure 5.18: (Left) Relationship between MOE and strength of 40 mm RCA concrete (Padmini et. al. 2009). (Right) The relationship between concrete properties elastic modulus, compressive strength and replacement ratio (Eguchi et. al. 2007).

5.5.4 Summary

Research shows that the compressive strength, modulus of elasticity, creep and shrinkage properties of concrete worsen with increased substitution of RA materials. This impact may not be significant for lower strength concrete and higher quality RAs.

It is generally accepted that RCAs derived from higher strength parent concrete may be used in lower strength concretes but, RCA derived from parent concrete with a lower strength than that of the design strength of RCA concrete, should not be used. For a given strength of concrete, the modulus of elasticity of RCA concrete is generally lower than that of parent concrete. Shrinkage properties are more variable as it is thought that the brick particles may be acting as a self-curing agent by holding the initially absorbed mixing water in its pores for longer periods and releasing it slowly as the concrete ages. Therefore, drying shrinkage is delayed since the hydration continues due to the presence of internal moisture.

5.6 Conclusion

The above section discusses the physical properties, fresh properties and hardened properties of burnt clay brick aggregate, concrete brick aggregate and recycled concrete aggregate. This is in order to develop a greater understanding of the contribution of these individual materials to the performance of mixed recycled aggregate products in the Western Cape, identify wider potential for the use of these materials and further investigate the potential of efforts to promote on-site C&D material separation, processing and use. This allows for more educated decisions to be made around the selection of masonry materials and highlights possible concerns one might expect when these materials are to be used as coarse aggregates for concrete.

The Use of C&DW in Concrete in Cape Town

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6 Experimental Program

6.1 Introduction

The current use and disposal of aggregate material within the construction industry is contributing to illegal dumping activities, poor quality recycled aggregate products, an increased environmental burden and the depletion of landfill airspace in Cape Town.

C&D waste recyclers generally receive a mixed waste stream. RA products therefore have an extremely variable composition and separating these materials is an extremely time consuming and costly procedure. Consequently, potential for their use is often stifled by the varying quantities of poor materials in their make up.

Identifying, separating and manually processing C&D wastes on-site has the potential to remove the contaminants that are associated with current RA materials and yield more homogenous RAs that may have less variable material properties. This approach also has the potential to reduce the operational costs and the environmental burden associated with complex, large scale crushing operations and material transportation when producing RA products commercially.

The purpose of this research is to gain a greater understanding of the potential of on-site C&D material separation and processing actions, investigate the technical potential of these individual C&D materials to be used as coarse aggregates in concrete applications and develop a greater sense of the contribution of these individual materials to the performance of mixed recycled aggregate products in Cape Town.

The testing regime followed by this study aims to achieve the goals mentioned above and is made up of six stages.

- Stage one is the selection of various C&D materials that are typically acquired on a construction and/or demolition site in the Cape. These include burnt clay brick (stock and engineering), concrete brick and waste concrete materials.
- Stage two involves breaking down the individual RA materials with the use of a small jaw-crushing unit similar to the small mobile crushers available for on-site crushing operations.

The Use of C&DW in Concrete in Cape Town

- Stage three involves the manual separation (sieving) of the crushed material into a coarse aggregate fraction greater than 4.75 mm and less than 26 mm.
- Stage four is the determination the physical characteristics and properties of the individual coarse RAs and comparing these properties to the coarse natural aggregate currently used by industry, material standards and the findings of other researchers.
- Stage five is to develop a mix design and concrete mixing procedure that facilitates on-site RA concrete production and takes into account the properties of various RAs in particular water absorption potential.
- Stage six covers the testing of hardened concrete samples in order to evaluate the performance and potential of the RAs when utilised as coarse aggregates for concrete.

This complete testing regime is summarised at the end of this chapter.

6.2 Materials

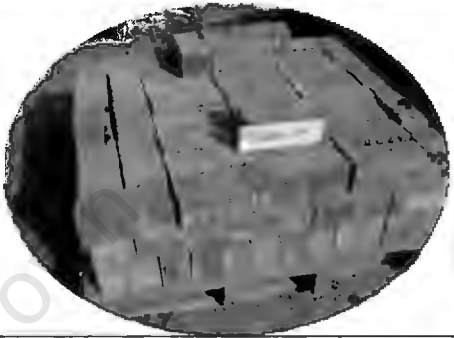



6.2.1 Summary of Materials to be Processed into RAs

C&D waste can consist of multiple material components including brick, concrete, plaster, mortar, ceramics, natural aggregates, asphalt, plastics, woods, paper and soil. This study concentrates on masonry and waste concrete materials as these are thought to contribute the majority of material in the C&D waste stream. One recognised natural aggregate is chosen as a control.

A summary, description and quantity of the samples evaluated is shown in Table 6.1 below:





The Use of C&DW in Concrete in Cape Town

Table 6.1: Summary of RA materials

Summary of RA Materials					
Material	Reference	Source	Description of Material	Grade/ Comp. Strength (MPa)	Illustration
Virgin plastering brick	NFP (Plastered)	Corobrik	Stock or general purpose brick. Clay bricks suitable for general building work that is to be plastered	7	
Virgin facing or plastering brick	NFX (Extra)	Corobrik	May be used for stock or general building work under damp conditions where durability rather than aesthetics is the criterion for selection	14	
Virgin engineering/ paving brick	FBE45	Corobrik	Clay bricks that are selected or produced for their durability and high uniformity in size, shape and colour	45	
Virgin concrete brick	CMA	CapeBrick	Virgin concrete hollow core and solid masonry	7-14	

The Use of C&DW in Concrete in Cape Town

Table 6.1 continued: Summary of RA materials

Site derived facing/ engineering brick	BCA-MC	CapeBrick	Mixed clay brick waste, mixed with mortar, plaster and soil contamination	Unknown (Variable)	
	BCA-MV	Illegally dumped rubble. Voortrekker Road, Koeberg Interchange Bridge	Mixed clay brick waste, mixed with mortar, plaster and soil	Unknown (Variable)	
Site Derived Concrete	RCA-45	Concrete Units	Waste concrete sample, 45MPa waste concrete used for precast concrete members	45	
	RCA-MC	supplied to CapeBrick by various demolishers such as Skye Demolition	Commercially crushed concrete waste/recycled concrete aggregate (RCA), mixed concrete samples	Unknown (Variable)	

6.2.1 Virgin Masonry Samples

Virgin masonry is chosen as the strength (grade) of these materials is known and external contaminants are not present. This removes a number of variables from the testing regime. The virgin masonry aggregates are made of two stock or general purpose bricks in the NFP and NFX clay bricks, as well as one high strength clay brick, referred to as FBE45. These clay brick products are all solid bricks purchased from COROBRIK brick manufacturers. Illustrations of these materials are shown below in Figure 6.1.

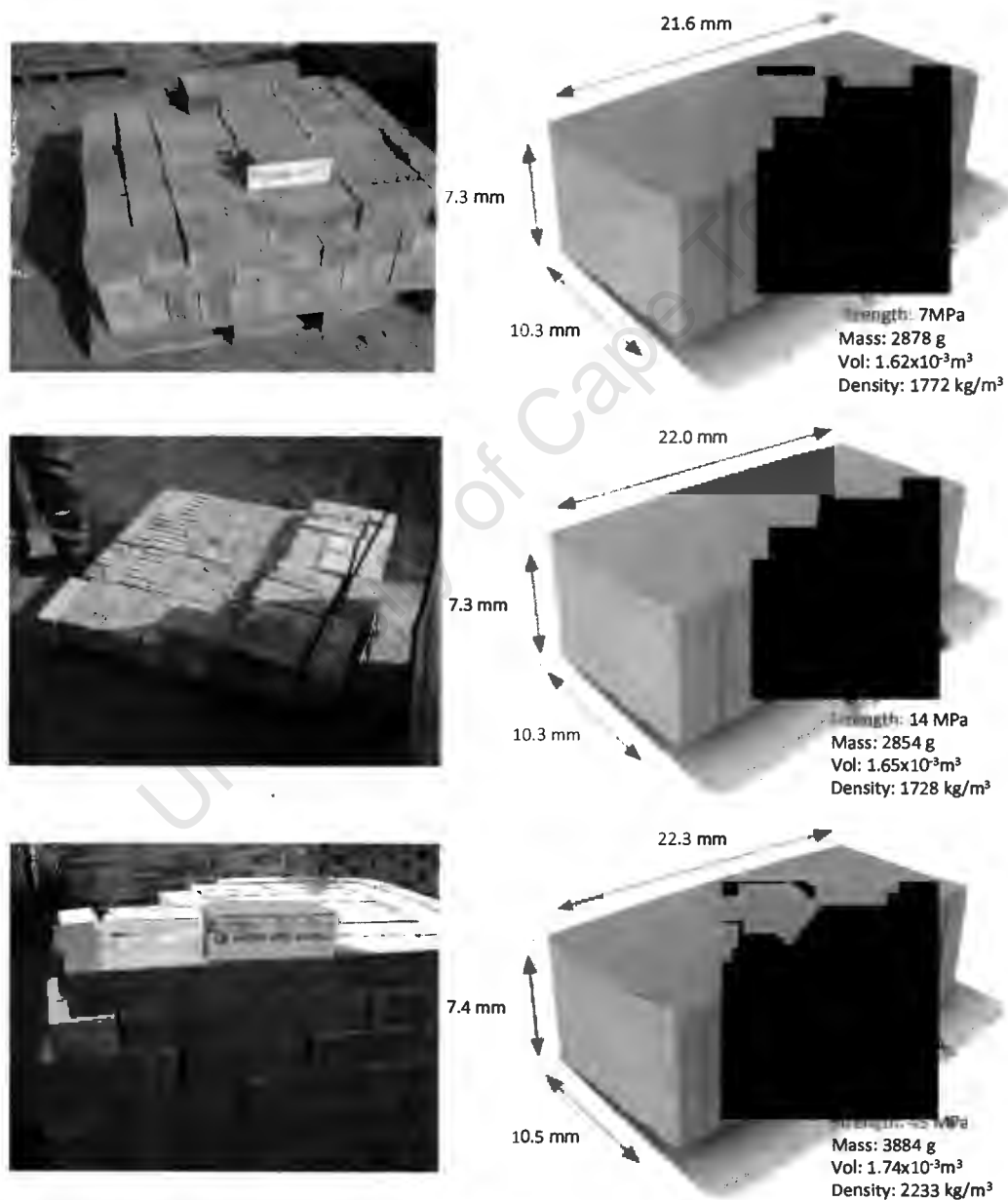


Figure 6.1: Illustrations of the virgin clay masonry materials

The Use of C&DW in Concrete in Cape Town

Virgin S3 Plaster NFP bricks are coal fired at 700-800°C to produce 7 MPa non-facing, plastering clay brick typically used for general building work that is to be plastered. This may include single storey or the upper storey of masonry constructed domestic houses, internal walling and for brick fill applications between concrete structural members. These bricks had an average mass of (10 samples) of 2878 g and a dry density of 1772 kg/m³.

Imperial NFX bricks are coal fired at 800-900°C to produce a 14 MPa non-facing, extra clay brick suitable, plastered or unplastered, for general building work. This may be in the lower storeys of multi-storey masonry structures, below damp-proof course, under damp conditions or below ground level where durability rather than aesthetics is the criterion for selection. These bricks had an average mass (10 samples) of 2854 g and a dry density of 1728 kg/m³.

De Hoop Red Saturn Paver (FBE45) is a 45 MPa masonry unit produced by coal firing at 1100°C for paving applications or for structural and load bearing purposes in face or non-face work. Generally, these products are used for larger multi-storey masonry structures or as fill between concrete structural frames that are designed for large loads, such as in basements. The increase in strength of these bricks is largely due to the use of clays with higher iron and manganese contents, which decreases porosity and therefore increased the density of these bricks (COROBRIK 2012). These bricks have an average mass (10 samples) of 3884 g and a dry density of 2233 kg/m³.



Figure 6.2: Concrete blocks used to produce concrete masonry aggregate (CMA)

The Use of C&DW in Concrete in Cape Town

The fourth virgin masonry aggregate is made up of concrete blocks. These blocks have a 14 MPa masonry strength and are referred to as the ¹²CMA sample. CapeBrick supplied the concrete masonry materials analysed in this study. Their products consist of up to 70% recycled C&D material made up of concrete and masonry construction wastes. Crushed concrete materials are preferred for concrete brick products. Waste material is put through a primary jaw crusher, a secondary gyro crusher and a primary separation phase to remove most contaminants such as plastic, paper, asphalt etc. This produces an aggregate of approximately 10 mm in size that is then used for the production of concrete bricks. Major demolition companies in the Western Cape including Skye Demolition and Ross Demolition provide these materials to CapeBrick for a nominal fee (CapeBrick 2012). This material is of interest not only because it is a readily used construction material in the Cape but also, by processing and reusing concrete bricks, insight into the potential of 2nd generation recycled material is gained.

The mixed masonry, BCA, samples are discussed next.

6.2.2 Mixed Masonry Materials

Masonry obtained from demolition activity often consists of a variety of brick types and contains varying quantities of contaminants. The presence of contaminants such mortar and plaster are thought to lower the performance of RA materials when used as aggregate in concrete (Hu et. al. 2011; Eguchi et. al. 2007; Padmini et. al. 2009).

The effects of these contaminants are gauged from 2 contaminated burnt clay brick samples in the BCA-MC¹³ and BCA-MV samples. These samples are characterised by an unknown grade of brick, as they are sourced from dumpsites, and varying quantities of mortar, plaster, paint traces and soil contamination and their surfaces.

The BCA-MC sample was sourced from the recycling stockpile at CapeBrick. Solid clay brick samples were hand picked from a stockpile for this study. This consisted of different types of clay bricks either clean or with small quantities of mortar, paint and plaster attached. Contaminants such as wood, plastic and textiles were excluded from the sample. The stockpile and the various components from which clay bricks were selected are shown in the Figure 6.3.

¹² CMA refers to concrete masonry aggregate

¹³ BCA is the reference for **burnt clay aggregate** with the suffix, "M", denoting a mixed material sample from a specific location, either Voortrekker road or CapeBrick.

The Use of C&DW in Concrete in Cape Town



Figure 6.3: Construction debris stockpile from which the BCA-MC sample was selected

The BCA-MV sample was collected from illegally dumped construction waste off Voortrekker road in Salt River, Cape Town. This sample also consisted of varying types of clay brick aggregate. These were often hollow core clay bricks with thick mortar layers still attached to the faces of the bricks. Quantities of soil contamination were also present in this sample. The origin of this sample is shown in Figure 6.5.

Figure 6.4 below shows some contaminants that were present in the BCA-MC sample. Various clay brick types, separated mortar pieces and attached paint and plaster particles can be seen on the coarse aggregate pieces.

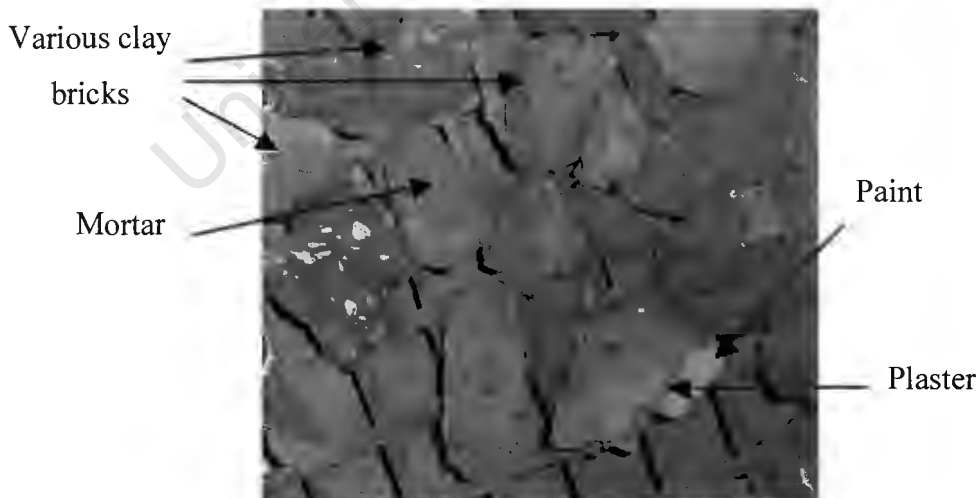


Figure 6.4: BCA-MV sample with contaminants



Figure 6.5: BCA-MV, illegally dumped rubble sample, sourced from Voortrekker Road, Salt River

6.2.3 Waste Concrete Samples

The use of commercially produced RCA products in concrete is widely recognised and documented. RCAs are often made up of various concrete grades and may have contaminants such as timber, plastics, metals and soil. This study analyses RCA materials from two waste concrete sources.



Figure 6.6: (Left) RCA-45 sample being collected from Concrete Units and being broken down by manual jack hammering before processing (Right)

The RCA-45 sample was sourced from a specialised concrete precast and prestressing company called Concrete Units based in Airport Industria, Cape Town. They provided a 45MPa concrete waste sample, made with granite coarse aggregate from precast elements in their precast yard. This sample is of known origin and design strength. This sample is shown in Figure 6.6.

The second sample is the RCA-MC¹⁴ aggregate. As with the BCA-MC sample, these materials are purchased by CapeBrick from various demolition contractors. The RCA-MC sample had been put through a commercial primary crushing stage for ease of handling and transport. This sample does not contain any contaminating material but is made up of various waste concrete sources with varying parent concrete strengths and possibly parent aggregate. This material is shown in the Figure 6.7.



Figure 6.7: (Left) RCA materials being delivered to CapeBrick for storage and use in the manufacture of concrete masonry elements. (Right) Pre-crushed RCA used in this study

6.2.4 Discussion

One of the outcomes of this study is to gauge the ease with which on-site separation practices might take place. One way in which this is achieved is by visual indicators, which may show the origin of the waste sources, as records of waste material strengths and origin are rarely available.

There is very little visual or physical difference between NFP and NFX bricks used in this study even though their compressive strengths differ. The lower grade NFP 7 MPa masonry is found to have an average density and mass that is very similar to the 14 MPa NFX masonry. Virgin masonry is not only produced to fulfil a strength requirement but also to achieve an aesthetic appeal. Masonry products are therefore extremely variable in colour and size. It was found that burnt clay masonry between the grade of 7 MPa – 25 MPa does not show significant visual or physical indications of their varying strength. The only apparent trend is that high strength bricks may be darker and denser than the lower strength

¹⁴ This refers to a recycled concrete aggregate of mixed origin sourced from CapeBrick.

The Use of C&DW in Concrete in Cape Town

bricks. This can be seen in Figure 7.1 where a higher average mass and dry density of 3884 g and 2233 kg/m³ was found for the FBE45 brick, when compared to 2854 g and 1728 kg/m³ of the NFX brick.

A visual indication of varying RCA quality is also difficult to gauge. This is especially true of the Cape region as the majority of concrete mixes employ similar materials from a few concrete and aggregate suppliers. A basic indication of strength may be shown by the use of instruments such as a Schmidt Hammer, however this only provides a broad estimation. If concrete recycling practices are to develop further in the Cape, it is important that adequate records are kept and made available to recyclers of the strength and material components within concrete elements.

6.2.5 Control Coarse Aggregate

19 mm crushed Greywacke is used as the control coarse aggregate. It is made up of quartz, feldspar, mica and iron oxides that formed through the thermal metamorphism of argillaceous rocks in the Western Cape, Malmesbury group (Kutugeza 2004). The particle shape of this aggregate tends to be elongated and flaky. This may therefore decrease the workability of fresh concretes somewhat (Grieve 2009).

6.2.6 Fine Aggregates

A 50/50 blend of Klipheuwel and Phillipi Dune sand is used in all concrete samples in this study. Both sands are natural fine aggregates used extensively in the Cape. A blend of Klipheuwel and Dune sand is used in the Cape as this creates a fine aggregate with a more continuous grading.



Figure 6.8: Phillip Dune sand and Klipheuwel crusher sand

Klipheuwel sand is a pit, natural sand having a rounded particle shape with a continuous particle distribution. It has been noted to contain significant amounts of fines is typically finer than Dune sand (Kutugeza 2004). The Klipheuwel sand used had a fines modulus of 1.36.

Phillipi Dune sand is a natural aeolian sand found in the low-lying coastal region of the Cape Peninsula. This suggests that this aggregate might be rather small in size but the Dune sands of the Cape tend to be

The Use of C&DW in Concrete in Cape Town

larger than in the interior of the country (Grieve 2009). The Dune sand use in this study had a FM of between 1.41.

The particle distribution diagram, the SANS 1083 upper and lower recommended limits and illustrations of the fine aggregate materials is shown below.

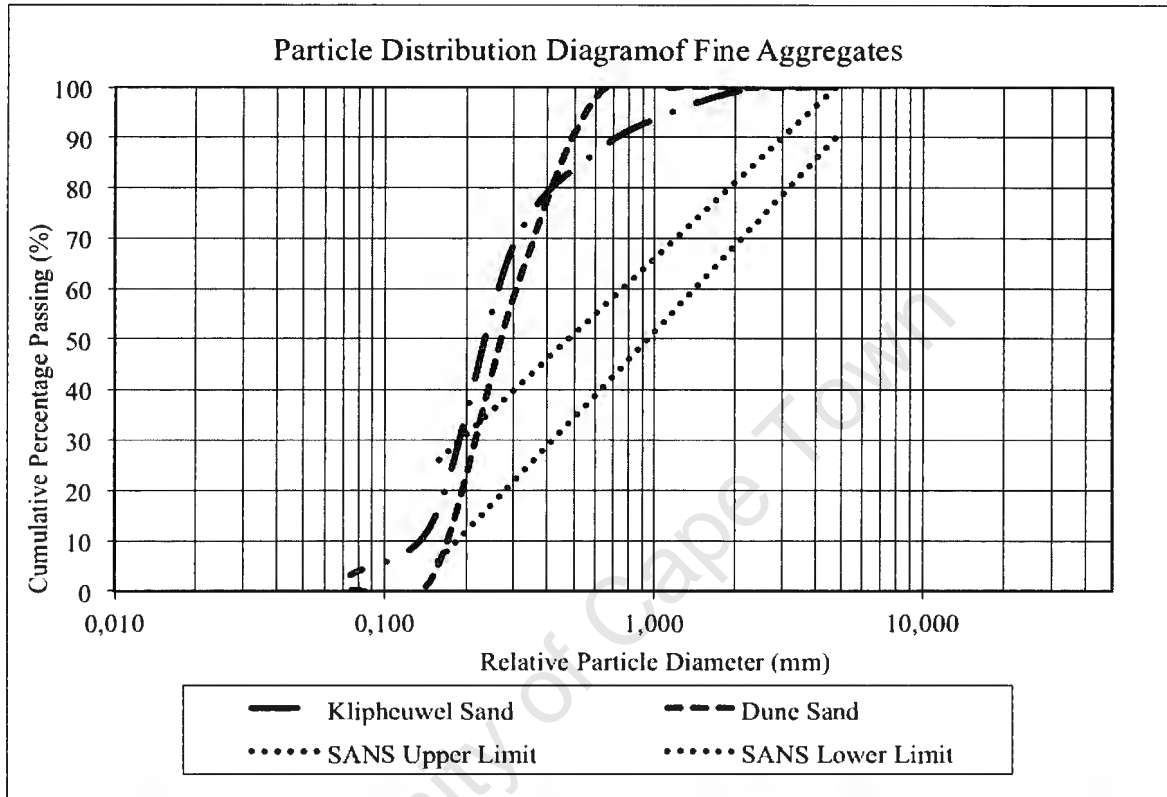


Figure 6.9: Particle distribution of Klipheuvel and Dune fine aggregates

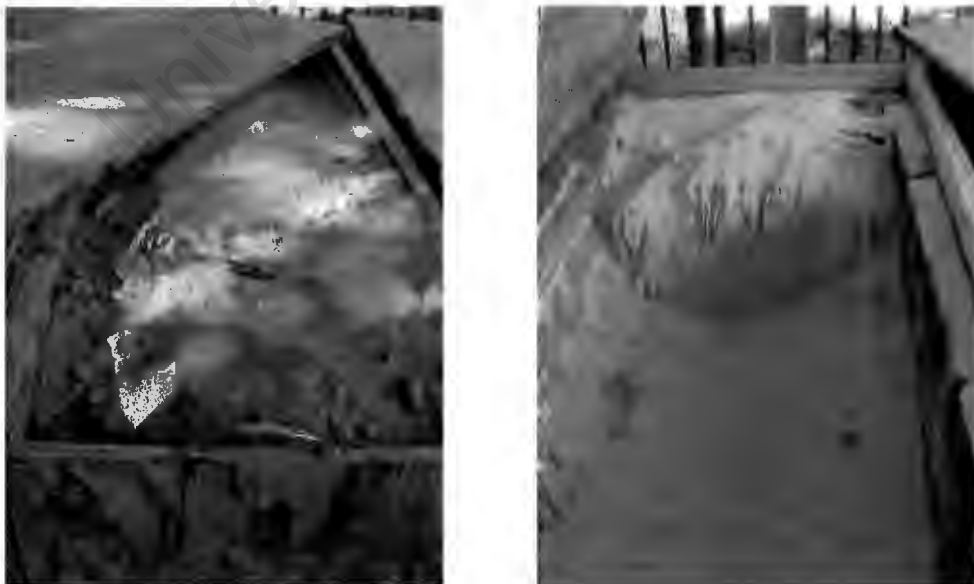


Figure 6.10: Klipheuvel sand (left) and Phillipi Dune sand (right)

6.2.7 Binder

SUREBUILD CEM II/B-M (L-S) 42.5 N binder, supplied by PPC Cement, was used for all the concrete mixes under question. This is a general-purpose cement used in the Cape for a variety of applications such as concrete, shotcrete and soil stabilization. CEM II/ B-M (L-S) 42.5 N is known a normal setting, mixed blended cement consisting of approximately 20% - 35% combined limestone and blast furnace and/or Corex slag. No admixtures were used to improve workability in fresh concrete samples.

6.2.8 Water

Ordinary tap water is used in the mixing of all concrete samples.

6.3 Physical Properties of Recycled Aggregates

6.3.1 Crushing Operation

All C&D materials were crushed with the use of small jaw crushing unit similar to small on-site mobile crushing units available on the market. Materials were crushed to the size of the control, 19 mm Greywacke coarse aggregate. After crushing all the materials were sieved through a sieve with apertures of 4.75 mm in size to remove fines. Coarse aggregate is classified as particles passing a 19 mm sieve and retained on a sieve that has apertures of a nominal size of 4.75 mm.

6.3.2 Properties of Crushed RA Material

The physical properties of the recycled aggregate materials were evaluated after the crushing procedure. The crushing procedure was evaluated to gain a greater understanding of the efficiency and practicality of small crushing operations. The properties analysed include:

- Grading and fines content
- Yield rate & material losses
- Dust content
- Chloride content
- Flakiness index
- Water absorption
- Surface saturated dry (SSD) density
- Oven dried density
- Relative density
- Bulk density
- Aggregate crushing value (ACV)
- 10% Fines aggregate crushing value (10% FACT)

Dry sieve analysis for particle distribution, fine and dust content are performed as specified by SANS 201: 2008. Flakiness index was performed as per SANS 5847: 2006. Water absorption testing followed SANS 5843: 2008. The analysis of the relative, bulk and SSD densities of the RAs in accordance with SANS 5844: 2006, the pycnometer method. Bulk density according to SANS 5845:2006. Lastly, ACV and 10% FACT tests were carried out in accordance with SANS 5841: 2008 and SANS 5842: 2006 on dry and wet samples.

Physical properties are tested to establish whether the RA materials conform to SANS 1083: Natural Aggregates – *Coarse Aggregates for Concrete*, HB 155-2002 – *Guide to the use of recycled concrete and masonry materials* and to identify properties that may negatively effect the potential of these RAs to be used in concrete.

6.4 Fresh Properties of Recycled Aggregate Concrete

The section on fresh concrete properties follows a discussion of concrete mixing procedures used to mitigate the absorptive properties of RAs as well as a break down of the multi-stage mixing procedure adopted in this study. Workability, consistency, slump and segregation are assessed by means of various trial mixes. These properties were determined using a standard slump cone apparatus as per SANS 5863-1. Due to the varying nature of the aggregates a relatively wide slump range of between 80 mm ± 20 mm is used as a benchmark.

6.4.1 Concrete Mix Designs

The Cement and Concrete Institute (C&CI) method was used as a guideline to design the concrete mixes in this study. A basic outline of this procedure is discussed below.

Concrete strengths of 20, 30, 40 MPa were chosen for all the RAs under question. Water-binder ratios for these strengths of 0.80, 0.60 and 0.80 were then established from the characteristic compressive strength charts provided by local cement suppliers. The stone content was calculated using an equation specified by the C&CI. This takes into account the coarse aggregate characteristics compacted bulk density, relative density and fine aggregate fineness modulus. These values were established from literature and tests performed. Fine aggregate content was finally calculated to make up material for each 1 m³ concrete mix.

Various trial mixes were performed to gauge the initial water content needed to create a concrete of good workability and consistency within the slump constraints. Nine mixes were prepared with only the coarse aggregate type being varied in each mix. Binder and fine aggregate were kept constant as SUREBUILD CEM 11/B-M (L-S) 42.5N and a 50/50 blend of Klipheuwel/Dune sand.

6.4.2 Concrete Mixing Procedure

A multi-stage mixing procedure is used to reduce the absorptive effects of the RAs and achieve the desired workability. This follows the following procedure.

In stage 1 all of the coarse RA is added to the mixer immediately followed by the added water. Added water is calculated as 80% of the 24-hour absorption water value of the individual RA and is added per mass of coarse aggregate. Stage 2 and 3 involve adding half the fine aggregate and cement content followed by half of the mix water, while continuously mixing. It is recommended that mixing takes place for approximately 60 seconds to ensure that the coarse RAs are properly coated in concrete paste and added water absorption has been achieved. In stage 4 the other half of the fine aggregate and cement is added. Followed by stage 5 where the remaining mix water is added and mixed in. This is a mixing phase where all the remaining concrete paste is combined, lubricating the mix and completing mixing process. This is illustrated in Figure 6.4.

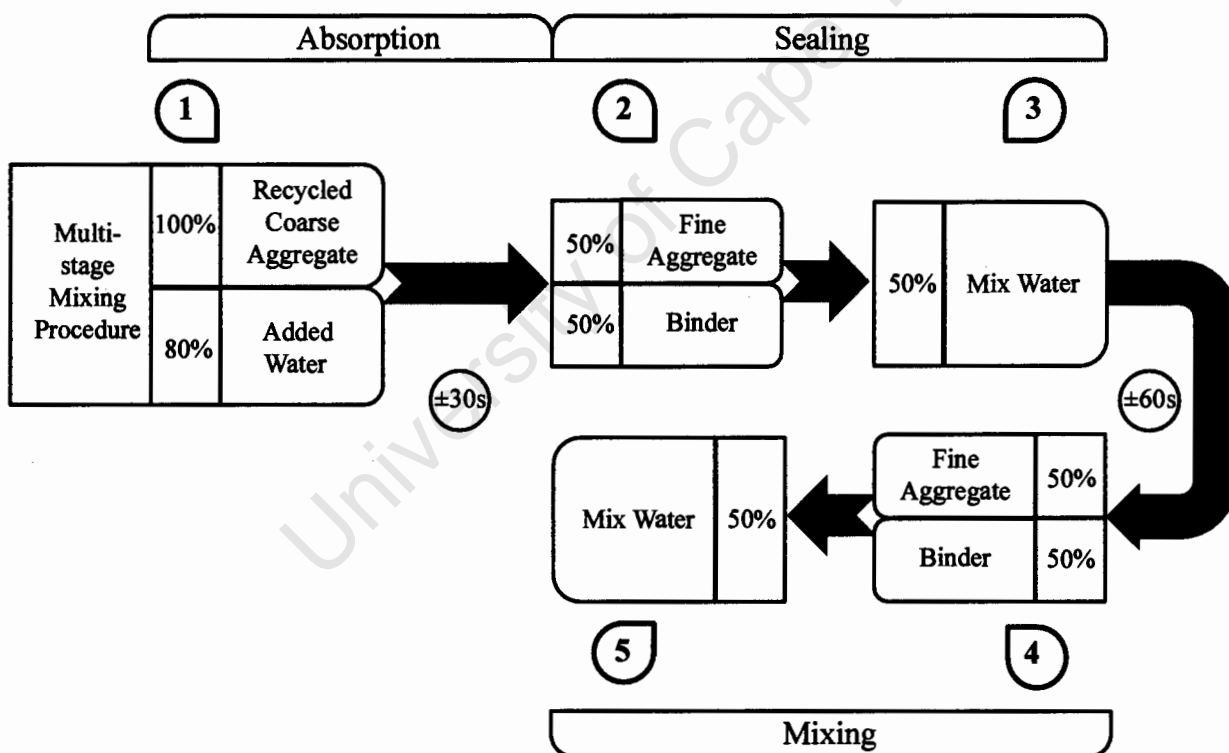


Figure 6.11: Multi-stage mixing procedure

Mix water is described as the water required to satisfy the w:b ratio and hence achieve ultimate strength of the hardened concrete. Added water is the excess water added, above the mix water, in order to satisfy the absorption requirement of the recycled aggregate so that it does not adversely influence the workability.

The Use of C&DW in Concrete in Cape Town

6.4.3 Detailed Composition of Concrete Mix Designs

Each concrete mix was prepared for a design strength of either 20, 30 or 40 MPa. This corresponds to w:b = 0.80, 0.60 and 0.50 for SUREBUILD CEM II/ B-M (L-S) 42.5 N cement.

Detailed information of each concrete mixes material proportions are shown below:

Table 6.2: Detailed Concrete Mix Design

Concrete Mix Designs								
Mix	W:B Ratio	Target Strength (MPa)	Material Content					
			Binder	Stone*	Sand	Mix Water	Free Water	Total Water
			kg/m ³			litres/m ³		
NFP	0.50	40	400	760	865	180	87	267
	0.60	30	330	760	920			
	0.80	20	280	760	965			
NFX	0.50	40	400	755	875	180	95	275
	0.60	30	335	755	930			
	0.80	20	280	755	965			
FBE45	0.50	40	400	925	750	180	58	238
	0.60	30	330	925	795			
	0.80	20	280	925	830			
CMA	0.50	40	355	915	805	160	70	230
	0.60	30	290	915	865			
	0.80	20	245	915	885			
BCA-MC	0.50	40	400	890	790	180	74	254
	0.60	30	330	890	840			
	0.80	20	280	890	875			
BCA-MV	0.50	40	400	855	780	180	77	257
	0.60	30	330	855	840			
	0.80	20	280	855	875			
RCA-45	0.50	40	400	1010	670	180	44	224
	0.60	30	330	1010	725			
	0.80	20	280	1010	760			
RCA-MC	0.50	40	400	1050	645	180	39	219
	0.60	30	330	1050	690			
	0.80	20	280	1050	725			

The Use of C&DW in Concrete in Cape Town

GREY	0.50	40	400	1075	870	180	1	181
	0.60	30	330	1075	935			
	0.80	20	280	1075	975			
*Stone values differ due to varying relative densities of the aggregate types								

6.4.4 Curing

Test specimens were cured in their moulds and covered in atmospheric conditions for 24 hours. Specimens to be tested for compressive strength were then demoulded and placed in a curing bath at a temperature of 22 – 25 °C until they were tested. After a 7 day period, the drying shrinkage cylinders were removed from the curing bath stored and stored in a controlled environment at 22 – 25 °C for the remainder of their monitoring.

6.5 Hardened Properties of Recycled Aggregate Concrete

Tests to assess the performance of the hardened concrete specimens include:

- Compressive strength
- Density
- Drying shrinkage
- Elastic modulus

The compressive strength of hardened concrete is performed on 100 mm concrete cubes at ages of 3, 7, 14, 28 and 56 days according to SANS 5863:2006. Concrete prisms with dimensions 100 x 200 mm were used to gauge drying shrinkage from an age of 7 days to 56 days as per SANS 6085:2006. Concrete cylinders with dimensions 100Φ x 300 mm are used to gauge drying shrinkage over a 56 day period. The density of 28 day samples is calculated as per SANS 6251:2006. Young's modulus of elasticity is determined as per ASTM C 469-02 at 28 and 56 days curing.

6.6 Summary of Testing Regime

A summary of the entire testing program for this study is shown in Table 6.3.

Table 6.3: Summary of testing program

Summary of Experimental Program			
Test	SANS	Experiment	W/B Ratio's
Physical Properties	201	Grading Analysis	
		Fines Content	
		Dust Content	

The Use of C&DW in Concrete in Cape Town

	5847	Flakiness Index	
	5844	Relative Density	
		SSD Density	
		Oven Dried Density	
	5845	Bulk Density	

Table 6.3 continued: Summary of testing program

		Compacted Bulk Density	
	5843	Water Absorption	
		Absorption Rate	
	Titration	Chloride Content	
	-	Yield Rate and Material Losses	
	5841	ACV (Dry and Wet)	
	5842	10% FACT (Dry and Wet)	
Fresh Properties	5862-1	Water Requirement	
		Workability	
Hardened Properties	5863	Compressive Strength (3,7,14,28 and 56 days) 100 mm Cubes	0.50, 0.60, 0.80
	6251	Density (3,7,14,28 and 56 days) 100 mm Cubes	
	6085	Drying Shrinkage (56 days) 100 x 200 mm Cylinders	
	BS 1881- 121:1983/ ASTM C 469- 02	Elastic Modulus (28 and 56 days) 80 x 150 Cylinders	

6.7 References

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7 Physical Properties of Recycled Aggregates

7.1 Introduction

Commercial RAs are extremely variable in composition and the potential for their use is often stifled by the varying quantities of C&D materials that are seen as contaminants. On-site C&D waste recycling practices offer the opportunity to separate materials and then process and utilise these materials in various applications, according to their physical properties and effects on fresh and hardened concrete. This approach is mirrored by international RA standards, such as EN 12620 and HB 155-2002, which generally define RAs into streams with varying compositions. These standards allow for the use of RAs under a range of exposure classes and in multiple applications.

This study makes use of the current SANS 1083:2006 - *Aggregates for use in concrete*, which is the recognised standard for aggregate production and use in South Africa, and the Australian HB 155-2002, *Guide to the use of recycled concrete and masonry materials*, to compare and gauge the physical properties of various RAs. SANS 1083:2006 has yet to follow a direction in which aggregates are defined according to their varying properties. This does not promote the use of RAs as they often do not conform to this recognised Standard and therefore are seen as unfit for use in concrete.

Recycled aggregates (RAs) have a significant effect on fresh and hardened concrete as aggregate materials consists of approximately 70% of the volume and 80% of the mass of concrete. Investigating the properties of various RAs is therefore of paramount importance if civil engineers are to use RA concrete, which fulfils design requirements such as being workable in its fresh state and strong and dimensionally stable in its hardened state. The aim of this chapter is therefore to make reference to the current SANS 1083 and the HB 155-2002 guidelines to assess the processing of C&D materials and physical properties of the resultant RA materials. This is to identify the properties in which single component RAs differ to natural aggregates in order to more fully understand these materials. This may facilitate greater on-site recycling practices and recycled material use as well as shed light on the properties of the various components within the C&DW stream in the Cape.

This chapter begins with an outline of all the RA materials, including virgin masonry, mixed masonry and recycled concrete aggregates covered by this study. The crushing and sieving procedures used to acquire 19 mm coarse aggregate for use in concrete are then discussed. This is followed by a comparison of the resulting particle distribution, fines and dust contents of the RAs. These parameters are analysed both after initial crushing and after the sieving procedures. The yield and material losses

experienced during this processing are also briefly discussed to judge the economy of these actions. Further properties in chloride content, particle shape in flakiness index and water absorption are then overviewed. Density characteristics in surface saturated, oven dried, apparent relative and bulk density are then discussed. Finally, the strength of the various RAs are analysed in both a wet and dry 10% FACT and ACV tests. A summary of the results of the testing is shown at the end of this chapter.

7.2 Recycled Aggregate Materials

C&DW can consist of multiple material components including brick, concrete, plaster, mortar, ceramics, stone, asphalt, plastics, woods, paper and soil. An important distinction needs to be made between upcycling, recycling and down-cycling. Upcycling refers to using waste materials for a higher-grade application than what was initially required. This could take place when engineering grade bricks previously used for paving are cleaned and utilised in a structural application. Recycling refers to using waste materials in a similar application as was previously used. This could entail reusing precast concrete components or cleaning and reusing bricks. Downcycling should be the last resort to managing waste. Crush C&DW into aggregate for varying applications can be described as downcycling.

This study concentrates on the downcycling of two C&D materials, namely masonry and waste concrete. These materials are processed to yield eight RA samples that are thought to be a good representation of selected materials within the C&DW stream in the Western Cape. One recognised natural aggregate is chosen as a control. These materials are described below:

- Masonry material
 - Virgin 7 MPa, stock/general purpose, coal fired plastering clay brick, referred to as ¹⁵NFP
 - Virgin 14 MPa, stock/general purpose, coal fired non-plastering/plastering clay brick, referred to as NFX
 - Virgin 45 MPa coal fired, clay engineering/paving brick, referred to as FBE45
 - Virgin concrete masonry block and brick aggregate, referred to as CMA
 - Two mixed burnt clay brick aggregates contaminated with mortar and/or plaster, referred to as the BCA-MC and BCA-MV samples

- Concrete material

¹⁵ Burnt clay brick abbreviations, NFP, NFX and FBE45 follow recognised industry notations. i.e. FBE45 – facing brick, engineering strength 45 MPa.

The Use of C&DW in Concrete in Cape Town

- 45 MPa waste concrete, referred to as RCA-45
- Mixed waste concrete, referred to as RCA-MC
- Natural aggregate
 - Greywacke stone

Further details on these materials are described in section 6.2.

The following section discusses the approach used to process the RAs into coarse aggregates.

7.3 Processing - Crushing and Sieving

The scale of a crushing operation and the crushing equipment used to process C&D materials has a significant effect on the properties of RA products and can produce very different samples, even from homogeneous materials (Padmini et. al. 2009; Eguchi et. al. 2007).

A larger, commercial operation usually consists of primary, secondary and/or tertiary crushers. The primary crusher is generally used to break down larger pieces of waste into manageable sizes ('fist size'). Secondary and/or tertiary processes are used to achieve a specific material size and aggregate shape. These larger scale operations are known to pulverise weaker masonry or concrete waste. This may result in a large quantity of fines and/or dust particles and a lower yield of aggregate materials. Smaller on-site operations can consist of only primary crushing with the use of smaller, mobile jaw crushers or manual processing with the use of a large labour force with hammers or chisels. Smaller operations produce more variable materials.

Sieving is done to acquire certain material sizes and remove fines or contaminants. This can be done once, or through secondary operations that seek to obtain multiple particle sizes or blended particle of various diameters. In mechanised operations, mechanical vibrating grids or screens are used to sieve materials often in conjunction with washing, air and magnetic separation. In on-site operations this can also be achieved by manually shaking grids.

7.3.1 Crushing and Sieving Procedure

This research seeks to mimic small, on-site crushing operations. Therefore the crushing procedure was carried in two phases namely splitting and crushing.

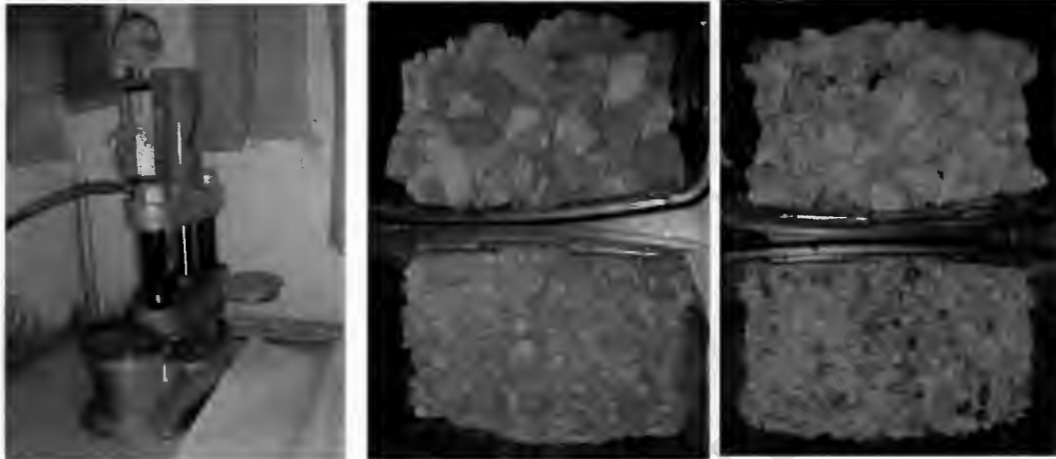


Figure 7.1: Hydraulic splitter (Left). Split and crushed clay brick and concrete materials

All material was initially split into manageable pieces with a hydraulic splitter. This usually involved splitting virgin bricks into approximately 6 pieces. Other materials were split into fist-sized particles. The hydraulic splitter and split and crushed materials are shown in Figure 7.8.

Once materials were split, they were hand fed into the crusher. The crusher jaws were adjusted to produce 19 mm materials by feeding 19 mm Greywacke stone through the jaws until the stone was not affected. The crusher and materials within the crusher mouth are shown below in Figure 7.9.

Manual sieving was used in this study. A large stainless steel grid with apertures of 4.75 mm was constructed to manually vibrate the crushed materials. Materials were poured over the grid and manually shaken for approximately 1 minute above a waste bin that collected the fines. This was followed by approximately 30 seconds of shaking to discharge the usable materials (greater than 4.75 mm in diameter) into a collection bin. See Figure 7.10.

The Use of C&DW in Concrete in Cape Town



Figure 7.2: Fixed jaw crusher (Left). Figure showing FBE45 material being fed into jaw crusher mouth (Right)



Figure 7.3: The manual sieving procedure. (Top figures) Materials being loaded and shaken to remove fines. (Bottom figures) Coarse aggregate being shaken into a storage bin

7.3.2 Discussion

By splitting the materials into manageable sizes and hand feeding the crusher, choke feeding was avoided. Choke feeding refers to crushing aggregates with a completely filled crushing chamber. Guimares et. al. (2006) comments that choke feeding promotes particle interaction and may result in more rounded or cubic aggregates but may also drastically increase fines production.

Crushing was carried out with a small, fixed jaw crusher. This machinery is similar to some small mobile units that can be used to process demolition waste on-site. Particles that are fed slowly into a

The Use of C&DW in Concrete in Cape Town

crusher mouth have minimal contact area between each other and are more likely to be point loaded and loaded at opposite poles, which results in more flaky particles. Minimal dust was produced during processing as a result of the small crushing equipment and feeding approach discussed above.

Padmini et. al. (2009) state that the crushing characteristics of RCA are largely dependant on the size of NA used in the parent concrete and strength of the parent concrete. This is because the smaller the size of parent aggregate used in a parent concrete, the higher the surface area available for mortar to adhere to when the parent concrete is crushed into RCA. Also, as parent concrete strength increases, so does the size and quantity of both attached and larger free mortar pieces in coarse RCA, due to the stronger bond between materials in the parent concrete matrix.

From the results of this study it seems that crushing characteristics are not as dependent on the strength of the parent mortar but on the scale and type of crushing equipment. This is seen in the distinction between the RCA-MC and RCA-45 materials. Larger crushers pulverise and remove large quantities of weak concrete mortar from the surface of RCAs. This is seen in the RCA-MC sample that was commercially crushed before being jaw crushed again in this study. The smaller equipment used in this study split materials along their weakest bonds reducing the fines quantity but increasing the quantity of attached mortar as is seen in the RCA-45 sample. This shows that the crushing characteristics of hardened concrete are not significantly affected by grade or quality of original concrete in small primary crushing operations. Similarly, larger layers of mortar were often removed from the masonry to produce larger plate-like 'mortar aggregate' pieces. This is the weakest bond in these mixed masonry materials.

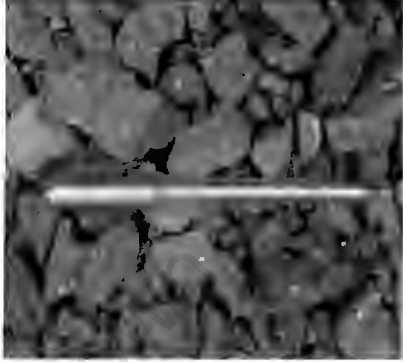
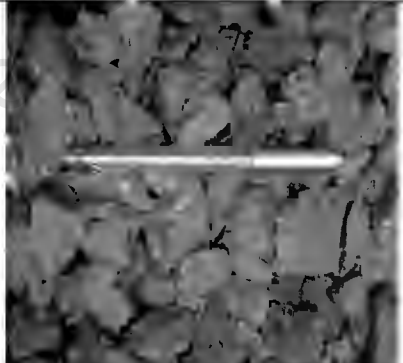
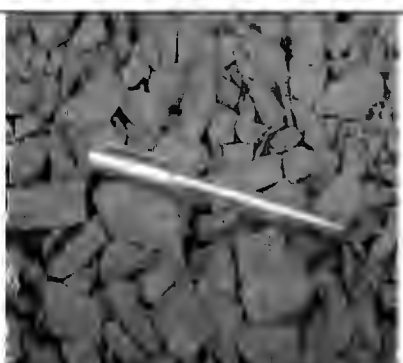
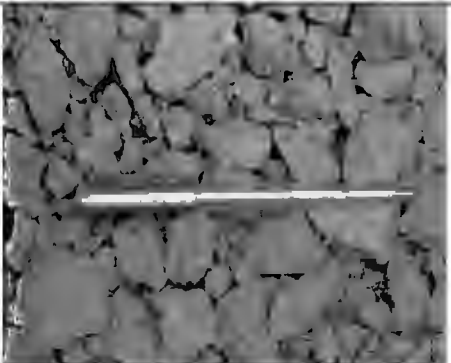
After crushing, the materials were sieved to acquire coarse aggregates for use in concrete. The manual sieving procedure is far more vigorous than using a vibrating plate to sieve, as is done in a laboratory. It was very efficient in removing fines material and is thought to be more efficient in removing flaky particles.

7.3.3 Summary of Aggregate Materials

All tabulated experimental results are referred to in order of virgin clay brick masonry, virgin concrete masonry, mixed clay brick masonry, recycled concrete and Greywacke stone. A summary of each material's reference, source, description and grade is shown in Table 7.1.

The Use of C&DW in Concrete in Cape Town

Table 7.1: Summary of RA materials

Summary of RA Materials					
Material	Name	Source	Description of Material	Grade/Comp. Strength (MPa)	Illustration
Virgin clay brick	NFP	Corobrik	Stock/general purpose, virgin burnt clay brick masonry aggregate	7	
	NFX	Corobrik	Stock/general purpose, virgin burnt clay brick masonry aggregate	14	
	FBE45	Corobrik	Engineering/paving, virgin burnt clay brick aggregate	45	
Virgin concrete brick	CMA	CapeBrick	Virgin concrete masonry aggregate	7-14	

The Use of C&DW in Concrete in Cape Town

Table 7.1 continued: Summary of RA materials

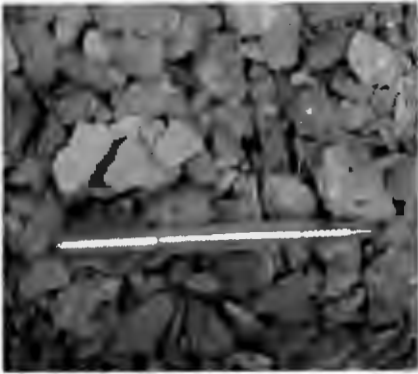
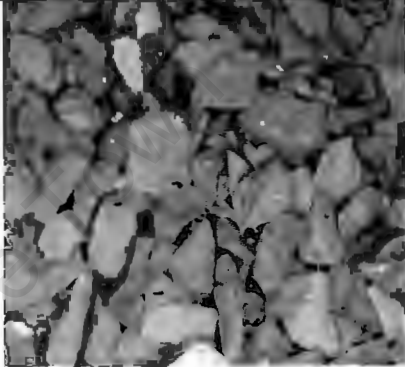
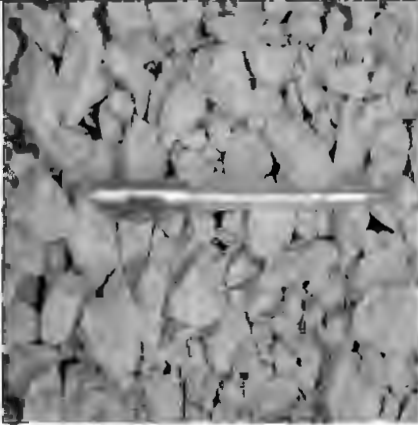
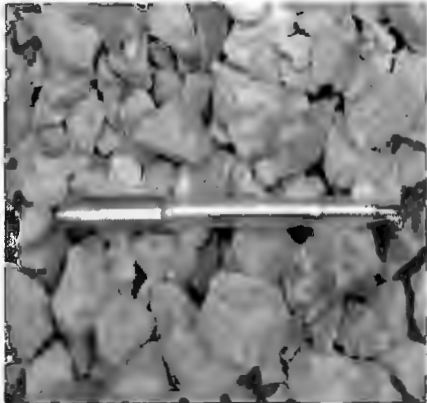
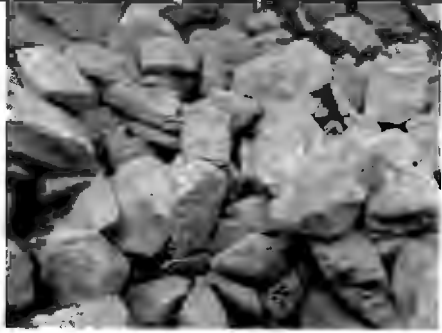
Mixed clay brick	BCA-MC	CapeBrick	Burnt clay brick aggregate, mixed with mortar, plaster and soil contamination, CapeBrick sample	Unknown /Variable	
	BCA-MV	Illegally dumped rubble. Voortrekker Road, Koeberg Interchange Bridge	Burnt clay brick aggregate, mixed with mortar, plaster and soil	Unknown /Variable	
Recycled concrete	RCA-45	Concrete Units	Recycled concrete aggregate, 45MPa precast concrete, granite virgin aggregate	45	
	RCA-MC	CapeBrick	Recycled concrete aggregate, mixed concrete and virgin aggregate	Unknown /Variable	

Table 7.1 continued: continued: Summary of RA materials

Stone	Greywacke	Peninsula Quarry (AfriSam)	19mm Greywacke stone (Malmesbury Shale)	-	
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7.4 Grading

Grading refers to the distribution of various particle sizes within a material. Particle size distribution is closely related to the crushing process and crushing machinery used to create the aggregate materials. Grading, more so with fine aggregates, has an impact on the workability, cohesiveness and bleeding of concrete (Grieve 2009). Grading analysis provides insight into the proportions of materials that may be used in a concrete mix. It also provides insight into what coarse, fine aggregate and/or extender could be selected in order to achieve a concrete with a continuously graded aggregate quantity. Continuous grading is known to result in less segregation in wetter mixes and less sensitive fresh concrete to slight changes in water content. This is advantageous when uniform workability is required (Kutugeza 2004).

This section compares the particle distribution before and after sieving to establish the effectiveness of the manual crushing and sieving procedure. It also gauges whether the RAs conform to SANS 1083:2006 recommendations for stone of 19 mm in size and the possible effect of the particle distribution on fresh and hardened concrete.

7.4.1 Test Procedure

Dry grading analyses were carried out according to SANS 201:2006 – *Sieve Analysis, Fines Content and Dust Content of Aggregates*.

7.4.2 Results and Discussion

Materials that have been through primary crushing only are referred to as ‘crushed’ materials. RAs that have had their fines removed by manual vibration through a 4.75 mm aperture sized sieve, are referred to as ‘sieved’ materials.

SANS1083:2006 prescribes stone size limits for certain sized aggregates. The shaded vertical bands in Figure 7.11 illustrate the recommended particle distribution for various aggregate sizes. The most commonly used coarse aggregate for concrete is 19 mm single-sized (gap graded) stone. The 19 mm

The Use of C&DW in Concrete in Cape Town

stone should fall within the purple band in Figure 7.11. These recommendations are prescribed because stone is typically purchased by nominal size in South Africa and then be blended in a mixer to achieve a desired grading. SANS 1083:2006 permits the use of aggregates that fall outside the suggested limits provided sufficient testing has been undertaken to show suitability for a specific purpose (Grieve 2009).

Figure 7.12 and 7.13 show the particle distribution of each RA after crushing (no removal of fines) has taken place. The dashed lines indicate the lower and upper particle distribution boundaries for 19 mm stone for use in concrete, as recommended by SANS 1083:2006. The red, vertical, dashed line indicates a relative particle size of 4.75 mm. This is to show particle sizes that are accepted as coarse aggregate.

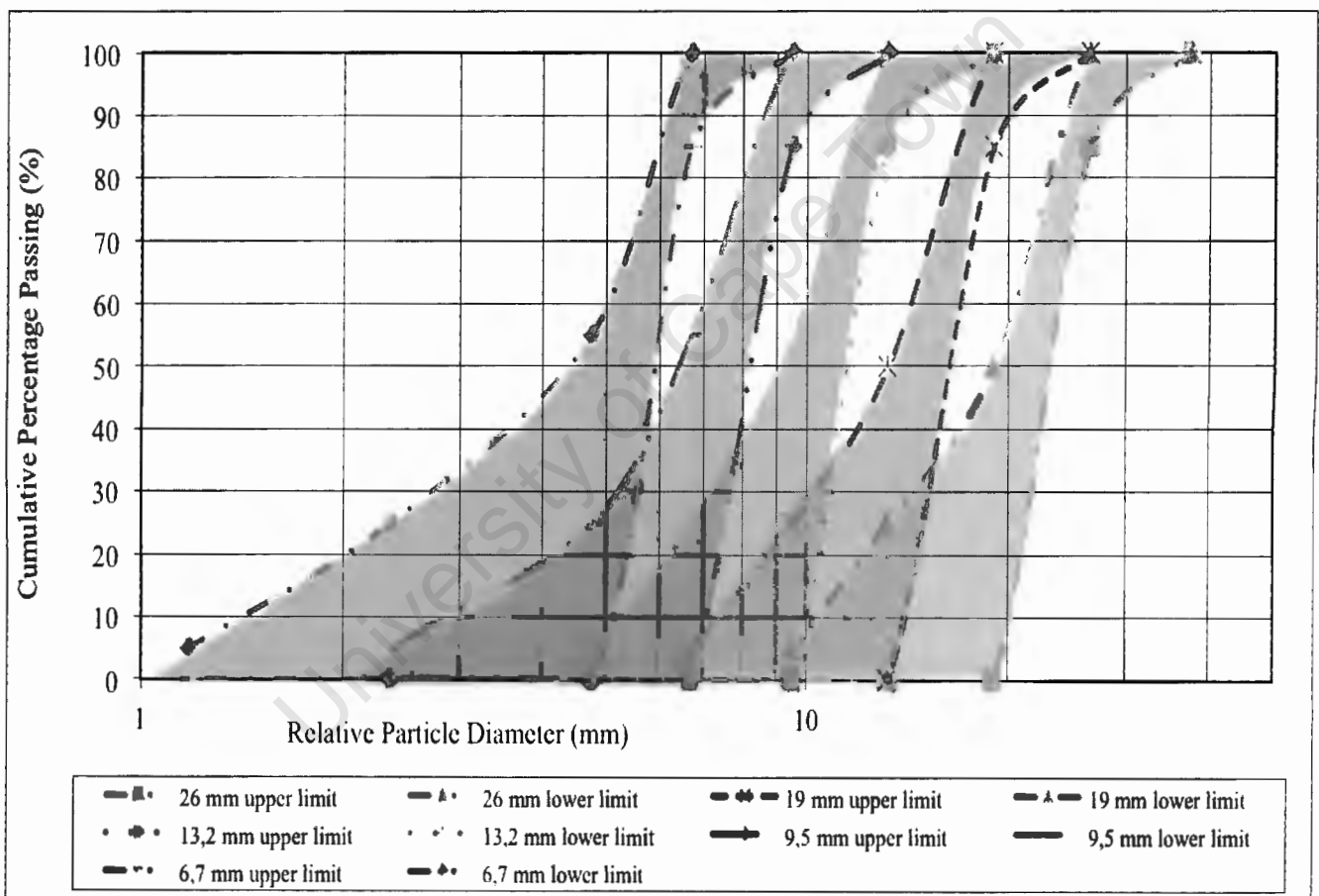


Figure 7.4: Coarse aggregate particle distribution boundaries as prescribed by SANS 1083: 2006

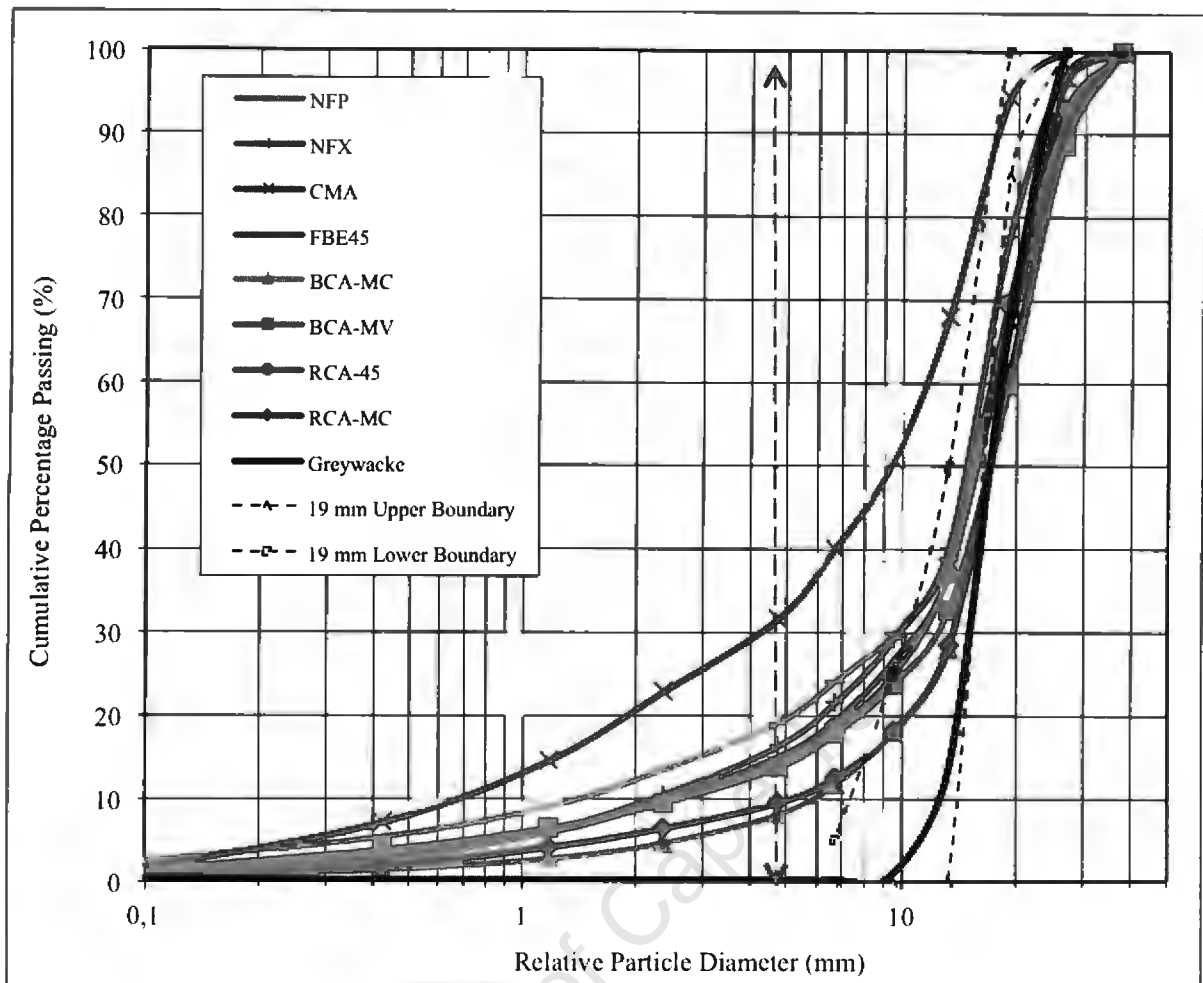


Figure 7.5: Particle distribution of RAs after crushing (vertical line represents 4.75 mm boundary)

The majority of samples are continuously graded before they were sieved with the weaker masonry materials having a greater number of fines than the recycled concrete aggregates. CMA has the most continuous particle distribution with the largest quantity of finer particles. The study by Hu et. al. (2011) also yielded a wide band of particle sizes after small scale jaw crushing however, he found that recycled masonry aggregates, in particular the concrete masonry aggregates, to be coarser than the natural aggregates. This is contrary to the trend found in this study.

Results show that as the strength of the masonry aggregate increases, so does the coarseness of its particles. This is illustrated by the particle distribution curves in Figure 7.12. It can be seen that the stronger virgin clay masonry aggregates lie further to the right of the Figure.

Figure 7.13 shows the particle distribution of the RAs after sieving. The red, vertical, dashed line indicates the boundary for 4.75 mm relative particle diameter and the black dashed line the SANS 1083 19 mm classification of coarse aggregate. The effectiveness of the manual sieving at removing fines can be seen by the reduced quantity of material that falls to the left of this red line in Figure 7.13 when compared to Figure 7.12. It can be seen that none of the RAs and control aggregate fall strictly within

the range of the 19 mm SANS standard. The size limits recommended by SANS 1083 are extremely narrow (single-sized) and while most of the samples fall within the finer fraction prescribed, they contain a higher proportion of larger 26.5 mm particles. The SANS 1083 requirements are applied more strictly to fine aggregates than coarse aggregates. As mentioned stone of nominal size is often preferred in South Africa. However this single-sized stone commonly contains fractions that are undersized rather than oversized (Grieve 2009).

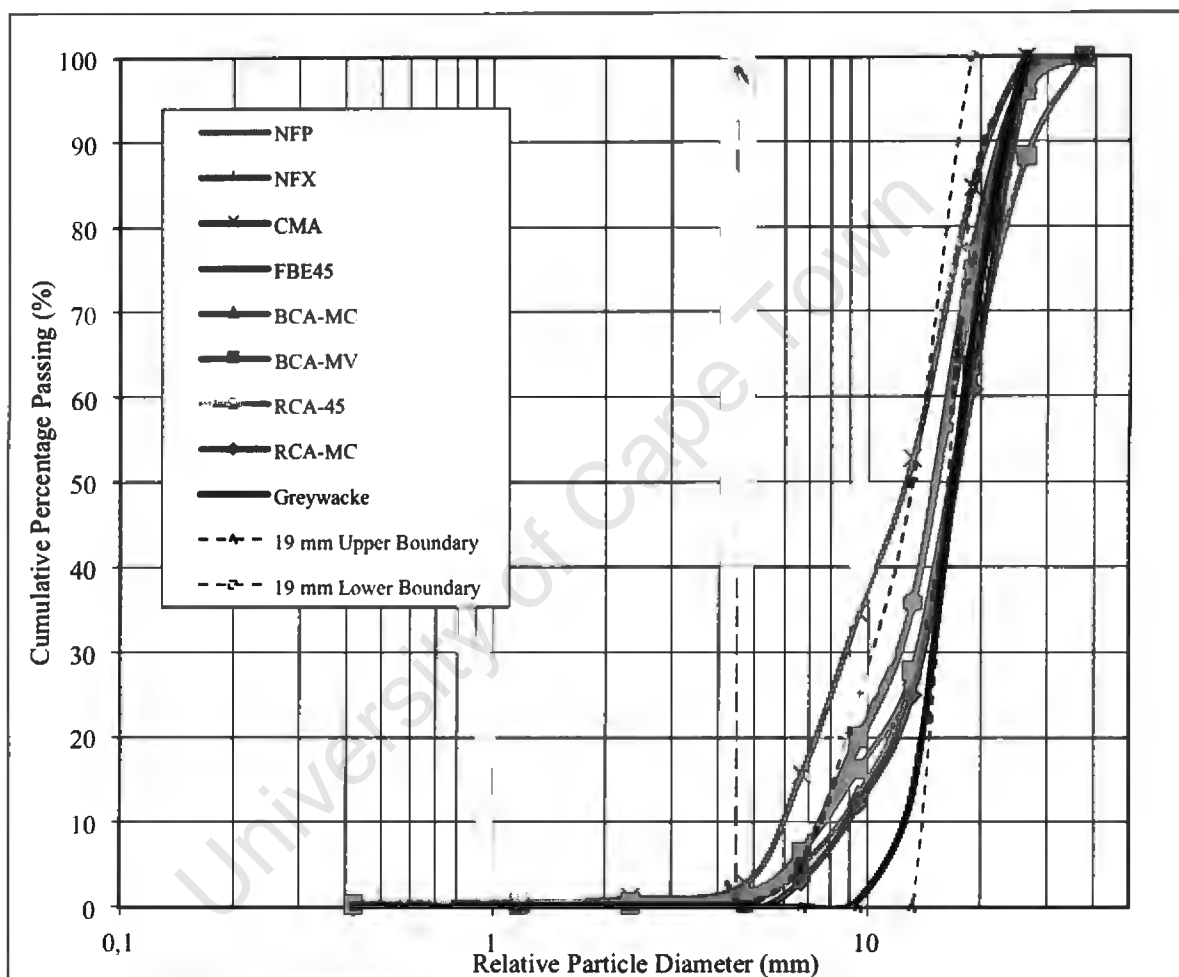


Figure 7.6: Particle distribution of coarse RAs after sieving (fines removed; vertical line represents 4.75 mm boundary)

The vigorous manual sieving proved to be very effective. The elongated and rough particles tended to get trapped during laboratory sieving on a vibrating plate. With manual shaking, greater quantities of fine materials are dislodged and fall through the sieve.

The sieved distribution curves of the RAs under question can be described as narrow or single-sized. As discussed this is common with most commercially produced stone in South Africa. The RAs show higher quantities of larger materials but these do not deviate excessively from the control Greywacke aggregate except for the BCA-MV sample, which contains the highest quantity of larger particles. This

may be due to the hollow nature of the BCA-MV clay bricks, which contained larger pieces of angular, 'column' shaped aggregate particles after being crushed.

Narrowly graded stone has some advantages including greater sensitivity to changes in water content, greater response to vibration and less likelihood of particle interference. Larger stone sizes also create less water demand (Grieve 2009). However, reduced water demand from specific grading is unlikely to be felt with the RAs under question, as they have extremely high absorption properties when compared to commercial stone.

7.5 Fines Content

Fines content refers to materials that are less than 4.75 mm in size. This parameter is important as excessive fines, with the addition of fine aggregate, greatly affects water demand, workability, cohesiveness and bleeding of fresh concrete (Grieve 2009). It is also of relevance to this section as coarse aggregate is defined as materials greater than 4.75 mm in diameter and the effective removal of this fraction through manual processing is under question.

This section compares the fines content before and after sieving to establish the effectiveness of the manual crushing and sieving procedure.

7.5.1 Test Procedure

Dry grading analyses were carried out according to SANS 201:2006 – *Sieve Analysis, Fines Content and Dust Content of Aggregates*.

7.5.2 Results and Discussion

Fines content results are shown in Table 7.2.

Table 7.2: Comparison of Fines and Dust content before and after sieving

Recycled Aggregate	Fines Content (% Mass)		
	<i>Crushed</i>	<i>Sieved</i>	<i>Difference</i>
NFP	24.2	6.7	17.5
NFX	21.6	6.4	15.2
FBE45	19.4	6.3	13.1
CMA	40.2	15.7	24.5
BCA-MC	11.8	4.9	6.9
BCA-MV	17.8	6.5	11.3
RCA-45	18.5	6.3	12.2
RCA-MC	9.5	3.8	5.7
Greywacke	0.0	0.0	0.0

The Use of C&DW in Concrete in Cape Town

In the virgin masonry materials the fines content suggests that fines are related to virgin strength. This is seen with the weakest aggregate, NFP, which contains the most fines, followed by the NFX. The strongest FBE45 aggregate contains the least fines. This relationship is not proportional to virgin strength as the fines contents differ but not by substantial quantities. This shown in the FBE45 having a fines content of 6.30% and the NFX 6.36% even though their virgin strength differs by over 30 MPa.

CMA is brittle and weak. This can be seen in the high fines content of 40.2% and 15.8% after crushing and sieving. Abrasive sieving or handling procedures may generate fines in the CMA sample.

The BCA-MC has a lower fines content than the BCA-MV, 11.8 % and 17.8% respectively. This is trend is repeated with values of 4.9% and 6.5% after sieving. This may be attributed to the larger quantity of weak mortar present on the BCA-MV sample, which may be crushed more readily during the mechanical crushing operations.

In the recycled aggregate samples, the fines content is higher in the RCA-45 sample than in the mixed RCA-MC sample, 6.3% and 3.8%. This is thought to be a result of the initial processing of these two RAs. The RCA-MC had already been put through a commercial crushing operation. This resulted in the RCA-MC having more concrete paste removed from the virgin stone surface than the RCA-45 aggregate. This is illustrated in Figure 7.14 where the red arrows show the exposed virgin rock of the RCA-MC sample on the left compared to the RCA-45 sample on the right.

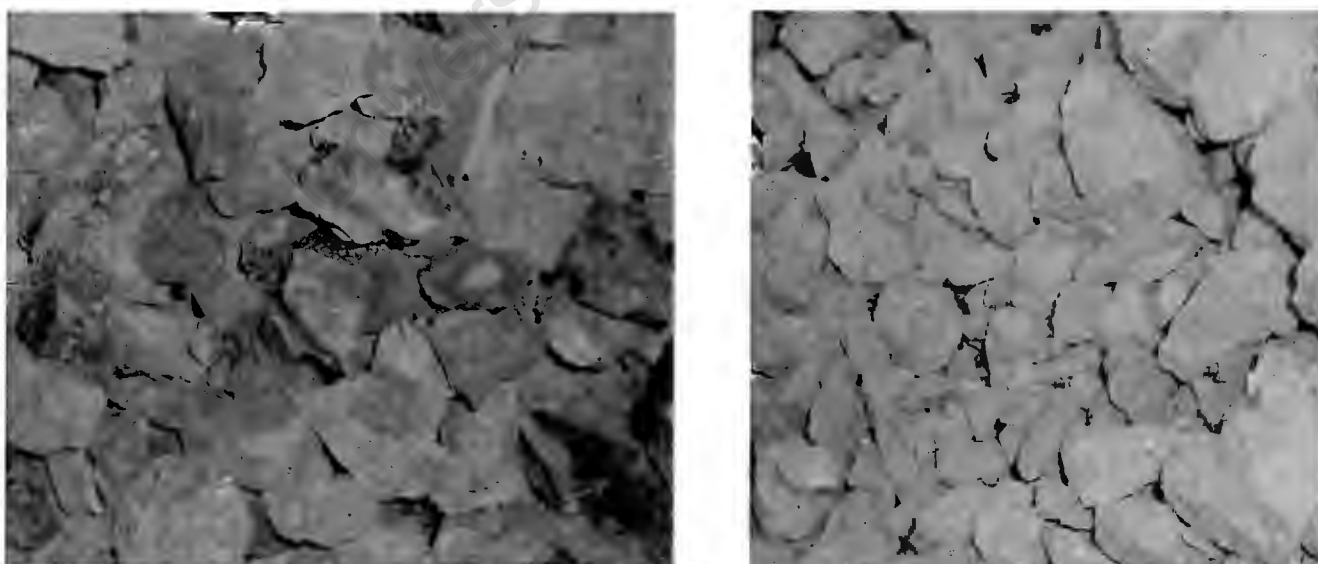


Figure 7.7: RCA-MC (Left) and RCA-45 (Right) aggregates. The red arrows show the exposed stone faces of the RCA-MC aggregate due to commercial crushing operation

7.6 Yield Rate & Material Losses

It is useful to get an indication of the efficiency of the small scale processing actions that were undertaken in this study. The potential of C&D waste materials to be processed and used as coarse RA can be gauged by a simple yield rate and material loss quantity analysis.

Yield rate refers to the percentage of usable coarse RA, 19 mm – 4.75 mm, acquired from a batch of C&D waste through the crushing and sieving actions described above. Material losses describe the fines removed from sieving the materials in order to acquire a coarse aggregate fraction. This material would have to be disposed of or reused possibly for landscaping or as fill material. This is assuming minimal loss of usable coarse materials during processing.

These variables give an indication of the feasibility of using manual labour and small crushers to create usable coarse RAs on-site, and also the potential waste material that would have to be dealt with from the processing of these materials.

7.6.1 Analysis Procedure

Yield rate is calculated as follows:

$$\text{Yield (\%)} = (M_{\text{aggregate} > 4.75 \text{ mm}} / M_{\text{crushed aggregate}}) \times 100$$

Equation 1: Yield of crushed aggregate

Where: $M_{\text{crushed aggregate}}$ is the mass of aggregate after initial crushing

$M_{\text{aggregate} > 4.75 \text{ mm}}$ is the equivalent mass of coarse aggregate greater than 4.75 mm after sieving.

7.6.2 Results and Discussion

The results of the yield rate analysis are shown in Table 7.3.

The basic jaw crushing and manual sieving procedure produced an average yield of 82% of the mass of the materials under question. Yield ranges from 71% in the CMA to 90% in the RCA-MC. Material losses do not vary excessively with virgin material strength. This is illustrated in the small difference between the virgin clay masonry aggregates when compared to each other, 19% - 16%, as well as the RCA materials, 10% -15%.

The largest factors contributing to low yield appears to be mortar content. This is seen in the difference in yield between the BCA-MC, 86%, and BCA-MV, 78%, as well as the RCA-MC, 90%, and the RCA-45, 85%. The BCA-MV and RCA-45 contained increased quantities of mortar, had increased fines and therefore lost more mass during sieving.

Table 7.3: Yield rate and material losses to acquire coarse aggregate materials.

Recycled Aggregate	Yield Rate	Losses
	(% Mass)	
NFP	81	19
NFX	84	16
FBE45	84	16
CMA	71	29
BCA-MC	86	14
BCA-MV	78	27
RCA-45	85	15
RCA-MC	90	10
Average	82	18

The largest material losses of 29% were experienced by the CMA sample. This is due to the weak nature of this materials' matrix, which consists of compacted cement, sand and brick particles. The largest yield is that of the RCA-MC sample which had undergone preliminary commercial crushing before being received in this study

7.7 Dust Content

Dust content is defined as materials that pass a sieve with apertures of less than 0.075 mm. Similarly to fines content, dust content affects water demand, workability, cohesiveness and bleeding of fresh concrete. SANS 1083:2006 requires a dust content of below 2% for coarse aggregates.

This section overviews whether to aggregates conform to the SANS dust content limits as well as the effectiveness of removing dust after crushing and sieving.

7.7.1 Analysis Procedure

The test procedure is as described in Section 7.1. – *Grading*.

7.7.2 Results and Discussion

Table 7.4 shows the reduction in dust content from crushing to manual sieving. The large reduction shows that manual sieving is effective in removing dust from RAs.

The Use of C&DW in Concrete in Cape Town

Table 7.4: Dust content of RAs after crushing and sieving

Recycled Aggregate	Dust Content (% Mass)		Max. Dust Content (%)	
	<i>Crushed</i>	<i>Sieved</i>	SANS1083:2006	HB 155-2002
NFP	3.02	1.19	2	2
NFX	2.30	1.59		
FBE45	1.04	0.98		
CMA	1.04	1.10		
BCA-MC	1.25	0.81		
BCA-MV	1.69	0.84		
RCA-45	1.19	0.95		
RCA-MC	0.83	0.76		
Greywacke	-	0.01		

Similarly to fines content, dust content is highest in the weaker masonry aggregate materials. The NFP and NFX materials have the highest dust contents of 1.19% and 1.59%. The aggregate derived from the highest strength brick, the FBE45 aggregate, has the lowest dust content of the masonry materials at 0.98%. When comparing the BCA-MC and BCA-MV materials, the BCA-MV has a higher dust content of 0.84% when compared to a dust content of 0.81% of the BCA-MC. The RCA-45 sample also has a higher dust content of 0.95% compared to 0.76% of the RCA-MC sample. Both these relationships are attributed to the higher mortar content on the BCA-MV and RCA-45 samples.

Figure 7.15 gives a good visual indication of the composition of various RAs. The varied clay type with increased feldspar, iron and/or manganese content of the FBE45 RA is seen in the darker red colour of this material, when compared to the NFX and NFX RAs. BCA-MV has a brown appearance showing the increased mortar content when compared to the BCA-MC materials. The darker red colour of the BCA-MC RA might also indicate a higher virgin brick strength as is with the FBE45 sample. The RCA-MC can be seen to have a slightly darker appearance to that of the RCA-45. This shows a reduced concrete mortar content when compared to the very grey RCA-45 sample.

The low dust content values are thought to be a result of the small crushing machinery used and the manner in which the machinery was operated. As discussed, larger crushers are known to pulverise weaker materials such as masonry and weak concrete. By using a small jaw crusher that is fed in manually, far less fines material is produced. Sieving operations taking place outdoors in windy environments can also aid in reducing the dust content present in crushed materials.

The Use of C&DW in Concrete in Cape Town

All the aggregates conform the SANS 1083: 2006 and HB 155-2002 criteria of containing less than 2% of material that passes as sieve of less than 0.075 mm.

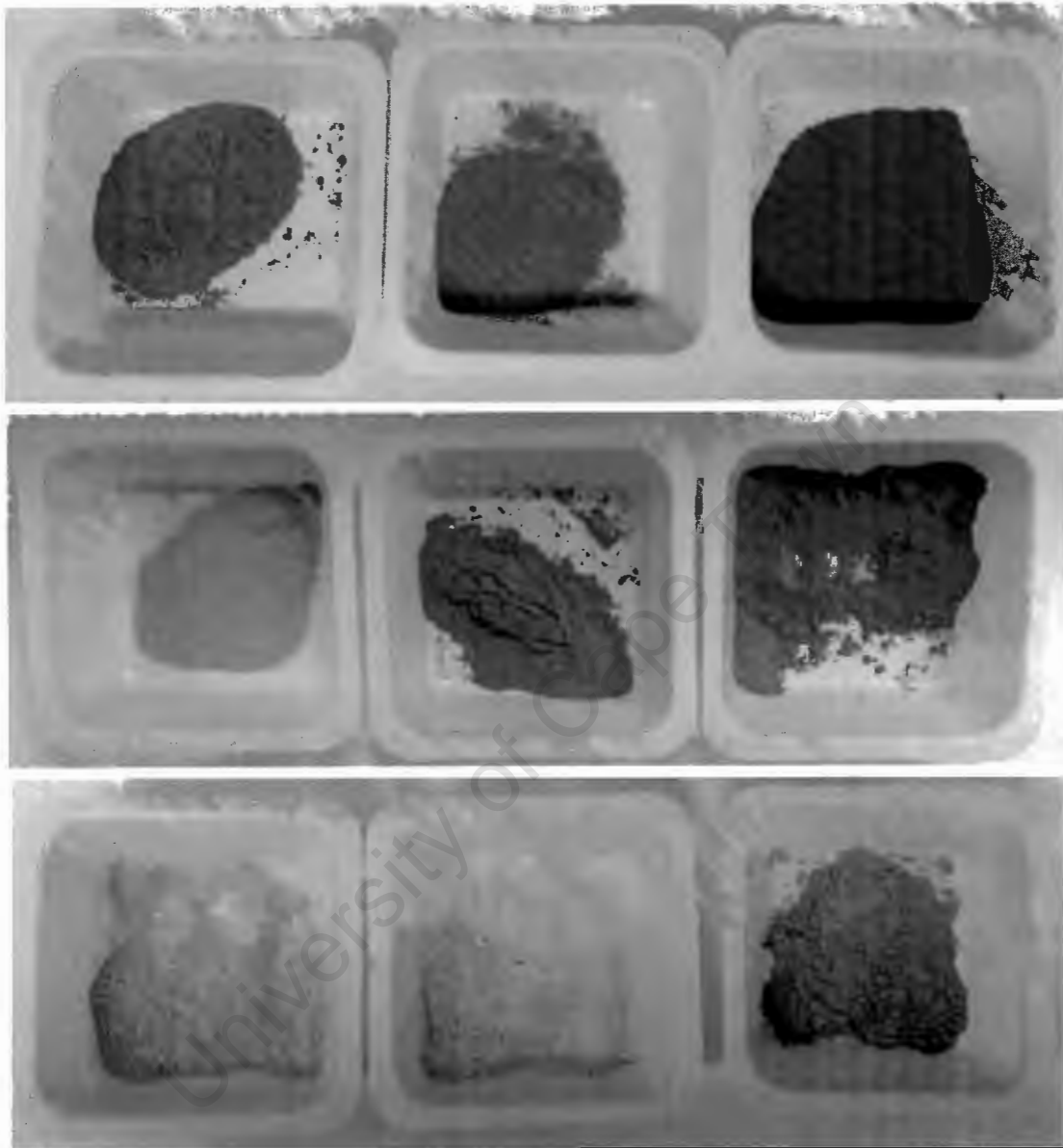


Figure 7.8: Dust particles of each RA. From left to right (Top) NFP, NFX, FBE45, (Middle) CMA, BCA-MV, BCA-MC, (Bottom) RCA-MC, RCA-45 and Greywacke

7.8 Chloride Content

The presence of chlorides in concrete can lead to depassivation and result in corrosion of steel reinforcement. Chloride content may be exaggerated by the porous and absorptive nature of RA materials especially the masonry aggregates. Consequently, chloride content in aggregates is largely dependant on the location from which the aggregates are sourced. Chlorides can be removed by certain actions such as soaking aggregates for an extended period before use (Alexander et. al. 2002).

The Use of C&DW in Concrete in Cape Town

This section analyses whether the RAs conform to the chloride limits set by HB 155-2002 in order to establish whether concrete may be contaminated when these RAs are utilised.

7.8.1 Test Procedure

The test for chlorides follows a titration procedure. The samples were prepared for the diffusion analysis by adding a small quantity of demineralised water to 2.1 – 2.5 grams of sample to produce a sticky paste. 2.0 ml of nitric acid (HNO_3) is then added and the solution is left to stand for more than 30 minutes. 2.5 ml of sodium acetate (NAC) is then added and the solution is filled up to 60 ml with demineralised water. These samples are then loaded into the titration equipment to be analysed for chloride content. The titration apparatus used is shown in the Figure 7.16 below.

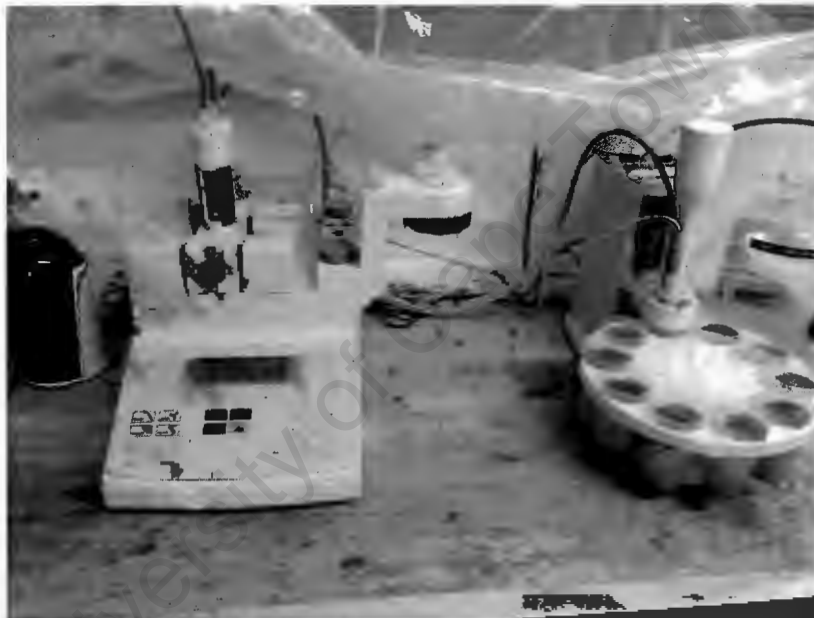


Figure 7.9: Titration equipment used to test for chlorides by titration

7.8.2 Results and Discussion

Chloride content results are shown in Table 7.5.

The virgin masonry materials, NFP, NFX and FBE45, have the lowest chloride contents of 0.039%, 0.041% and 0.038%. This is expected as these materials are derived from new, unused clay bricks in an inland brick yard. These aggregates conform to the chloride limits set by the HB 155-2002 Guide of 0.05%, as well as the EU limits of the same value (Martin-Morales et. al. 2011).

The CMA has a slightly higher chloride content of 0.07% as it is made of 70% recycled materials which may have had contact with materials derived from chloride rich environments. This makes this material's chloride content highly variable.

The Use of C&DW in Concrete in Cape Town

Table 7.5: Chloride content of RAs

Recycled Aggregate	Chloride Content	Max. Chloride Content (%)
	% mass	HB 155-2002
NFP	0.039	0.05 ^φ
NFX	0.041	
FBE45	0.038	
CMA	0.070	
BCA-MC	0.159	
BCA-MV	0.067	
RCA-45	0.097	
RCA-MC	0.071	
Greywacke	0.096	

^φ Class 1A RCA

The highest chloride content is 0.159% in the BCA-MV samples. This material was situated close to a body of water that is near the Black River mouth, Salt River, Cape Town. This may have led to heightened exposure to salty seawater or air.

The RCA-45 and RCA-MC samples have chloride contents of 0.097% and 0.071%. These values are lower than the values for chlorides of 0.152% found by Alexander & Heiyantuduwa (2002). They reduced chloride content of their RCAs to 0.042% by soaking them in water for seven days.

There are only prescribed limits for chloride content in fine aggregates in South Africa. HB 155-2002 classifies Class 1A RCA as having a chloride content of less than 0.05%. RCA-45 and RCA-MC therefore fail this requirement. The only materials that fall below the limit of 0.05% chlorides set by HB155-2002 are the virgin clay masonry aggregates however this classification is currently for RCA materials only.

In analysing the HB 155-2002 chloride boundary value further, for a coarse aggregate content of 800 kg/m³, a chloride content of 0.05% equates to 0.4 kg of chloride per m³. For a binder content of 400 kg/m³, this results in 0.1% chloride by mass of binder. This is a relatively low chloride content. Furthermore, the application of these materials is not recommended for highly reinforced, high strength concrete section. Therefore, even though the aggregates under question do not conform to the recommended limit of 0.05% chlorides, it is not thought that these chloride content quantities would be of major concern, depending on the application of the concrete mix. These chloride content results do not provide valid conclusions as to the suitability of these aggregates for use in concrete.

7.9 Particle Shape - Flakiness Index

Aggregate particle shape is one of the most important factors that determine the performance of stone aggregates in fresh concrete. This is because this property has a strong influence on water requirement. The more spherical or cubical the aggregate shape, the less the surface area, and hence the lower the water requirement. Conversely the more elongated or angular the shape, the more water the mix will require. Surface area is also increased with greater roughness or surface texture, which in turn also affects water requirement. Surface texture also increases friction and mechanical interlock between particles affecting workability (Grieve 2009). Crushing machinery and the scale of production is known to play a significant role in the shape of RAs. Jaw crushers are known to produce more angular, sharper edged aggregates. Gyro and impact crushers produce finer more rounded aggregates.

Particle shape is quantified as Flakiness. Flakiness is measured in what is referred to as Flakiness Index (FI). SANS1083:2006 requires Flakiness Index to be below the value of 35 for particles between 19 mm – 13 mm in size.

This section allows one to gain an understanding of the particle shape of each RA in order to gauge the effects this might have when these materials are used in fresh and hardened concrete. It also investigates whether the RAs under question conform to the SANS 1083:2006 Flakiness Index limits.

7.9.1 Test Procedures

The Flakiness procedure involves performing a grading analysis and separating approximately 2 kg of aggregate of 19 mm and 13.2 mm in size following SANS5847:2008 – *Flakiness Index of Course Aggregates*.

7.9.2 Results and Discussion

The FI results shown in Table 7.6 are an indication of the particle shape of the 19 mm - 13 mm particles. This Table shows that only the CMA, BCA-MC, BCA-MV, RCA-45 and RCA-MC conform to the recommended FI. The commercial stone exceed the SANS 1083:2006 FI limit with a value of 39.

The Use of C&DW in Concrete in Cape Town

Table 7.6: Flakiness Index values of all RAs

Recycled Aggregate	Flakiness Index	Max. Flakiness Index
	%	SANS 1083:2006
NFP	40	35
NFX	40	
FBE45	41	
CMA	8	
BCA-MC	15	
BCA-MV	31	
RCA-45	16	
RCA-MC	26	
Greywacke	39	

Flakiness index (FI) results show that the masonry RAs are the most elongated and irregularly shaped, with the NFP, NFX and FBE45 having FIs of 40, 40 and 41 respectively. The shape of the FBE45 sample is shown in Figure 7.17 below. Jaw crushing procedures in which the clay brick masonry material shattered and splintered when put under pressure in the jaw mouth contribute to high FI values. This is verified by Hu et. al (2011) and Padmini et. al. (2009) who both comment that masonry aggregates have more planar and angular shapes. These values are similar to that of the Greywacke stone has a high FI of 39.



Figure 7.10: Splintered, flaky nature of FBE45 and NFX aggregates

The BCA-MC sample has a much lower FI of 15 when compared to the BCA-MV sample at 31. This is thought to be a result of the majority of the BCA-MV materials being made up of hollow core blocks that splinter into column like shapes. The BCA-MV sample also contained more layers of attached

The Use of C&DW in Concrete in Cape Town

mortar on the clay bricks. These layers of mortar often ‘popped’ off during jaw crushing resulting in elongated plate like pieces of mortar aggregate. This is shown in Figure 7.18.

The RCA-MC has a higher FI of 26 when compared to an FI of 16 for the RCA-45. This is a consequence of the higher concrete mortar content on the RCA-45 as well as the rounder granite virgin coarse aggregate. This corresponds to research by Martin-Moralez, M. et. al. (2011) who comments that residual mortar attached to RCA particles make them more rounded. The commercial crushing procedure that produced the initial RCA-MC material, removed a lot of the surrounding concrete mortar on this sample. This created large planar areas of exposed Greywacke stone resulting in an increased flakiness.

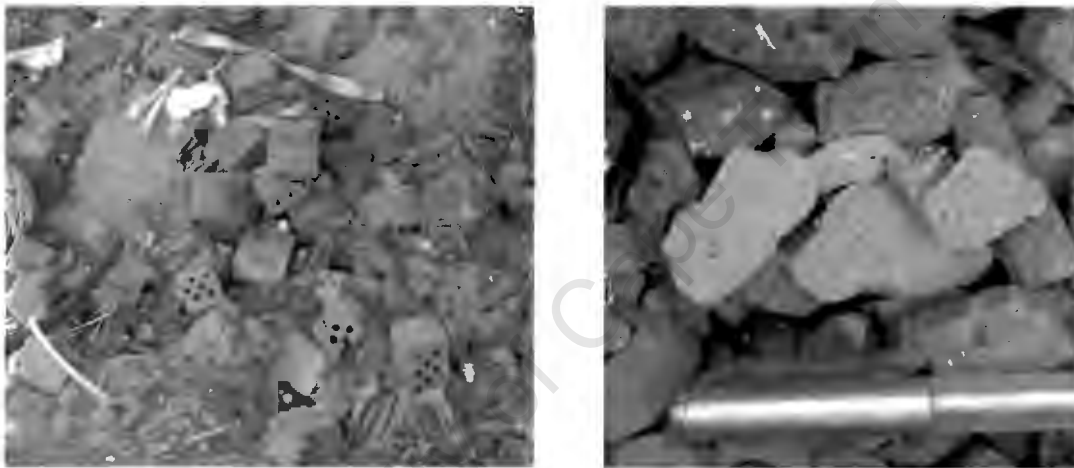


Figure 7.11: Hollow core clay brick components of BCA-MV sample (Left). ‘Mortar aggregate’ in BCA-MV sample.

7.10 Water Absorption

Absorption is described as the extent to which pores can be filled with liquid. RAs are known to be extremely porous and therefore water absorption is one of the most significant characteristics that differentiate RAs from stone aggregates. Bricks are manufactured to allow for a capillary effect as this helps regulate temperature and humidity in masonry applications. This may affect water demand, workability and cohesiveness in fresh concrete made with brick aggregates. Furthermore, this property may have a significant effect on the ITZ of masonry aggregates as discussed in the literature review. Absorption as a result of high porosity may also reduce resistance of aggregates to aggressive environments.

Absorption is typically described as the 24-hour percentage mass of water absorbed by a particular aggregate. Water absorption rate is the rate at which water is absorbed over a 24-hour period. 24 hours is assumed to be the point at which the aggregate is fully saturated and will not absorb a more substantial quantity of liquid. In masonry applications, this is usually described as initial absorption rate

The Use of C&DW in Concrete in Cape Town

(kg/m²/min), which is measured to gauge the effects of the bond between bricks and mortar during laying. In the context of this study, absorption rate as a percentage mass of absorbed water may allow one to gauge the extent to which water may be removed (absorbed) from a fresh concrete when RAs are added to the concrete mix. This is also significant as it indicates the extent to which an RA needs to be saturated in order to reduce their absorption properties before they are used fresh concrete. RAs are typically pre-soaked, pre-wetted or combined in a multi-stage mixing procedure to reduce their absorption properties.

The outcomes of this test are to establish the 24-hour absorption value of each aggregate and compare it to the HB 155-2002 criteria. Also to establish the rate at which the aggregates absorb water over a 24-hour period. This may allow for more effective pre-soaking, pre-wetting or multi-stage mixing.

7.10.1 Test Procedure

The 24-hour absorption testing is described by SANS 5843:2008 – *Water Absorption of Aggregates*. Multiple batches of materials were put through this process in order to obtain average values. An absorption rate test was performed on each sample to get an indication of the water absorption potential over time. Dried samples were immersed in water, drained for 5 minutes and then towel dried to achieved SSD condition at intervals of 2, 5, 10, 30 minutes, 1 hour, 2 hours and 6 hours.

7.10.2 Results and Discussion

Table 7.7 shows the percentage of water absorbed by each RA after a 24-hour period.

Table 7.7: 24 Hour water absorption values

Aggregate	24-Hour Water Absorption (%)	Max Absorption (%)	
		HB 155-2002	
		Class 1A	Class 1B
NFP	12.7	6	8
NFX	14.8		
FBE45	7.8		
CMA	9.6		
BCA-MC	10.4		
BCA-MV	11.3		
RCA-45	5.5		
RCA-MC	4.7		
Greywacke	0.4		

The Use of C&DW in Concrete in Cape Town

The control aggregate, Greywacke stone, has 0.4% water absorption. This is typical of stone aggregates used in South Africa, which normally have a water absorption value of below 0.5% (Grieve et. al. 2009). Data from commercial aggregate suppliers AfriSam specify a water absorption value of between 0.6% and 0.3% for their 6.7 - 25 mm Greywacke aggregates (Kleyn 2013). Absorption calculations are variable in Greywacke because it is essentially non-porous with long smooth surfaces. Absorption is therefore an indication of the amount of water on the surface of the stone at a surface saturated dry condition.

The masonry materials have the highest water absorption and therefore porosity. The lower grade clay bricks, NFX and NFP have the highest absorption at 14.8% and 12.7%. The higher grade FBE45 RA shows a lower absorption value of 7.8%. The flakey, honeycombed and porous nature of the surface of these aggregates is shown in Figure 7.19 below.



Figure 7.12: Flakey, honeycombed and porous surface of the NFX RA compared to FBE45 RA

These absorption values correspond to literature, which suggests that well burnt brick, such as FBE45, should have absorption of less than 10%. It can be seen in Figure 7.22 that the FBE45 RA absorbs material at a slower rate and to a lower extent than the other masonry aggregates. This data suggests that absorption values decrease with increased strength of the parent material. This correlation was also suggested by Egutchi et. al (2007), Hu et. al. (2011) and Zhang & Ingham (2010) for parent concrete strength.

The grade of clay brick of the BCA-MC and BCA-MV materials is unknown. The higher porosity values of the BCA-MV is thought to be the result of the increased quantities of mortar and mixed lower grade brick in its contents. These materials have absorption values of 10.4% in the BCA-MC sample and 11.3% in the BCA-MV sample. These values are similar to the work of Padmini et. al. (2009).

The Use of C&DW in Concrete in Cape Town

The CMA sample is made up of small clay brick fragments and a dry cement mix and with an absorption value of 9.6%. This shows the high level of compaction that is achieved when concrete masonry is produced with smaller sized aggregates, sand and cement. This predominantly cement and sand matrix should have a very high absorption value. There may be a certain degree of hydration that takes when this aggregate is exposed to water, which may affect absorption results. The highly compacted, granular nature of CMA is shown in the Figure 7.20.



Figure 7.13: Compact, granular surface of CMA

The RCA-45 and RCA-MC samples have lower absorption values of 5.5% and 4.7%. The RCA-45 material has a higher absorption value due to the greater quantities of concrete paste on the surface of the virgin stone as a result of the single stage jaw crushing procedure. The RCA-MC sample had noticeably less cement paste on the surface of the virgin stone and consequently has a lower porosity. These results correlate to results of between 4.4 - 7.7% achieved by Egutchi et. al (2007), Hu et. al. (2011) and Zhang & Ingham (2010). Increased absorption with increased mortar content was also reported by Padmini et. al. (2009). However, he comments that increased absorption is often a result of increased parent concrete strength. This is because higher strength parent concrete might not be broken down during commercial crushing operations resulting in increased mortar content. From this study, it is thought that parent strength in RCAs is not a critical factor. The type and size of the crusher, the number of processes through which the materials is put and the state of the material when received is believed to far more influential on the absorption values. This increased mortar content in the RCA-45 sample is illustrated in Figure 7.21.

The Use of C&DW in Concrete in Cape Town

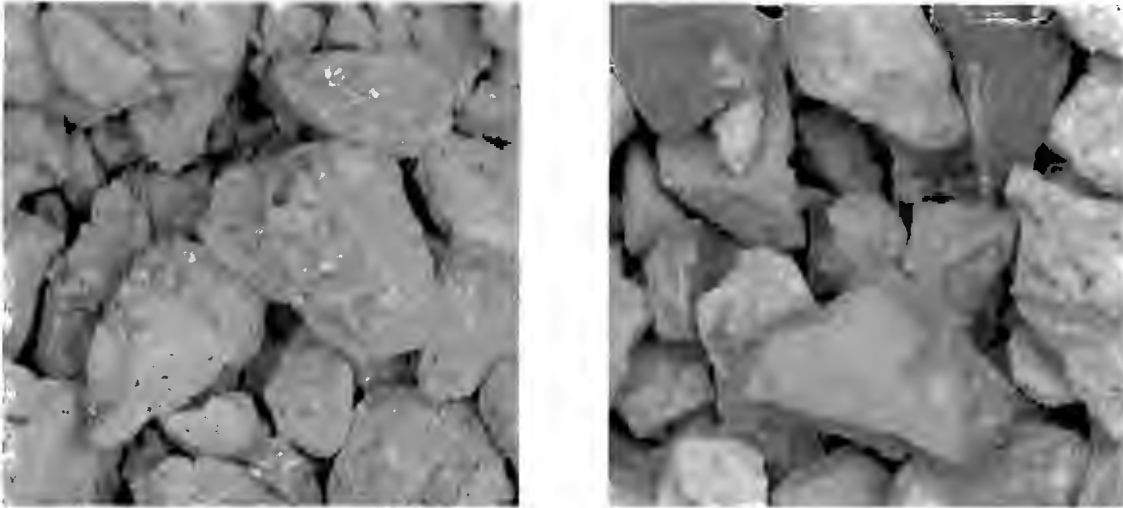


Figure 7.14: Rough, cement paste covered RCA-45 sample (Left) compared to the smoother surfaces of the RCA-MC (Right)

Both RCAs fall under the classification of Class 1A RCA according to their water absorption values that fall below 6%. The FBE45 masonry aggregate may be classed as Class 1B as it falls below the limit of 8%. No other materials conform to the HB 155-2002 recommendations.

Figure 7.22 below shows the rate of absorption over a 10-minute period.

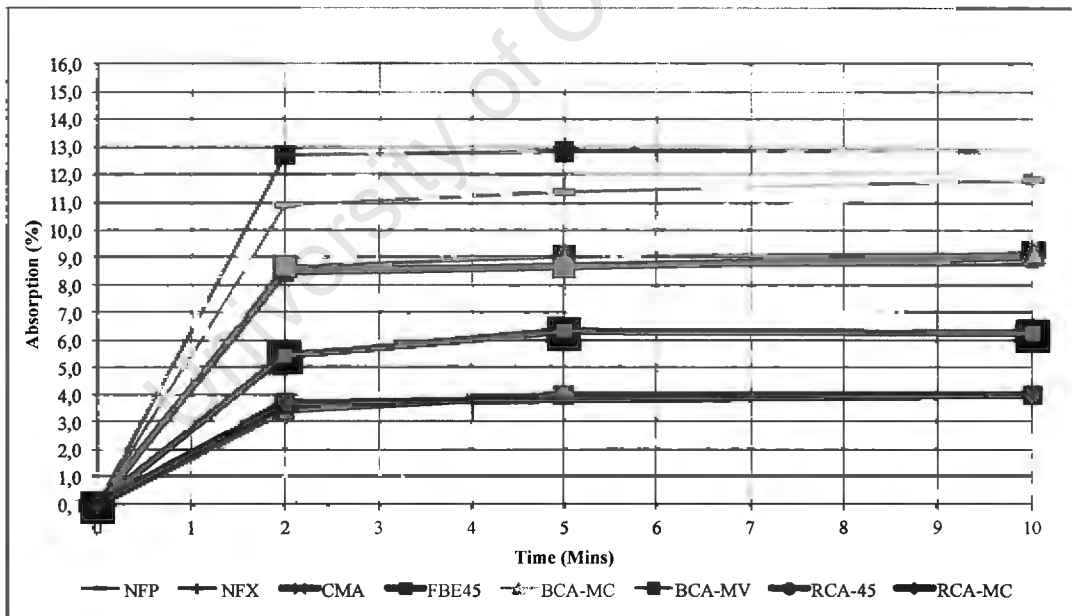


Figure 7.15: Rate of absorption over a 10-minute period.

All of the samples absorbed approximately 80% of their 24 hours absorption value within 2 minutes of wetting. This shows that pre-soaking aggregates for periods of up to 24-hour period may not be an efficient approach to pre-wetting (Bento et. al. 2012; Hansen 1992). Pre-wetting aggregate before use is discussed further in the section on the fresh properties of RAs.

The Use of C&DW in Concrete in Cape Town

The porosity of the aggregates can also be gauged by comparing the difference between SSD density and dried density. This shows the change in density as a result of the absorbed water within the aggregates pores. Therefore, the larger the difference between SSD and dried densities, the greater the absorption and hence porosity of the aggregate. When one analyses this difference, the results are consistent to those found in the 24 hour absorption test with the most absorptive materials being the NFX, NFP and BCA-MV and least being the FBE45, RCA-45 and RCA-MC samples.

7.11 Surface Saturated, Oven Dried and Apparent Relative Density

Definitions of the various density parameters are as follows:

Particle apparent relative density also known as specific gravity, ρ_{RD} , is the ratio of the mass of a dried sample of aggregate to a mass of an equal volume of water. This includes voids and water-impermeable pores that are filled with water when in surface saturated dried (SSD) condition (SANS 5844:2006). Problems with mixing, transporting, placing, compacting and finishing have been known to occur in aggregate outside the range of relative density between 2.5 – 3.0. Particle relative density is also an important variable in concrete mix design in the C&CI mix design method and dictates the quantity of coarse aggregate used in a concrete mix. Since aggregates make up approximately 80% of the mass of concrete, relative density of the aggregate used in the concrete has significant effects on the density of the concrete. This then influences the hardened properties of the concrete (Grieve 2009).

Dry density, ρ_D , refers the ratio of a sample of aggregate particles to the volume it occupies in an oven-dried condition, where all surface and pore water has been removed (SANS 5844:2006).

Saturated surface dried density, ρ_{SSD} , refers to ratio of a sample of aggregate particles to the volume it occupies in a condition that been soaked for 24 hours and then towel dried to remove surface water. This assumes that the water permeable pores are filled with water but the surface of the aggregate is dry (SANS 5844:2006).

This section is important as particle density variables enable one to calculate the solid volumes of materials from their masses. This allows one to calculate the yield of a concrete mix by the C&CI method.

7.11.1 Test Procedure

The pycnometer method as described in SANS 5844:2006 – *Particle and Relative Densities of Aggregates* is used to determine density values.

7.11.2 Results and Discussion

Table 7.8 shows SSD, dry and apparent relative density results.

Table 7.8: SSD, dried and apparent relative density values

Recycled Aggregate	Saturated Surface Dried Density (ρ_{SSD})	Dried Density (ρ_D)	Apparent Relative Density (ρ_{RD})
	kg/m ³		
NFP	2060	1800	2.44
NFX	2050	1780	2.45
FBE45	2300	2120	2.58
CMA	2210	2020	2.45
BCA-MC	2260	2040	2.58
BCA-MV	2180	1950	2.52
RCA-45	2370	2230	2.59
RCA-MC	2410	2290	2.60
Greywacke	2720	2600	2.77

The lower grade masonry RAs in the NFP and NFX have the lowest SSD, dried and relative densities of 2060 kg/m³ and 2050 kg/m³, and dried densities of 1800 kg/m³ and 1780 kg/m³. Their relative density values of 2.44 and 2.45 are known to cause problems such as mixing, transporting, placing, compacting and finishing in concrete. The clay masonry densities are similar to results of 1797 kg/m³ found by Poon et. al. (2006) and Poon & Chan (2006). The density values of the aggregates seem to relate to the grade of virgin material that the masonry RAs originated from. Dried density can be seen to increase with increased virgin masonry strength in the NFX, NFP and FBE45 samples. Values of 1780 kg/m³, 1800 kg/m³ and 2120 kg/m³ were found for these samples. This is in keeping with results by Zhang & Ingham (2010) and Padmini et. al. (2009).

This trend may indicate that the BCA-MC sample contains higher strength clay brick materials than that of the BCA-MV sample. These RAs have dried relative densities of 2040 kg/m³ and 1950 kg/m³ respectively. This difference in density also shows the effect on RA materials with increased quantities of mortar content, as the BCA-MV sample contained substantially more mortar than the BCA-MC sample and hence has a lower density.

The Use of C&DW in Concrete in Cape Town

Concrete masonry products are known to be made with a w:b of approximately 0.3, that is highly compacted to form masonry elements. This may result in further hydration in this material when wetted and dried. This may increase the mass of the particles therefore increasing particle density values.

The RCA samples have higher density values than those of the other RAs. The RCA-MC sample had the lowest mortar content of the RAs and has an apparent relative density of 2.60. The RCA-45 sample had a relative density of 2.59. These relative densities are slightly higher than the values found by Eguchi et. al. (2007) of between 2.38 and 2.46 for 20 mm RCA however, parent aggregate plays a large role in dictating RCA density values. The RCA-MC had small quantities of mortar attached to its Greywacke surface and the high strength of the RCA-45 mortar mix is thought to be the cause of the relatively high relative density results. Adhesion of mortar particles to coarse RCA is known to lower density values (HB 155-2002). The effect of the excess mortar is illustrated by the lower dry density of the RCA-45, 2230 kg/m³, when compared to 2290 kg/m³ of the RCA-MC.

The Greywacke stones relative density, 2.77, is similar to recent relative density values achieved by the 19 mm Greywacke stone from AfriSam in Contermanskloof of 2.72. This value is greater than the RA sample's.

All the RAs fall within the particle density limit of 1800 kg/m³ for Class 1B aggregate in HB 155-2002. Only the NFP and NFX fall outside of the 2100 kg/m³ limit of Class 1A aggregate.

7.12 Bulk Density

Bulk density refers to the mass of aggregate that fills a container of a certain volume. Bulk density is measured as 'loose' bulk and 'compacted' bulk density. Loose bulk density is a measure of aggregates that have been placed without compaction. Compacted bulk refers to particles that have been compacted in layers within the container. Properties such as grading and particles shape influence bulk density values. Void ratio is calculated using bulk density values.

7.12.1 Test Procedure

Loose bulk density was calculated by SANS5845:2006 – *Bulk Densities and Voids Content of Aggregates*.

7.12.2 Results and Discussion

Loose and compacted bulk density results are as follows:

The Use of C&DW in Concrete in Cape Town

Table 7.9: Loose and compacted bulk densities

Recycled Aggregate	Loose Bulk Density	Compacted Bulk Density
	kg/m^3	
NFP	890	990
NFX	890	980
FBE45	1100	1200
CMA	1050	1190
BCA-MC	1055	1155
BCA-MV	1010	1110
RCA-45	1170	1310
RCA-MC	1210	1360
Greywacke	1410	1535

The lowest loose and compacted bulk densities are those of the NFP and NFX RAs. The loose and compacted bulk density of the NFP RA is 890 kg/m^3 and 990 , as well as 890 kg/m^3 and 980 kg/m^3 for the NFX RA. Density values are expected to be close as these materials are very similar in composition.

The RCAs have the highest compacted bulk densities of the RAs. Loose and compacted densities are 1170 kg/m^3 and 1310 kg/m^3 for the RCA-45 and 1210 kg/m^3 and 1360 kg/m^3 for the RCA-MC.

The greywacke stone shows very similar loose and bulk density characteristics to the work done by Alexander & Heiyantuduwa (2002) who found average density values of 1400 kg/m^3 and 1525 kg/m^3 in his testing. The values found by this study of 1410 kg/m^3 and 1535 kg/m^3 also compare favourable to the loose and compacted density values obtained from AfriSam of 1370 kg/m^3 and 1490 kg/m^3 in April of 2013.

The RCA samples correlate to literature with the RCA-45 having a loose and compacted bulk density of 1160 kg/m^3 and 1310 kg/m^3 . The RCA-MC has a loose bulk density of 1220 kg/m^3 and 1350 kg/m^3 . The higher mortar content of the RCA-45 reduces density values of this sample.

All the RAs except for the NFP and NFX conform to the Class 1B recommendations in HB 155-2002 of a minimum bulk density of 1000 kg/m^3 . Only the RCA-MC may be classified as a Class 1A aggregate with a bulk density of greater than 1200 kg/m^3 .

7.13 Crushing Strength – 10% FACT and ACV

The aggregate crushing value (ACV) and 10% fines aggregate crushing test (FACT) are an indication of resistance of an aggregate to crushing under gradually applied loads. They may not give an accurate representation of the performance of aggregates within concrete but are useful indicators of overall aggregate quality (Grieve. 2009).

The aim of the 10% Fines Aggregate Crushing Test (10% FACT) is to determine the 10 % crushing value (10% FACT value) of an aggregate sample. This is achieved by measuring the force required to crush an aggregate, to the extent that 10 % of the material will pass a sieve with square aperture size of 2.36 mm in diameter. This test is performed on the aggregates in a wet and dry state. The results of this test indicate that 90 % of the available aggregate in a concrete mix will be able to resist the force and not be crushed to a size smaller than the required sieve size of the 10 % FACT load. SANS 1083:2006 requires coarse aggregates for use in concretes subjected to surface abrasion or for structural elements of a reinforced and/or a prestressed nature, to have a 10% FACT value of greater than 110 kN. Coarse aggregate not subjected to abrasion should have a 10% FACT value of greater than 70 kN.

The aggregate crushing value test (ACV) is similar to the 10% FACT and gives a representation of crushing force an aggregate can withstand while confined and subjected to a gradually applied force. It is expressed as the ratio of crushed material that passes a sieve with aperture size of 3.35 mm, to the mass of the original sample tested. This test is also performed on the aggregates in a wet and dry state. SANS 1083:2006 requires dry coarse aggregates for use in concretes to have a maximum dry ACV of 29%. This value represents the maximum percentage of aggregate that may be crushed, to the extent that it is smaller than 3.35 mm, under a gradually applied load of 400 kN.

The crushing strength of most commercial aggregates used in concrete is far in excess of the compressive strength of the concrete made with the aggregate. This test is useful as it serves as a guide to the general quality of aggregates and their ability to not produce excessive fines during mixing and handling. This is important for lower strength aggregates materials as is the case with the masonry aggregates being analyzed in this study. This may also provide a better understanding of the RA materials' behavior when they have absorbed water during storage, through pre-wetting or through fresh concrete mixing actions.

7.13.1 Test Procedure

For both the ACV and 10% FACT, the materials were prepared in a dry and wet condition as per SANS5841:2006 – *Aggregate Crushing Value of Coarse Aggregates*. 10% FACT follows

The Use of C&DW in Concrete in Cape Town

SANS5842:2006 – *FACT value (10% Fines Aggregate Crushing Value) of Coarse Aggregate*. For all the masonry materials, forces of approximately 400 kN, 200 kN and 80 kN was applied over a period of 10 minutes in each test. In the case of the RCA and Greywacke materials, forces of approximately 400 kN, 200 kN and 100 kN were applied over the 10-minute intervals. The ACV test follows the same procedure except the apparatus is loaded to a force of 400 kN in approximately 10 minutes.

7.13.2 Results and Discussion

Tables 7.10 and 7.11 show the wet and dry 10% FACT and ACVs for all the samples under question.

Table 7.10: 10% FACT values of recycled aggregates

Recycled Aggregate	10 % FACT		Min. Dry 10% FACT value* (kN)
	Dry	Wet	
	kN		SANS 1083:2006
NFP	71	95	110 ^a or 70 ^b
NFX	67	92	
FBE45	126	144	
CMA	-	-	
BCA-MC	90	91	
BCA-MV	33	62	
RCA-45	149	120	
RCA-MC	172	147	
Greywacke	294	281	

^aConcrete subjected to surface abrasion, reinforced or prestressed structural elements

^bConcrete not subjected to surface abrasion

Table 7.11: ACVs of recycled aggregates

Recycled Aggregate	ACV		Max. ACV (max. %)	
	Dry	Wet	SANS1083: 2006	HB 155-2002
	%			
NFP	38.8	34.9	29.0	30.0
NFX	37.8	33.8		
FBE45	31.3	27.5		
CMA	41.5	43.2		
BCA-MC	32.6	29.8		
BCA-MV	37.4	34.4		
RCA-45	26.4	27.6		
RCA-MC	23.6	24.1		
Greywacke	14.4	15.2		

The Use of C&DW in Concrete in Cape Town

CMA is the weakest material with a dry and wet ACV value of 41.5% and 43.2%. These values are thought to be an inaccurate representation of this material's strength as gradual compression during the crushing test may compact CMA particles, rather than crush the aggregate as with stone aggregates. Further hydration of the cement particles after wetting and oven drying causes the CMA particles to bond together. This reduces the quantity of materials that fall through the sieve apertures, therefore producing a higher crushing strength. The weak nature of this material is seen in the negative FACT values. This is therefore an invalid test. CMA fails both the 10% FACT and ACV requirements of SANS 1083.

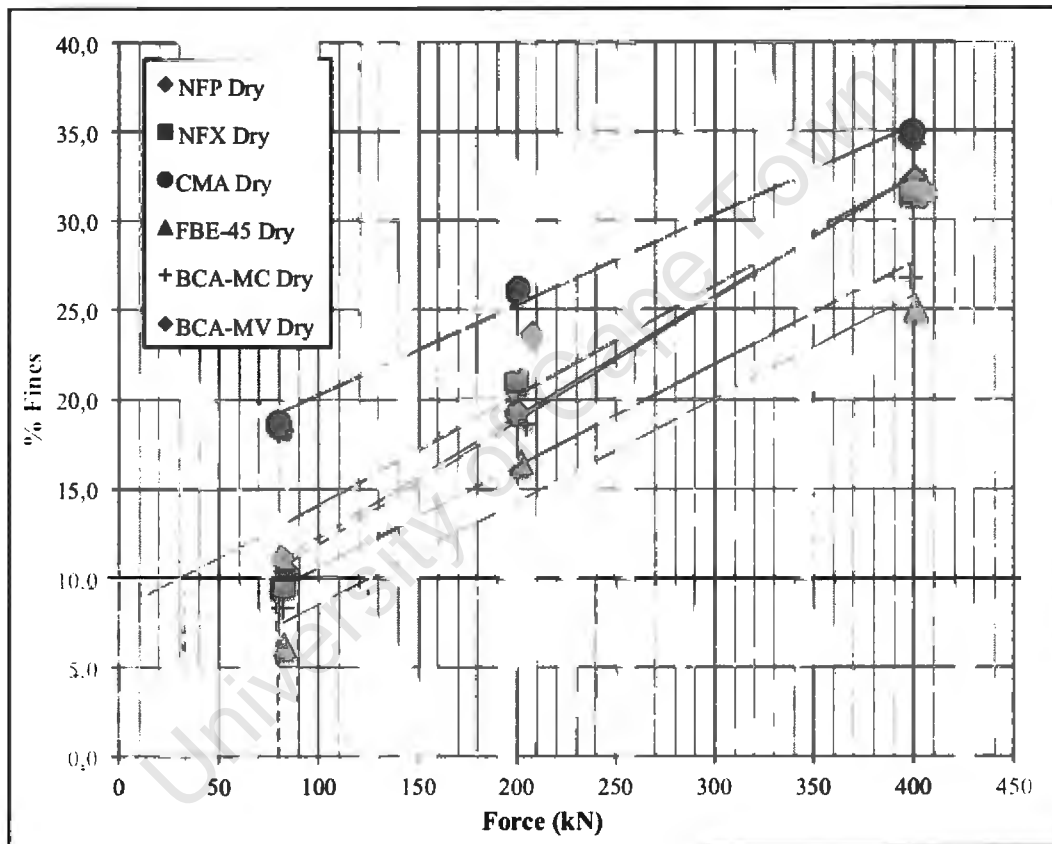


Figure 7.16: Dry 10% FACT of all masonry elements

The weakest mixed clay brick aggregate is the BCA-MV sample with dry and wet 10% FACT and ACV values of 33 kN, 62 kN, 37.4% and 34.4%. This shows the higher quantity of mortar in this sample. Brickwork mortar crushed into a finer material when put under a gradually applied load, when compared to the clay masonry material. This produces more fines and consequently a lower crushing value. BCA-MV fails both the 10% FACT and ACV requirements of SANS 1083. BCA-MC conforms to the 10% FACT requirement of SANS 1083 for use in concrete not subjected to abrasion however, both BCA-MV and BCA-MC fail the maximum ACV of 29%. These FACT and ACV values indicate a higher strength clay brick than the BCA-MV sample as well as a lower mortar content within this sample.

The Use of C&DW in Concrete in Cape Town

The wet and dry 10% FACT values of all the masonry aggregates are illustrated in the graphs below (Figures 7.23 and 7.24).

The FBE45 has much higher wet and dry 10% FACT and ACV results than NFP and NFX clay brick aggregates. The NFP and NFX aggregates have similar 10% FACT and ACV results as they have similar virgin brick strengths. The NFX RA marginally fails and the NFP marginally passes the dry 10% FACT requirements for use in low-grade concrete applications (HB 155-2002). The FBE45 surpasses the 110kN minimum dry value for use in concrete subjected to surface abrasion.

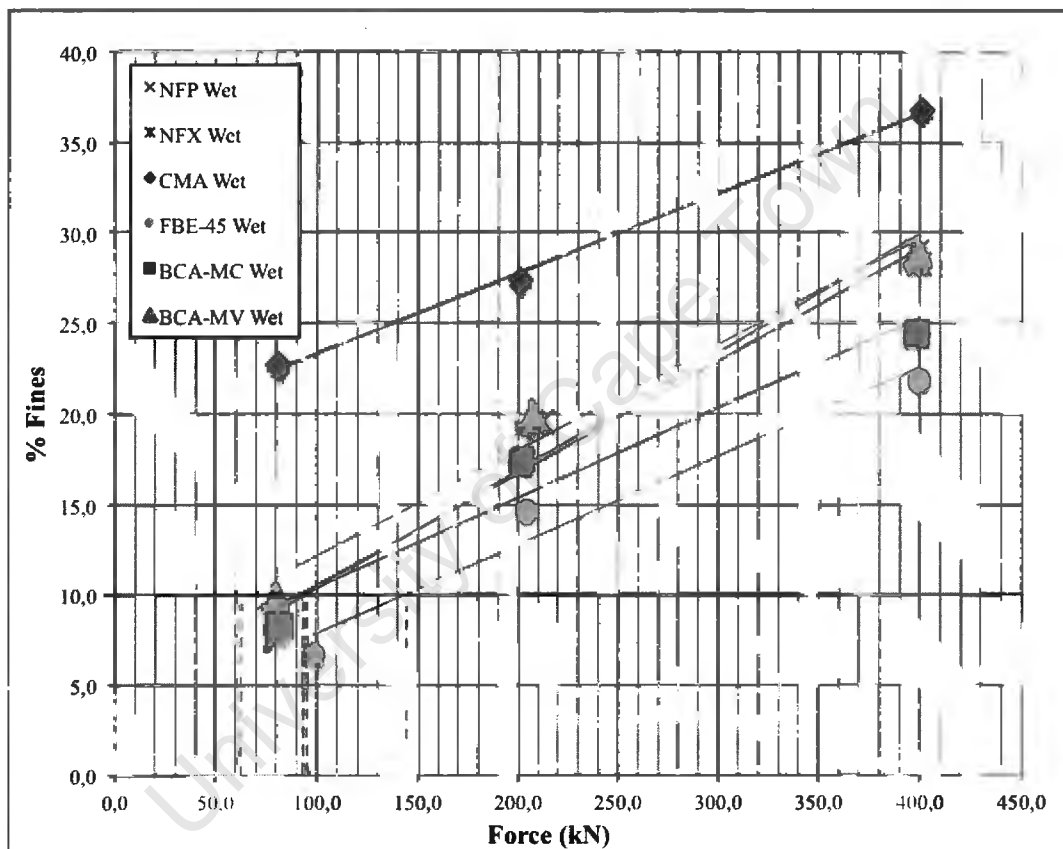


Figure 7.17: Wet 10% FACT of all masonry elements

The dry RCA 10% FACT results of other authors range from 146 kN – 190 kN in the dry 10% FACT (Alexander & Heiyantuduwa 2002; Kutugeza 2004; Poon & Chan 2006). These values are similar to results found in this study of 149 kN for the RCA-45 and 172 kN for the RCA-MC. Poon & Chan (2006) found dry 10% FACT values of between 72 kN – 107 kN for blended RCA and masonry aggregates. These also compare fairly well to the values found by this study of between 71 kN – 126 kN for the virgin clay aggregates.

The Use of C&DW in Concrete in Cape Town

The RCA-45 has reduced dry and wet 10% FACT values and increased ACVs when compared to the RCA-MC. This is a consequence of the higher concrete mortar content surrounding the RCA-45 material. This weak mortar is crushed under loading and produces increased fines quantities. As seen by the data points in Figure 7.25, at lower loads both RCAs have similar fines contents, but as loading increases, the RCA-45 fines content increases compared to similar loading in the RCA-MC. Only the RCAs produced dry and wet 10% FACT and ACV values that fall within the requirements of SANS 1083 and HB 155-2002 and allow them to be utilised in concrete of structural nature or subjected to surface abrasion.

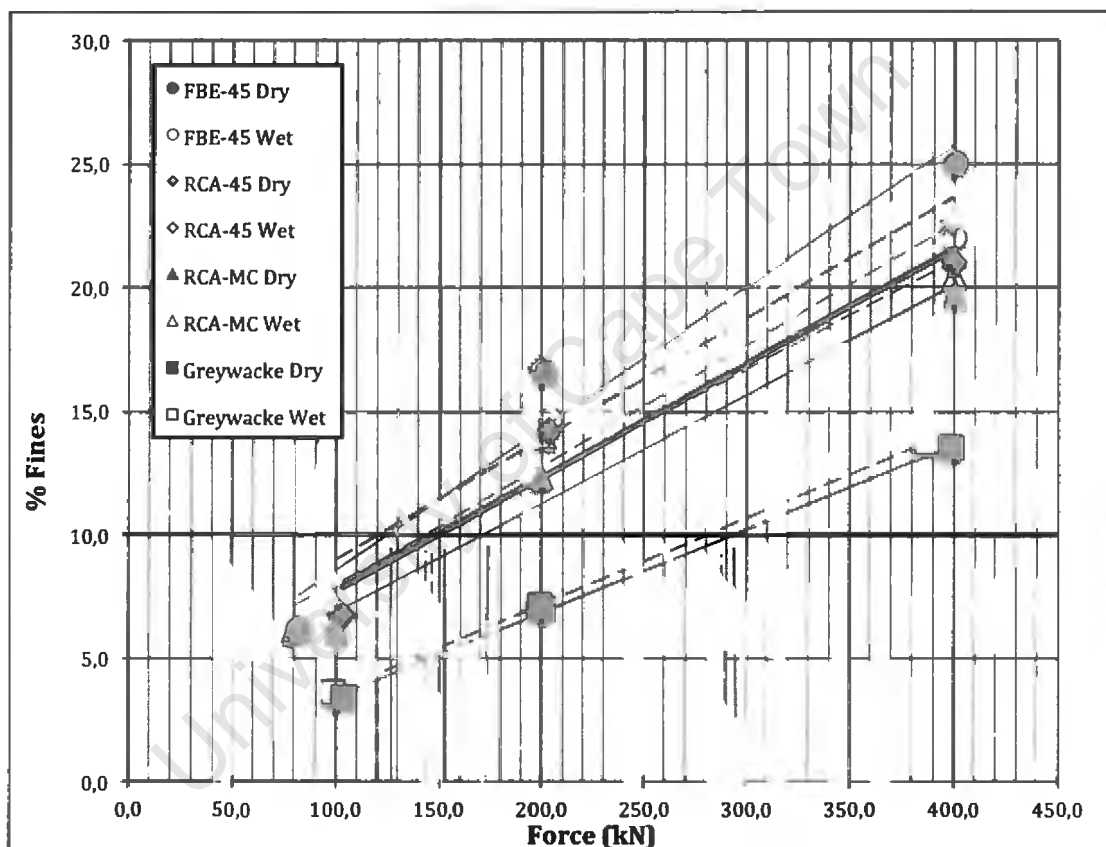


Figure 7.18: Dry and wet 10% FACT of FBE45, RCA-45, RCA-MC and Greywacke

Graphs representing the wet and dry 10% FACT values of the RCAs, control aggregate and strongest masonry aggregates, FBE45, can be seen in Figures 7.25. From these graphs one can see that the RCAs and FBE45 RA have relatively similar values. The control aggregate far surpasses these aggregates with dry and wet 10% FACT values of 294 kN and 281 kN. These values are similar to the dry values found by Alexander et al (2002) of 299 kN. This also holds true of the ACV test.

Wet crushing tests are performed on stone aggregate products to represent the 'worst case' scenario as confining pressure increases and friable particles are weakened due to the presence of water. This is

The Use of C&DW in Concrete in Cape Town

illustrated with the reduced 10% FACT values and increase in the ACVs of the RCA-45, RCA-MC and Greywacke stone in the wet crushing tests. In the case of the clay masonry aggregates, the wet 10% FACT values are higher than the dry 10% FACT values. Correlating to this, the wet ACV values are lower than the dry ACV values. This behaviour is contrary to the behaviour of stone aggregates.

Masonry RAs have high porosity characteristics. Therefore the increased water pressure during crushing, combined with their low density, is likely to shatter these materials into fine particles. It is therefore thought that the “increased strength” in the aggregates is due to the clay minerals within these RAs that when combined with water and dried, lead to the fines bonding together and forming larger pieces. These larger particles do not pass through the apertures of the sieves used to remove the fines material and therefore gauge crushing strength, during dry sieving. This results in a higher crushing strength when wet testing is done when compared to dry testing. 10% FACT and ACV testing therefore misrepresents the strength of BCAs in this study and it is recommended that wet sieving procedures are used when establishing the wet crushing strength of clay masonry RAs.

7.13.3 Summary of Aggregate Properties

The properties of each RA is summarised in Table 7.12 below.

Table 7.12: Summary of aggregate properties

Summary of Physical Properties of Aggregates										
Property	Aggregate Type									Rec. Limit*
	Virgin Clay and Concrete Masonry				Mixed Clay Masonry		Recycled Concrete		Stone	
	NFP	NFX	FBE45	CMA	BCA-MC	BCA-MV	RCA-45	RCA-MC	Grey.	
Dust Content (%)	1.19	1.59	0.98	1.10	0.81	0.84	0.95	0.76	0.01	< 2
Chloride Content (%)	0.039	0.041	0.038	0.070	0.118	0.067	0.119	0.071	0.096	< 0.05
Flakiness Index (%)	40	40	41	8	15	31	16	26	39	< 35
24 Hour Water Absorption (%)	12.7	14.8	7.8	9.6	10.4	11.3	5.5	4.7	0.0	< 8

The Use of C&DW in Concrete in Cape Town

Table 7.12 continued: Summary of aggregate properties

	NFP	NFX	FBE45	CMA	BCA-MC	BCA-MV	RCA-45	RCA-MC	Grey.	
Surface Saturated Density (kg/m³)	2060	2050	2300	2210	2260	2180	2370	2410	2720	> 1800
Oven Dried Density (kg/m³)	1800	1780	2120	2020	2040	1950	2230	2290	2600	
Apparent Relative Density (kg/m³)	2.44	2.45	2.58	2.45	2.58	2.52	2.59	2.60	2.77	
Compact Bulk Density (kg/m³)	990	980	1200	1190	1155	1110	1310	1360	1535	>1000
Dry 10% FACT (kN)	71	67	126	-	90	33	149	172	294	< 100 or < 70
Dry ACV (%)	38.8	37.8	31.3	41.5	32.6	37.4	26.4	23.6	14.4	< 29

*SANS 1083:2006 and HB 155-2002

The RAs tested consisted of four virgin masonry samples, which are made up of a 7 MPa, a 14 MPa and a 45 MPa burnt clay brick samples as well as a concrete masonry block sample. Two mixed masonry samples which contain varying quantities of mortar and two recycled concrete aggregate samples were also analysed. These are compared to the control aggregate, Greywacke stone.

All materials were split using a hydraulic splitter, crushed using a small jaw crusher and manually sieved to acquire a 19 mm coarse aggregate. Small scale jaw crushing produces angular, highly flaky masonry aggregates. Dust levels during crushing were low. From the results of this study, crushing characteristics of RAs are not as dependent on the strength of the parent materials but on the scale and type of crushing equipment.

A grading analysis was performed on all of the materials after being initially crushed as well after being sieved to analyse the effectiveness of small scale, manual processing. Primary jaw crushing and manual sieving produced recycled aggregates which were coarse and narrowly graded. This conformed to the grading requirements of SANS 1083 and particle size distribution was similar to that of the control aggregate. The majority of fines and dust were removed through vigorous manual sieving. This resulted in all the aggregates conforming the dust requirements of SANS 1083. Low dust content is also thought to be a result of the small-scale hand fed crushing machinery.

The Use of C&DW in Concrete in Cape Town

Water absorption was high in all the aggregates when compared to the control stone. This is especially true of the masonry aggregates which showed were 3 times the absorption than the RCA's.

Chloride content is relatively high compared in all the samples to the the HB 155-2002 guidelines and may be a concern in RAs. This is however dependant on the RA content and the intended use for the concrete.

The density values are proportional to virgin strength, that is the lower the virgin strength, the lower the density. Dried density values ranged from 1780 kg/m³ in the low strength NFX virgin brick to 2290 kg/m³ in the RCA-MC sample. Relative densities of the NFP, NFX and CMA samples are below the recommended 2.5 and may cause problems such as mixing, transporting, placing, compacting and finishing in concrete. Compacted bulk densities ranged from 980 kg/m³ in the NFX sample to 1360 kg/m³ in the RCA-MC. Bulk density values were similar to those found in literature. These results were lower than the control Greywacke stone that has relative, dry and compacted densities of 2.77, 2600 kg/m³ and 1535 kg/m³ respectively.

Low strength masonry RAs and RAs with a weak cement or mortar coating produced the worst crushing results. Thus, only the FBE45, BCA-MC and both RCAs conformed to the 10% FACT requirements of SANS1083 and only the RCA samples fall within the ACV requirements. Masonry materials performed better in the wet test than the dry test. This is contrary to the behavior of stone aggregates in which wet testes are seen as a worst-case scenario. This is shown by the RCA and Greywacke samples. When masonry RAs are crushed when wet and then dried, the fines in masonry aggregates bond together and form larger pieces. This reduces the quantity of materials passing the sieves in the crushing test consequently improving crushing values resulting in inaccurate results.

Using this data these materials can be designated according to HB 155. The overall performance of the RAs when compared to this classification shows that the RCA-45 and RCA-MC can be classified as a Class 1A recycled aggregate. The Guide is used to describe RCA materials but it is thought the FBE45 could pass as a Class 2 RA due to its material properties.

Therefore, this allows for safe substitution of 30% of RCA-45 and RCA-MV in an unreinforced and reinforced concrete mix of up to 40 MPa. It also allows for the 100% use of the RCAs and possibly FBE45 aggregate in a reinforced or unreinforced concrete mix, not meant for structural purposes with design strength of up to 25 MPa.

Furthermore, the RCA-45 and RCA-MV samples both conform to all the SANS requirements for use in concrete.

7.14 Conclusions

Processing

- The scale of the crushing equipment and method of crushing play an important role in defining the characteristics of RAs. Commercial crushing removes a larger quantity of mortar than small-scale jaw crushing in RCAs. Small jaw crushing operations that are fed with similar sized particles and are not choke fed produce small quantities of dust.
- Manual sieving is effective in removing fines and flaky particles.
- Small scale splitting, jaw crushing and manual sieving are effective in producing 19 mm coarse aggregate.
- Small scale jaw crushing and manual sieving are economical and results in a 19 mm coarse aggregate yield rate of over 85% in RCAs and approximately 80% for clay masonry aggregates.

Grading, Fines and Dust

- Small scale, on-site processing of C&D materials into 19 mm coarse recycled aggregates produces materials similar size to commercial stone aggregates. All the materials do not strictly conform the SANS 1083:2006 19 mm requirements.
- Increased virgin masonry strength results in coarser aggregate particles.
- Masonry materials produce more dust and fines materials than RCAs.
- Fines and dust content increase with increase brickwork mortar content in masonry aggregates.
- Fines and dust content increases with increased concrete mortar content in RCAs, rather than with increased concrete strength when RCAs are put through small scale jaw crushing.
- Dust content was below 2% for all the aggregates under question.

Chloride Content

- Chloride content may be high in RAs. Soaking may be employed to reduce chloride content.

Particle Shape

- Masonry wastes produce more angular, elongated and flaky aggregate particles when processed in the manner described in this study. Hollow core clay masonry may splinter and increase the likelihood of column like, flaky shape aggregates. Brickwork mortar often dislodges from masonry during crushing resulting in plate like mortar aggregates.

The Use of C&DW in Concrete in Cape Town

- Increased mortar content in RCAs produces a rounder aggregate shape.
- Virgin aggregate shape has an influence on the shape of RCAs. RCAs with granite virgin aggregate are more rounded in shape.

Absorption

- Increased absorption is experienced with lower virgin clay masonry strength, increased brickwork mortar and increased concrete mortar quantities.
- Absorption varies in clay masonry aggregate between 8 % for high strength masonry aggregate and 15% in low strength masonry aggregate.
- Absorption ranges from 4% - 5% in the RCAs.
- RAs absorb water rapidly and reach 80% of their 24 hours absorption within 2 minutes of wetting.

Density

- Surface saturate dried (SSD), dried and relative density in clay masonry aggregates increases with increase virgin strength.
- Increased cement and concrete mortar content decreases SSD, dried and apparent relative density.
- The clay masonry aggregates vary in dried density from 1780 kg/m³ to 2120 kg/m³. The RCA-45 and RCA-MV have dried densities of 2230 kg/m³ and 2290kg/m³. The control stone has a dried density of 2690 kg/m³.
- Apparent relative density is low in NFP, NFX and CMA RAs at 2.44, 2.45 and 2.45 and may cause mixing, transporting, placing, compacting and finishing problems in concrete.
- Compacted bulk density in the masonry aggregates ranged from 980 kg/m³ in the NFX to 1200 kg/m³ in the FBE45 samples. RCA-45 and RCA-MC have bulk densities of 1310 kg/m³ and 1360 kg/m³. These values are lower than the Greywacke stone at 1535 kg/m³.

Crushing Strength

- Crushing strength increases with increased virgin masonry strength.
- Increased cement and concrete mortar content reduces dry crushing strength.
- Crushing strength in RCAs is defined by the quantity of mortar on surrounding the virgin aggregate rather than the strength of the virgin aggregate.

The Use of C&DW in Concrete in Cape Town

- Dry 10% FACT results of the virgin masonry RAs NFP, NFX and FBE45 are 71 kN, 67 kN and 126 kN; the mixed clay masonry BCA-MC and MCA-MV are 90 kN and 33 kN; and RCA-45 and RCA-MC are 149 kN and 172 kN. Greywacke stone produced a result of 294 kN.
- The higher strength FBE45, the BCA-MC masonry aggregates and both the RCA-45 and RCA-MV conformed to the dry 10% FACT requirements of SANS1083.
- Dry ACV results of the virgin masonry RAs NFP, NFX and FBE45 are 38.8 %, 37.8% and 31.3%; the mixed clay masonry BCA-MC and MCA-MV are 26.4% and 37.4%; and RCA-45 and RCA-MC are 26.4% and 23.6%. Greywacke stone produced a result of 14.4%
- Only the RCA-45 and RCA-MC samples fall within the dry ACV requirements.
- Masonry materials performed better in the wet test than the dry test. This is contrary to the behavior of stone aggregates in which wet testes are seen as a worst-case scenario. The wet 10% FACT and ACV results are thought to misrepresent the strength of BCAs.
- Wet ACV and 10% FACT are not good indications of masonry aggregate strength. Wet sieving should be used to establish we crushing parameters.

Classification of Aggregates

- RCA-45 and RCA-MC can be classified as a Class 1A recycled aggregate.
- FBE45 could pass as a Class 2 RA due to its material properties. It only failes the SANS 1083:2006 specifications in flakiness characteristics.
- This allows for safe substitution of 30% of RCA-45 and RCA-MV in an unreinforced and reinforced concrete mix of up to 40 MPa. It also allows for the 100% use of the RCAs and possibly FBE45 aggregate in a reinforced or unreinforced concrete mix, not meant for structural purposes with design strength of up to 25 MPa.
- RCA-45 and RCA-MV samples both conform to all the SANS requirements for aggregate use in concrete.

8 Properties of Fresh Concrete made with RAs

8.1 Introduction

Aggregate standards recommend various coarse RA substitution ratios depending on the properties of the RA under question. The HB 155-2002 standards recommends only 30% RCA substitution for structural concrete applications up to 40 MPa or 100% substitution of RCA or a 30/70 BCA/RCA blend for non-structural applications up to 20 MPa. In light of the physical performance of the RCAs and higher strength FBE45 RA seen in the previous chapter, this study pursues a 100% substitution of coarse RA in all the RAC mixes under question. This gives an indication of the true performance of the RAs when used in concrete by eliminating a number of variables from the testing regime.

The properties of fresh concrete influence the ability of a concrete to be transported and handled, for the distribution of the contents within the mix and for the compaction capabilities to be gauged (Kutugeza 2004). Of importance to this chapter is the overview of the approached engineers might take to mitigate the absorptive properties of RAs and create workable mixes when using RAC.

This chapter begins with this overview of the potential concrete wetting approaches that may be taken before mixing fresh RA concrete. Added water content and multi-stage mixing procedure used in this study is then discussed. Lastly the total water content, workability and detailed concrete mix designs used in this study are presented.

8.2 Concrete Mixing Procedures

The mixing of fresh concrete made with NA generally follows a procedure where dry materials, followed by wet materials are added to a mixer and combined until the required concrete workability is achieved. RAs are highly absorptive and this procedure often leads to extremely dry mixes and little cohesion between materials. Two approaches are adopted to mitigate these effects. Either a plasticising agent is added to the mix or excess water is introduced to the dry RA in order to saturate it, reducing its absorption characteristics and increasing workability.

This study follows a direction whereby RAs may be produced by on-site processing and used with relatively simple techniques. Therefore, the approach whereby water is added to a concrete mix to

achieve the desired workability is explored. This is carried out in three recognized practices in pre-wetting, pre-soaking or multistage mixing. These procedures and their practicalities are discussed next.

8.2.1 Pre-wetting

Pre-wetting is the process whereby RAs are sprayed with water by a sprinkler system or a hand held hose, before being introduced into a fresh concrete mix. This may be the simplest approach to adding water to RAs and is very applicable to on-site mixing where stockpiles of RA may be generated, delivered or stored. However, the quantity of water added to the RAs may be variable in this procedure. Stockpile wetting may utilise a lot of water and result in the outer RA materials being soaked with the underlying material left dry, not achieving the desired saturation effect. Materials may be spread over a flat area and sprayed but this is often impractical with space constraints and contamination issues on site.

8.2.2 Pre-soaking

Pre-soaking is an approach often adopted by research analysing the properties of RAs (Alexander & Heiyantuduwa 2002; Kutugeza 2004; Padmini et. al. 2009; Hansen 1992). This involves RA materials being put into a water bath for an extended period of time, removed, allowed to drain, dried to achieve SSD condition and then added to a fresh mix. This is effective in saturating materials and has been proven to nullify the potential for absorption during the mixing of fresh concrete as well as reduce chloride content in RAs. This approach has been extremely effective in producing results that favour the use of RAs however, loading, storing and removing large quantities of aggregate materials into baths on-site is impractical. Allowing the materials to drain and dry before use may also be unfeasible.

8.2.3 Multi-stage Mixing

The last approach is known as multistage mixing. This involves introducing aggregate, water and cement materials into a concrete mixer at various intervals. This has been achieved by authors in a variety of ways, for example: Two-stage mixing involves adding half the water to the aggregates, mixing for a period of time and then adding the remaining materials (Tam et. al. 2005; Zhang & Ingham 2010). More stages may be introduced such as adding half the aggregates, half the water, the cement and then the remaining quantities of material and mixing for certain periods between material additions (Debieb et. al. 2010; Bento et. al. 2012). This approach to saturating RAs is seen as the most applicable for on-site applications and the most stringent with regard to adding specific quantities of water to a mix, in order to achieve the desired workability. Multi-stage mixing is therefore utilised in this study.

A detailed overview of the multistage mixing procedure used to reduce water requirements of a fresh mix is discussed next.

8.3 Water Requirement

Water requirement is described as the fresh water required to bring a concrete mix to a specified consistency (Kutugeza 2004). It has significant effect on the workability and consistency of fresh concrete, as well as implications for the w:b and hence strength of hardened concrete.

Water requirement is dictated by the material properties of the constituents of a concrete mix. With the use of 'normal' coarse aggregates (stone), water requirement is affected by parameters such as particle shape, size and texture. These materials generally have relatively low absorption properties and therefore fine aggregates play far more of a significant role in the water requirement of the concrete. With the use of recycled coarse aggregate, water absorption becomes extremely significant and the water requirement of both the coarse and the fine aggregate become a concern. This is illustrated in Table 8.1, which shows the 24-hour absorption properties of the RAs under question when compared to the reference stone aggregate.

Table 8.1: 24 Hour absorption properties of aggregates

Aggregate	24-Hour Water Absorption (%)
NFP	12.7
NFX	14.8
FBE45	7.8
CMA	9.6
BCA-MC	10.4
BCA-MV	11.3
RCA-45	5.5
RCA-MC	4.7
Greywacke	0.0

In order to overcome the varying absorption characteristics of RAs, a number of mixing procedures may be adopted to achieve fresh concrete with the desired workability and consistency. This is discussed further in the next section.

8.3.1 Added Water

The RAs under question have extremely variable absorption potential and therefore adding an average added water quantity to each fresh RAC is not feasible. From the absorption rate data, it was deduced that in most cases the RAs absorbed 80% of their 24-hour absorption water within 2 minutes of wetting.

Therefore, it is assumed that the value of 80% of the 24-hour water absorption may be added to each coarse aggregate batch during mixing. This mitigates the absorption effects of the dry aggregate materials and reduces the workability required of a fresh concrete mix. This leads to the distinction between two water contents in the mix namely mix water and added water.

Mix water is described as the water required to satisfy the w:b and hence achieve the mix design strength of the hardened concrete. Added water is the excess water added, above the mix water, in order to satisfy the absorption requirement of the recycled aggregate so that it does not adversely influence the workability.

The multistage mix procedure highlights the addition of these water contents and is discussed below.

8.3.2 Multi-stage Mixing Procedure

As discussed previously there are multiple approaches to multistage mixing used by various authors. The stages as well as the assumptions used in this study are described below. The major assumption is that this procedure achieves the desired workability without affecting the w:b of the concrete mix significantly. This mixing process is summarised in Figure 8.1.

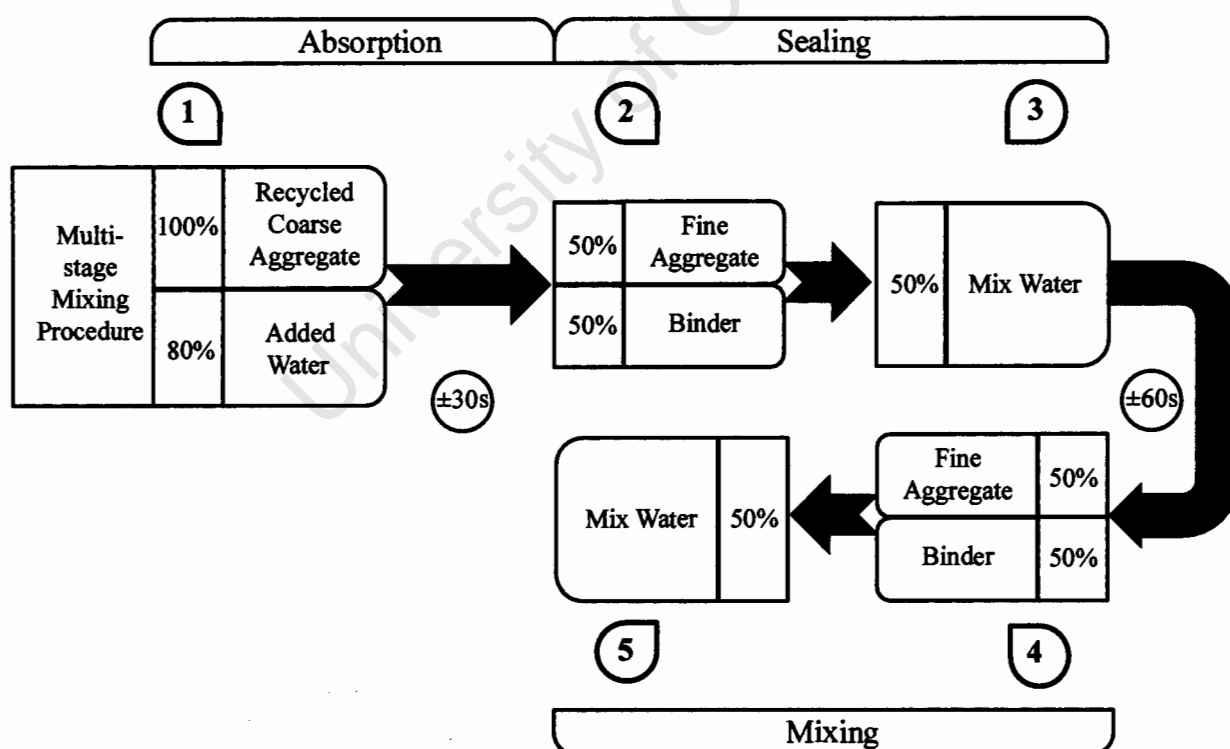


Figure 8.1: Multi-stage mixing procedure

In stage 1 all of the coarse RA is added to the mixer immediately followed the added water. Added water is calculated as 80% of the 24-hour absorption water value multiplied by the mass of coarse RA in the mix. This stage is referred to as an *absorption phase* where it is assumed that the dry aggregates will

The Use of C&DW in Concrete in Cape Town

absorb the added water relatively quickly. Mixing for longer than 30 seconds is recommended however, care should be taken as larger mixers may fracture weaker RAs and increase the fines content in RCAs with high mortar contents.

Stages 2 and 3 involve adding half the fine aggregate and cement content followed by half of the mix water, while continuously mixing. During this stage the RAs are coated in fresh concrete mortar. It is assumed that this coating seals the RAs and may prevent further substantial absorption from taking place. It is recommended that mixing take place for approximately 60 seconds to ensure that the coarse RAs are properly coated in concrete paste and significant added water absorption has been achieved. Stage 2 and 3 may be referred to as the *sealing stage*.

In stage 4 the other half of the fine aggregate and cement is added. Followed by stage 5 where the remaining mix water is combined in the mixer. This is a *mixing phase* where all the remaining concrete paste is combined, lubricating the mix and completing mixing process.

8.3.3 Discussion

A concern in adopting this mixing procedure is that the added water introduced into the fresh mix, followed by the mix water in relatively short succession, may increase the w:b, therefore decreasing mix design strength. This is discussed by Barra et. al. (2008) who comments that there are two directions this added water on the surface of the wetted aggregates could take. Water can either increase the w:b at the ITZ, thus reducing the strength of the bond between aggregate and cement paste, or be absorbed by the aggregate and migrate towards the paste after setting thus improving the microstructure of the concrete.

There are a number of assumptions made, which are validated by the results obtained in the physical testing chapter, which suggest that the ITZ may not be significantly affected by the added water content.

Firstly, the 24-hour absorption rate of these RAs has been shown to be high. Therefore rapid absorption of the added water when introduced to the aggregate can be expected. Fresh concrete remains in a dormant phase for 60-90 minutes so it can be expected that even the slower absorbing RAs will take in a substantial quantity of water in this time, provided the w:b ratio of the mix is greater than approximately 0.4. A conservative added water content of 80% is chosen to reduce the quantity of excess water from being added to the mix. The absorption potential of the fine aggregate must also be regarded and may be substantial.

Barra et. al. (1998) also comment that by mixing aggregates with water and cement first (or a prepared mortar), the pores and micro-cracks of the aggregates are coated (sealed) with cement paste. This reduces the high absorption properties displayed by RAs if they are mixed solely with water first. Tam

et. al. (2005) and Bento et. al. (2012) verify this 'sealing' process. The dry cement and sand materials cake the saturated RAs when added and with the addition of half the mix water, 'seals' the RA and prevents excessive absorption from occurring. The remaining water, cement and fine aggregate create the fluidity and workability of the fresh mix as they penetrate between the coated aggregate pieces. This is therefore referred to as the sealing phase of mixing.

The added water contents of the various RAs are discussed in the next section. It is with these assumptions that the fresh mixes were created and tested to establish whether they conformed to the target slump range. Precise water content quantities and these slump results are discussed next.

8.4 Workability and Water Content

The workability of a fresh concrete mix is the ease with which it can be transported, placed, compacted and finished without the individual materials within the mix segregating (Kutugeza 2004). The slump test is used to give an indication of workability as well as other properties such as cohesiveness and plasticity.

Workability is affected by the properties of the aggregate used in the mix. These properties include particle shape, size, porosity and surface texture. RA porosity and surface texture increase water absorption substantially, resulting in them usually having to be saturated in some manner to achieve a workable mix as discussed above. The binder type, admixtures, volume of the mix, weather conditions and time elapse also affect workability. Workability may be reduced on warmer, summer days as well as if the fresh mix to be tested is left to stand for a period of time.

8.4.1 Test Procedure

The slump test was carried according to SANS 5862-1:2006, *Concrete tests- Consistency of freshly mixed concrete- Slump test*. The slump test was carried on the final concrete mixes as well as on the trial mixes to establish the water demand of each aggregate. A slump of 80 mm \pm 20 mm is the benchmark for each mix in this study.

8.4.2 Trial Mixes

Using the multi-stage mixing procedure and a added water content of 80% of the mass of coarse aggregate, initial trial mixes to establish the water demand of aggregates under question were carried out. Multiple 10 litre concrete mixes were created by varying the coarse aggregate, fine aggregate and water content while maintaining a constant w:b. Mixes with 160 l, 180 l and 200 l mix water quantities were investigated. The slump of these mixes was measured and the mix water quantity estimated according to the variation in trial mix's slumps. Slump testing results can fluctuate substantially and are

The Use of C&DW in Concrete in Cape Town

affected by a number of variables as discussed above. These tests were carried out in the months of November to December, which are some one of the hottest months of the year in Cape Town. Slump testing is used as an indication of quality control between the mixes to check whether the mix conforms to the required workability interval in this study.

It was found that a mix water quantity of 180 litres satisfied the slump requirements of most of the mixes. The CMA mix however has a lower mix water requirement of 160 litres.

8.4.3 Results and Discussion

The slump and water content results are shown in Table 8.2.

Table 8.2: Slump and water content results

Slump and Water Content								
Mix	W:B Ratio	Slump (range 80 ± 20 mm)	Stone Content*	24-Hour Water Abs.	Mix Water	Added Water	% Increase	Total Water
		(mm)	kg/m ³	(%)				
NFP	0.50	60	760	12.7	180	87 ^a	48	267
	0.60	90	760					
	0.80	65	760					
NFX	0.50	85	755	14.8	180	95 ^b	53	275
	0.60	75	755					
	0.80	70	755					
FBE45	0.50	90	925	7.8	180	58	32	238
	0.60	100	925					
	0.80	80	925					
CMA	0.50	90	915	9.6	160 ^y	70	44	230
	0.60	75	915					
	0.80	70	915					
BCA-MC	0.50	70	890	10.4	180	74	41	254
	0.60	70	890					
	0.80	90	890					
BCA-MV	0.50	75	855	11.3	180	77	43	257
	0.60	70	855					
	0.80	85	855					

The Use of C&DW in Concrete in Cape Town

Table 8.2 continued: Slump and water content results

RCA-45	0.50	85	1010	5.5	180	44	25	224
	0.60	75	1010					
	0.80	90	1010					
RCA-MC	0.50	75	1050	4.7	180	39	22	219
	0.60	70	1050					
	0.80	85	1050					
GREYWAC KE	0.50	80	1075	0.0	180	0	0	181
	0.60	80	1075					
	0.80	85	1075					
^a 90% of 24-hour absorption value used to achieve slump ^b 85% of 24-hour absorption value used to achieve slump ^y Lower water demand required * 100% RA coarse aggregate content								

All the mixes conformed to required slump range and fell within the range of 60 mm – 100 mm as is shown in Table 8.2. Generally the materials with the highest absorption properties produced the lowest workability. This is seen in the clay brick aggregates in particular the NFP and NFX mixes. These mixes are found to be substantially harsher and stiffer than the RCA and NA mixes and added water content is adjusted to 90% and 85% of the 24-hour absorption values in order to achieve the slump range. It is noted that the NFP mix was tested on an excessively warm day. The RCA mixes fell more accurately within the desired slump range with slump values between 70 mm – 90 mm. The Greywacke mix was the most consistent mix with a slump range between 80 mm – 85 mm. This harshness is associated with high absorption values as when one compares the slump range of the NFP and NFX to the FBE45, which have similar FIs and composition, the FBE45 has a substantially lower absorption value and was less harsh and had a higher slump.

The slump data does not indicate a trend with regard to w:b but it was felt that the RA mixes showed less segregation and were more fluid with w:b = 0.50. It is thought that the mixes with higher w:bs promote segregation and produce harsher fresh concrete. This was more apparent in the clay masonry aggregates.

Added water quantities were extremely high at 87 l/m³ and 95 l/m³ in the NFP and NFX mixes. This reduced to 74 l/m³ and 77 l/m³ in the BCA-MC and BCA-MV mixes with the FBE45 mix having a

The Use of C&DW in Concrete in Cape Town

substantially lower added water demand at 58 l/m^3 . The RCA-45 and RCA-MC have an added water demand of 25 l/m^3 and 24 l/m^3 .

Added water quantities when compared to the mix water content were generally far higher in the clay brick mixes than RCA mixes. The percentage increase in water added to the clay brick mixes, due to their absorption characteristics, is 41 % - 53 %. This corresponds to a total water requirement of between $254 \text{ l} - 280 \text{ l}$ per m^3 . This is particularly apparent in the NFP and NFX mixes with 48% and 56% increases in water required and 267 l/m^3 and 280 l/m^3 needed to satisfy their workability requirements. The FBE45 mix is substantially lower with a 32% increase in water and a total water requirement of 238 l/m^3 . The RCA-45 and RCA-MV mixes present more favourable added water requirements of 25% and 22% and total water requirements per cubic meter of 257 l and 224 l .

Authors are often not very transparent about the quantities of added water used in their mixes. This is often a result of the mixing procedure and the technique used to mitigate the water absorption properties of their RAs. This may be the case with pre-soaking and uncontrolled pre wetting. When comparing the added water contents and total water content of the RCAs in this study, the results are favourable and similar to those of other authors.

Alexander & Heiyantuduwa (2002) found an increased added water quantity of 32 l/m^3 was required of their RCAs. This compares to 25 l/m^3 and 22 l/m^3 when one takes into account their mix water quantities of 160 l/m^3 compared to the 180 l/m^3 used in this work. Levy et. al. (2004) found total water requirements of 216 l/m^3 and 235 l/m^2 in his 30 MPa and 40 MPa mixes. Padmini et. al. (2009) also produced results of 217 l/m^3 , 206 l/m^3 and 200 l/m^3 in his 30 MPa, 35 MPa and 40 MPa mixes. All these authors results fall within the range of 219 l/m^3 and 224 l/m^3 produced by this work. The FBE45 with a total water requirement of 238 l/m^3 also falls near to upper range of these values. There is no apparent mix design data on the water requirement of 100% coarse masonry aggregate substitution in concrete to compare the remaining results to. The complete mix designs used in this study are overviewed in the final section of this chapter.

8.5 Detailed Mix Designs

Three concrete mixes were prepared from each of the RACs. SUREBUILD CEM II/B-M (L-S) binder is used and w:b of 0.50, 0.60 and 0.80 for a mix design strength of 40 MPa, 30 MPa and 20 MPa respectively. CEM II/ B-M (L-S) 42.5 N is a normal setting, blended cement consisting of approximately 20% - 35% limestone and blast furnace or Corex slag. Mix water is kept constant at 180 litres per m^3 in the majority of the mixes. Added water is the quantity of coarse aggregate in the mix

The Use of C&DW in Concrete in Cape Town

multiplied by 80% of its 24-hour water absorption value. A slump of 80 mm ± 20 mm is achieved for all of the mixes. Coarse aggregate is referred to as stone, fine aggregate as sand.

Table 8.3: Concrete Mix Designs for each aggregate material

Concrete Mix Designs								
Mix	W:B Ratio	Target Strength (MPa)	Material Content					
			Binder*	Stone**	Sand***	Mix Water	Added Water	Total Water
			kg/m ³			litres/m ³		
NFP	0.50	40	400	760	865	180	87 ^a	267
	0.60	30	330	760	920			
	0.80	20	280	760	965			
NFX	0.50	40	400	755	875	180	95 ^β	275
	0.60	30	335	755	930			
	0.80	20	280	755	965			
FBE45	0.50	40	400	925	750	180	58	238
	0.60	30	330	925	795			
	0.80	20	280	925	830			
CMA	0.50	40	355	915	805	160 ^γ	70	230
	0.60	30	290	915	865			
	0.80	20	245	915	885			
BCA-MC	0.50	40	400	890	790	180	74	254
	0.60	30	330	890	840			
	0.80	20	280	890	875			
BCA-MV	0.50	40	400	855	780	180	77	257
	0.60	30	330	855	840			
	0.80	20	280	855	875			
RCA-45	0.50	40	400	1010	670	180	44	224
	0.60	30	330	1010	725			
	0.80	20	280	1010	760			
RCA-MC	0.50	40	400	1050	645	180	39	219
	0.60	30	330	1050	690			
	0.80	20	280	1050	725			
GREY	0.50	40	400	1075	870	180	0	180
	0.60	30	330	1075	935			
	0.80	20	280	1075	975			

The Use of C&DW in Concrete in Cape Town

Table 8.3 continued: Concrete Mix Designs for each aggregate material

^a 90% of 24-hour absorption value used to achieve slump
^b 85% of 24-hour absorption value used to achieve slump
^c Lower water demand required
*SUREBUILD CEM II/B-M (L-S)
**100% RA
***50/50 blend of Klipheuwel and Dune sand

8.5.1 Summary

The high absorption characteristics of RAs make RA concrete mix designs and mixing procedures more complex than those of NA concretes. It is important that bulk density, relative density and absorption properties are carefully determined as these characteristics may vary substantially between RAs. This allows for more accurate mix designs of the required workability, cohesiveness and ultimate hardened strength to be achieved.

The major modification to RA concrete is the addition of added water to the mix to compensate for the high absorption of RAs. A multi-stage mixing procedure was chosen to mitigate this property. It is felt that this approach reduces the absorptive effects of RAs in the most accurate and water efficient manner. This procedure follows 3 phases of material additions namely an absorption, sealing and mixing phase, that are summarised as follows:

- Add 80% of the 24-hour coarse aggregate absorption quantity as added water to the RA to saturate the aggregate. Mix for 30 seconds.
- Add 50% of the binder and 50% of the fine aggregate, followed by 50% of the mix water to coat the RA in concrete paste. Mix for 60 seconds.
- Add the remaining 50% of the binder, fine aggregate and mix water to complete the fresh concrete mix.

The multistage mixing procedure is a successful approach to concrete mixing and with a mix water content of 180 l/m³, a slump of 80 ± 20 mm was achieved by each mix.

Added water quantities were extremely high in the NFP and NFX mixes. These mixes were also harsher and less cohesive than the others. It is recommended that the clay brick materials should probably be blended with NA to reduce the added water requirements. The FBE45 mix has a substantially lower added water demand when compared to the other clay brick mixes. The clay brick mixes were found to

be harsher and less cohesive at higher w:b ratios. Added water demand reduced significantly in RCA and RCA mixes.

8.6 Conclusions

- Absorption capacities can be estimated and should be adjusted according to individual RA properties. 80% of the 24-hour RA absorption value was used in this study for the majority of mixes.
- Added water quantities are 87 l/m³, 95 l/m³, 74 l/m³, 77 l/m³ and 32 l/m³ for the NFP, NFX, BCA-MC, BCA-MV and FBE45 mixes. 70 l/m³, 25 l/m³ and 22 l/m³ added water content were used for the CMA, RCA-45 and RCA-MC mixes.
- The multistage mixing procedure used is accurate in estimating water demand and an effective procedure when mixing fresh concrete.
- After trial mixes, a mix water quantity of 180 l/m³ was established for each mix.
- The added water contents show a 41% - 56% increase in water required by the clay brick aggregates, except for the FBE45 mix which requires a 32% increase in water. A 25% and 22% increase in water is required of the RCA mixes.
- A slump of 80 mm ± 20 mm is achieved by all the mixes. The RA, in particular the clay masonry RAs are harsher and less cohesive at higher w:bs.

8.7 References

Alexander, M. G. & Heiyantuduwa, R. 2002. *Recycled Concrete Coarse Aggregates and its Potential for use in Semi-Structural Concrete Mixes*. Collaborative research by the University of Cape Town and University of the Witwatersrand.

9 Properties of Hardened Concrete made with RAs

9.1 Introduction

The serviceability, durability and life span of a structure depend on the hardened properties of concrete. These properties are of further importance, as the physical characteristics of aggregate materials do not necessarily dictate the performance of hardened concrete. These properties are therefore of fundamental importance in gauging the potential of site derived coarse aggregates in concrete. The basic hardened properties including compressive strength, shrinkage and elastic modulus of RA concrete are analysed and discussed in this chapter.

9.1.1 Composition of RA Concrete

A photograph of the composition of each RAC is shown in the Figure 9.1.

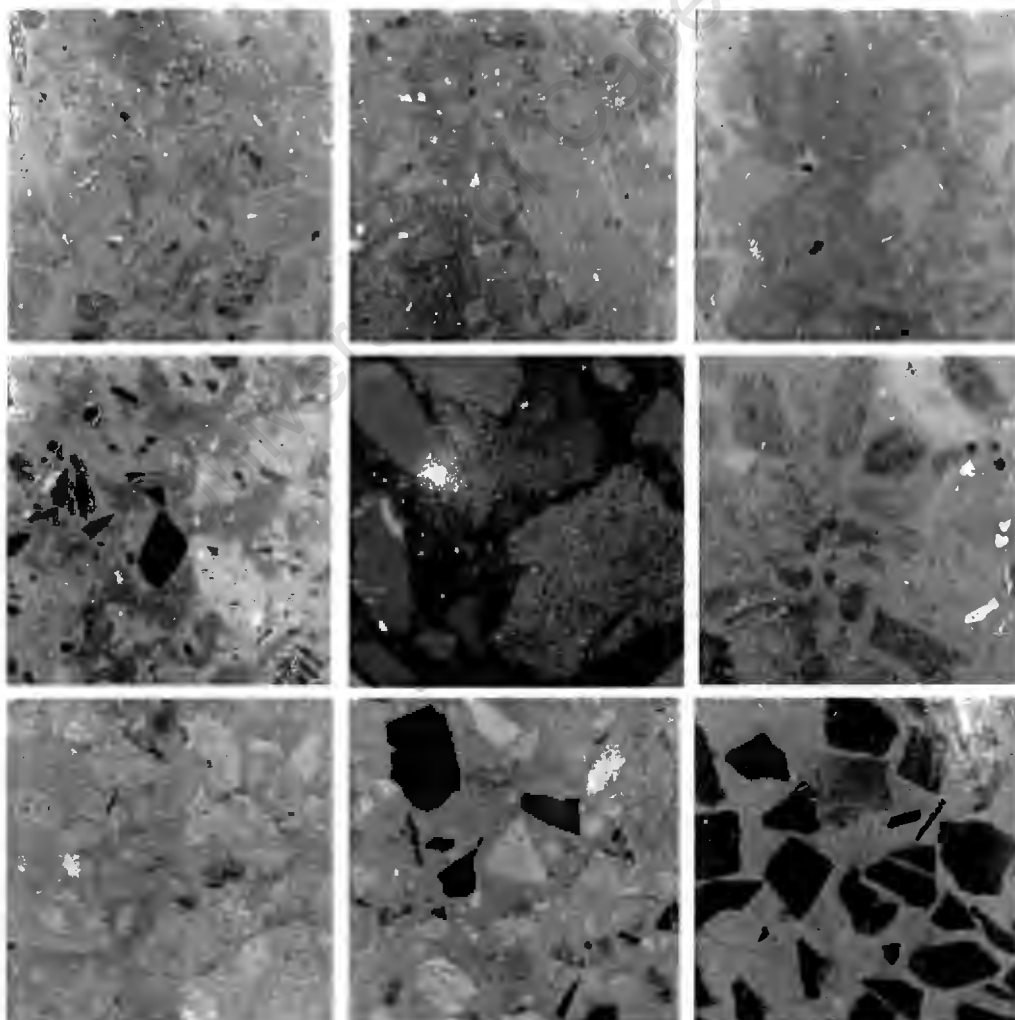


Figure 9.1: From Top, Left to Right, NFP, NFX, FBE45, CMA, BCA-MV, BCA-MC, RCA-45, RCA-MC and Greywacke RACs

A visual representation of the composition of the various RACs is useful to understanding the varied nature and performance of the hardened concrete specimens in this section. From left to right, top to bottom, the order of RACs are NFP, NFX, FBE45, CMA, BCA-MV, BCA-MC, RCA-45, RCA-MC and Greywacke.

The uniform composition of the NFP, NFX and FBE45 clay aggregates and varying composition of the CMA, BCA-MV and BCA-MC is illustrated. The uniform granite virgin aggregate and increased concrete mortar content in the RCA-45 sample is also noted. This is compared to the varied virgin aggregate particles in the RCA-MC sample. The detailed composition and physical characteristics of these aggregates is discussed in previous chapters.

9.2 Compressive Strength

Compressive strength is the most frequently specified property of hardened concrete and is of fundamental importance to structural engineers. The compressive strength of hardened concrete is governed by the strength of the aggregates, cement matrix and bond between the cement paste and the aggregates. The parameters varied between concretes in this study are coarse aggregate type and w:b.

With regard to these parameters, natural aggregates are generally stronger than the hardened cement paste and therefore strength is often dependant on the interfacial bond (ITZ) between the aggregate face and this paste. Results have shown that many of the RAs under question are far less dimensionally stable, have rougher surfaces and are substantially more porous than NAs. This section reveals the effects of these properties on hardened concrete strength. W:b = 0.50, 0.60 and 0.80 are used in each concrete mix. This corresponds to mix design strengths of 20 MPa, 30 MPa and 40 MPa for SUREBUILD cement.

9.2.1 Test Procedure

Compressive testing was carried out according to SANS 5863:2006, *Concrete tests – Compressive strength of hardened concrete*. 100 mm concrete cubes are cured in water at $23 \pm 1^\circ\text{C}$ and tested at 3, 7, 14, 28 and 56 days.

9.2.2 Results and Discussion

The 28-day compressive strengths of the samples is shown in the Table 9.1 below:

The Use of C&DW in Concrete in Cape Town

Table 9.1: 28-day compressive strengths of the RA concretes

Mean 28-Day Compressive Strengths (MPa)						
Aggregate	W:B Ratio					
	0.50	Std. Dev.	0.60	Std. Dev.	0.80	Std. Dev.
NFP	44.7	1.0	35.4	1.6	29.2	1.2
NFX	40.3	1.5	35.2	0.6	30.5	0.4
FBE45	40.7	1.2	34.8	1.1	26.9	0.8
CMA	34.9	0.7	27.2	0.3	20.2	0.6
BCA-MC	42.7	2.0	34.0	1.4	29.6	0.7
BCA-MV	39.7	1.0	33.5	0.6	28.0	0.4
RCA-45	47.9	0.4	38.3	1.3	32.1	1.2
RCA-MC	46.1	0.6	37.3	0.8	24.8	1.2
Greywacke	52.0	1.6	41.6	2.9	33.4	0.8

All of the clay masonry and RCA samples reached their mix design strengths of 40 MPa, 30 MPa and 20 MPa in the 0.50, 0.60 and 0.80 mixes. The RCA and Greywacke concretes exceeded their 0.50 mix target strengths by approximately 18% and 30%. The 0.60 and 0.80 w:b mixes all exceeded their 30 MPa and 20 MPa design strength, except for the CMA mix which reached a 28-day strength of 27.2 MPa in the 0.60 w:b concrete. The clay masonry concretes exceeded their 30 MPa and 20 MPa design strengths by approximately 15% and 44%. The RCA and Greywacke concretes surpassed their design strengths by 25% and 39% in the 0.60 mix and 42% and 67% in the 0.80 mix.

A relatively uniform increase in strength across most of the samples occurred between the 28-day and 56-day period. Strength increased by an average of 7% in the 0.50 w:b from 28 to 56 days. This compared to a 10% increase in strength in the 0.60 w:b and 8% in the 0.80 w:b concrete. 56 day data is shown in the Table 9.2 below:

The Figures below illustrate the strength development of the various RA concretes. Strength development is normal across the majority of RAs with the concrete gaining strength, at a decreasing rate with time. The RA concrete strengths are proportional to the strength of the RA in most cases with the Greywacke and RCAs having the greatest ultimate strength, followed by the clay masonry RAs in the FBE45, BCA-MC and other samples.

The Use of C&DW in Concrete in Cape Town

Table 9.2: 56-day compressive strengths of the RA concretes

Mean 56-Day Compressive Strengths (MPa)						
Aggregate	W:B Ratio					
	0.50	Std. Dev.	0.60	Std. Dev.	0.80	Std. Dev.
NFP	45.2	0.3	38.7	0.5	33.2	1.0
NFX	41.7	0.5	36.6	1.3	29.6	1.4
FBE45	46.7	0.8	39.7	0.6	29.4	1.0
CMA	35.8	0.8	29.2	1.0	22.3	0.6
BCA-MC	44.9	1.3	38.2	3.7	33.7	0.6
BCA-MV	44.0	0.2	37.7	1.6	30.8	1.1
RCA-45	50.5	0.6	41.5	0.7	34.5	0.1
RCA-MC	49.8	2.4	41.3	0.2	25.1	0.8
Greywacke	56.8	0.2	47.9	0.3	36.1	1.0

The NFP and NFX concretes develop in strength at varying rates and to different degrees in the 0.50 and 0.80 w:b concretes. This is of interest as these materials are of very similar virgin strength and composition. In the 0.50 w:b mix, the NFP develops at a greater rate and reaches a higher strength than the NFX. In the 0.80 w:b mix strength development from 3 days to 28 days is greater in the NFX concrete when compared to the NFP concrete. The development of strength in these concrete samples with a 0.60 w:b is almost identical.

The FBE45 concrete produces the strongest 56-day clay masonry concrete however strength development is the slowest between the 3 to 28-day period in all the mixes. Increased late strength development between 28 and 56 days is seen in the 0.50 and 0.60 w:b mixes.

The BCA-MC and BCA-MV samples develop strength at a late age. The BCA-MV sample produced the highest early age strength progression between 0 to 7 days in all the mixes. This samples contained the most brickwork mortar in its composition.

The RCA concretes showed increased strength development when compared to the clay masonry concrete. The RCA-MC has higher initial, 0 - 3 day, strength progression when compared to the RCA-45 in the 0.50 and 0.60 mixes. However, the RCA-45 concrete shows greater strength over late ages. This may be a result of the rough surface texture and greater concrete mortar with a low w:b surrounding this coarse aggregate. This may increase the strength of the interfacial bond between the concrete mortar and aggregate as the concrete develops in age.

The Use of C&DW in Concrete in Cape Town

The RACs show erratic strength development in the highest w:b of 0.80. It can be seen that strength development in the RCA-45, BCA-MV and NFX samples is rapid from 0 to 7 days. The rate of strength development then decreases in the RCA-45 and BCA-MV concretes as curing continues. The RCA-MC concrete mix did not develop as expected and is below the RCA-45 concrete in strength. This may have been a result of an error during fresh concrete mixing. Further unusual behaviour is seen in the high strength of the NFP and NFX concretes when compared to the lowered strength of the FBE45 concrete. It is thought that the extremely high water content and low binder content adversely effected these mixes potentially altering the w:b in many of the concretes. The RAs with higher absorption characteristics such as the NFP, NFX, BCA-MC and BCA-MV all show a greater strengths at the 0.80 w:b ratio. This may indicate that more water is stored in the aggregate pores therefore reducing the adverse effects of the increased water content. This is illustrated in the Figures 9.2, 9.3 and 9.4. A comparison of individual RA concrete with varying w:b ratio can be seen in Appendix J.

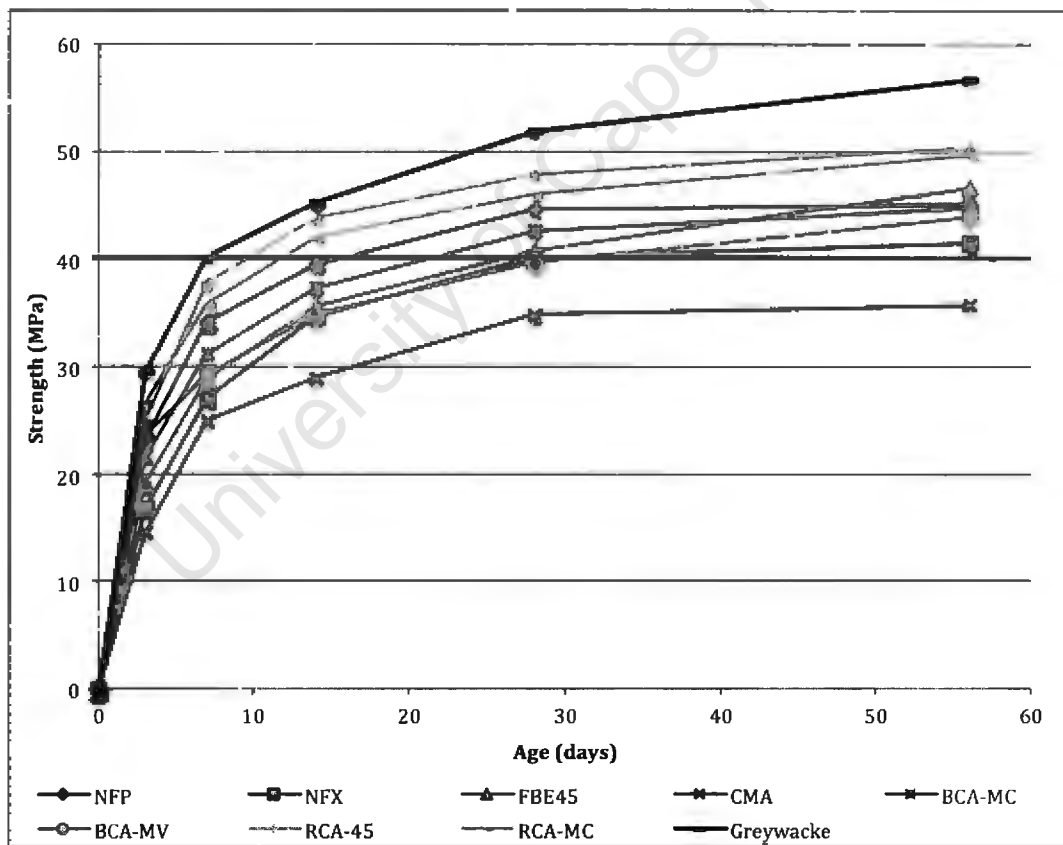


Figure 9.2: Compressive strength development w:b = 0.50 (40 MPa target strength shown by red line)

Figure 9.5 shows the variation in compressive strength between w:bs. Compressive strength decreases with increased w:b as expected. An unusual variation in compressive strength development in the 0.80 concrete mix can be seen in the RCA-MC and FBE45 concretes. The mixes show the largest deviation in strength reduction from 0.60 to 0.80 w:b ratios.

The Use of C&DW in Concrete in Cape Town

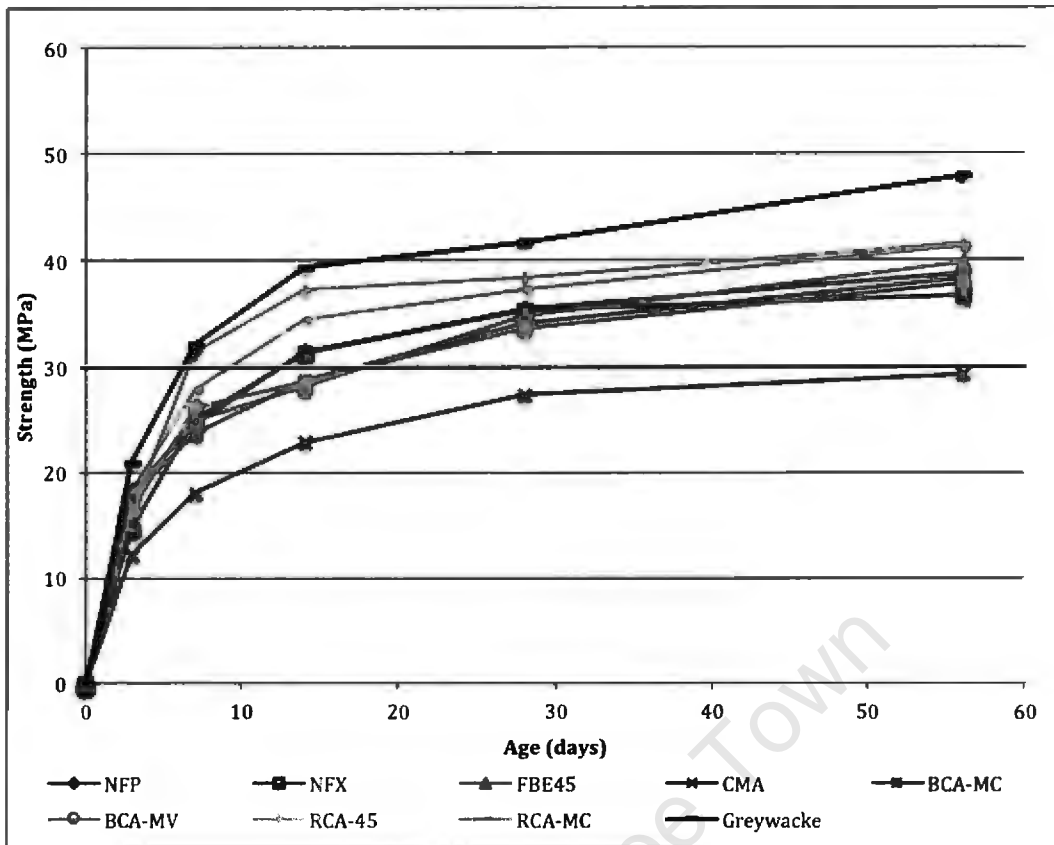


Figure 9.3: Compressive strength development w:b = 0.60 (30 MPa target strength shown by red line)

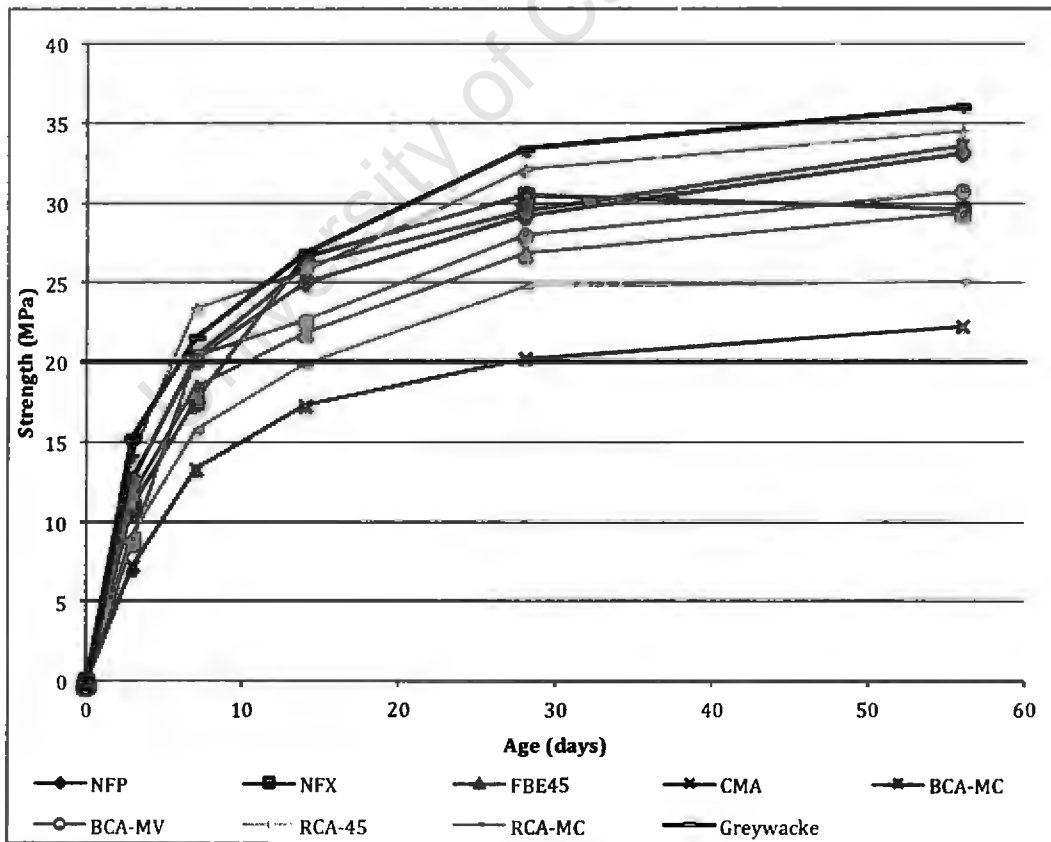


Figure 9.4: Compressive strength development w:b = 0.80 (20 MPa target strength shown by red line)

The Use of C&DW in Concrete in Cape Town

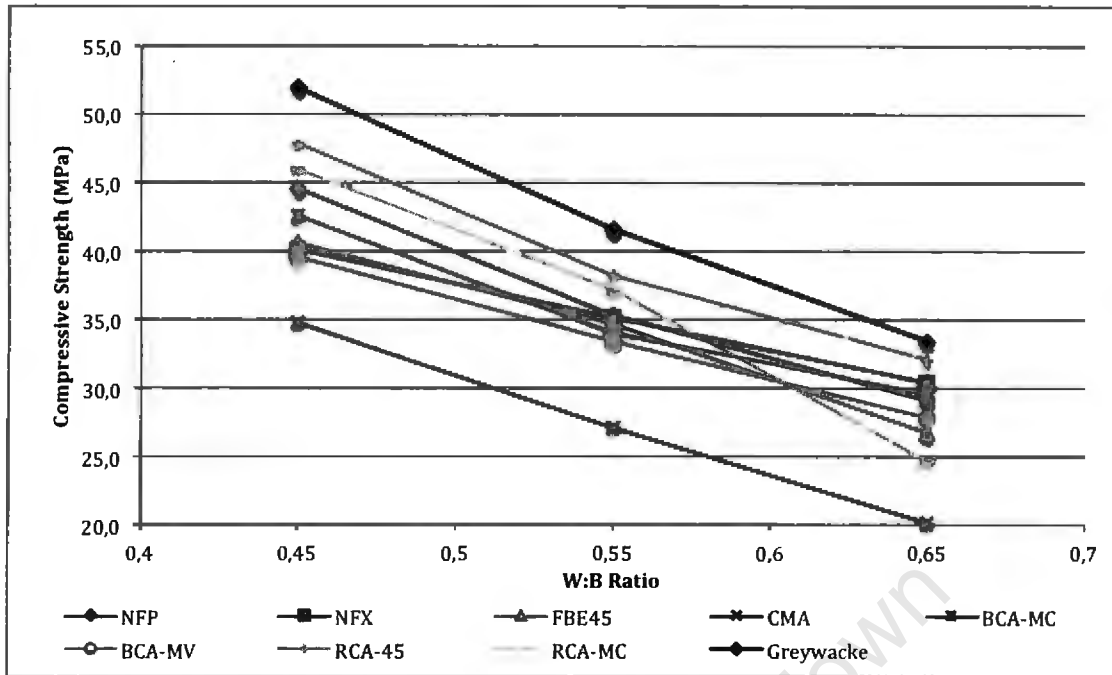


Figure 9.5: Variation in 28-day compressive strength between w:b ratios

These variations are generally more linear at 56-days, especially between the 0.60 and 0.80 w:bs. However, the FBE45 and RCA-MC samples still deviate from the trend between mixes.

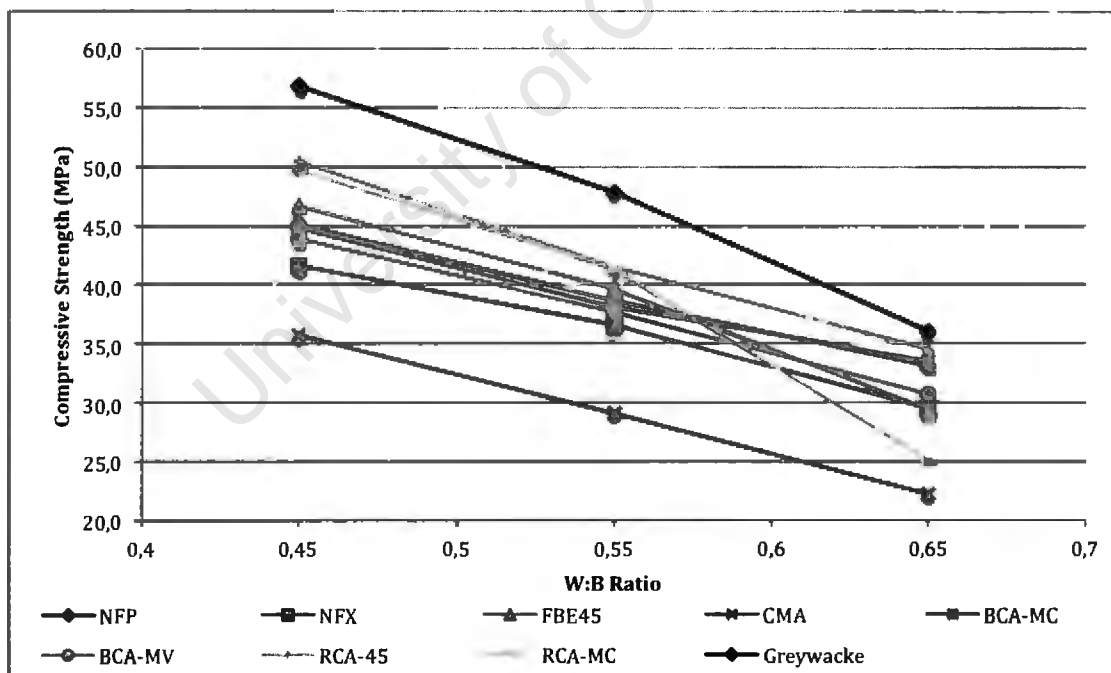


Figure 9.6: Variation in 56-day compressive strength between w:b ratio

There are large variations between the NAC and RACs in Figure 9.5 and 9.6. Consequently, cement content to achieve similar NAC compressive strengths increases substantially with RAC use. This is demonstrated in the Greywacke concrete, which reaches a 56 day compressive strength of 52 MPa with a w:b of 0.5. Comparatively the same 0.5 w:b results in concrete compressive strengths of 45 MPa in the

The Use of C&DW in Concrete in Cape Town

RCAs and between 39 MPa and 43 MPa in clay masonry RAs. These disparities decrease with higher w:bs showing that these materials are suited to lower grade applications.

The increased binder content required to achieve the same target compressive strength when using the various RAs is tabulated in Table 9.3. This shows the percentage increase in binder content required to achieve a 28-day strength of 35 MPa with each aggregate type using Figure 9.5.

Table 9.3: Percentage increase binder content required to achieve a 35 MPa target strength

35 MPa Target Compressive Strength		
Aggregate	W:B Ratio	Increase in binder quantity
		%
NFP	0.55	12.7
NFX	0.55	12.7
FBE45	0.55	12.7
CMA	0.45	28.6
BCA-MC	0.54	14.3
BCA-MV	0.53	15.9
RCA-45	0.60	3.2
RCA-MC	0.57	9.5
Greywacke	0.63	0.0

Binder (cement) is seen as one of the largest contributors to the environmental impacts of concrete. As is seen in Table 9.3, increased binder content is required to achieve similar 28-day concrete strengths to that of Greywacke stone. This reveals that RA use may negatively affect sustainability in some cases. However, when materials that are sourced on-site, thereby mitigating material transportation impacts, and with labour intensive on-site processing, CO₂ emissions and energy usage reductions may prove to be more substantial than the increased binder use. This quantification is beyond the scope of this study.

9.2.2.1 Density

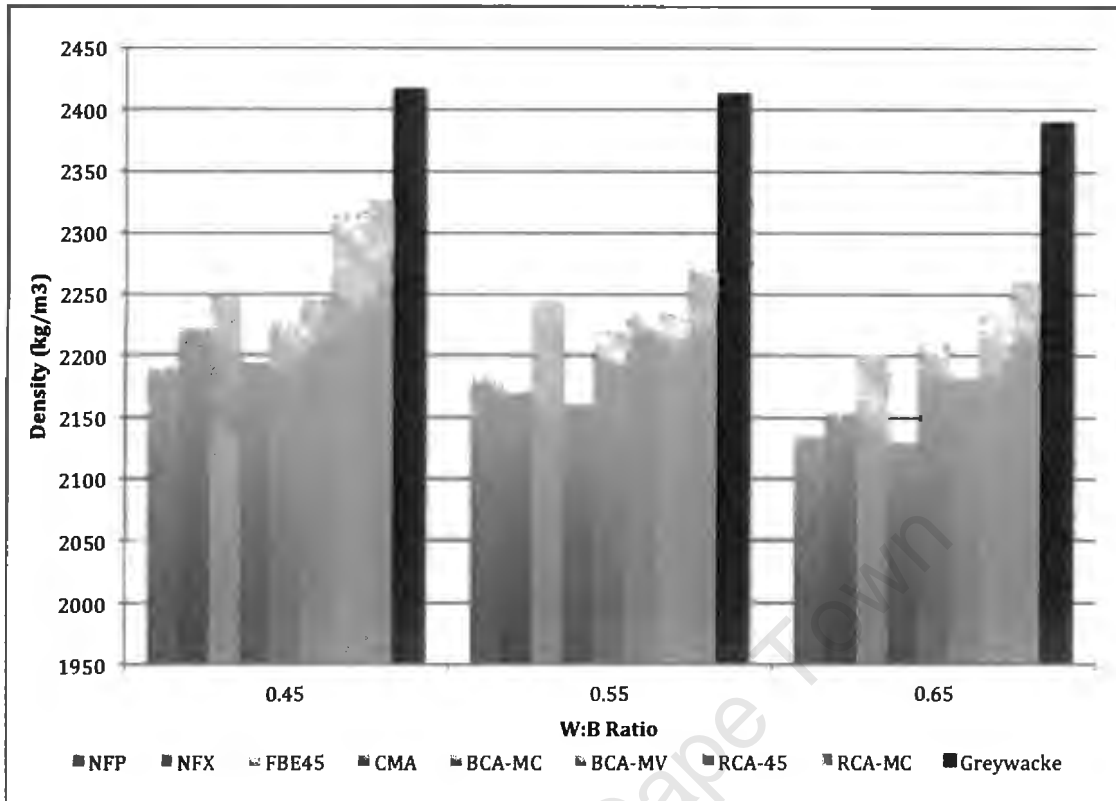


Figure 9.7: 28 Day Density of Hardened Concrete 80 (the bars follow the order of the legend)

When comparing the density of the RAs at 28 days, the density of the masonry concretes is approximately 10% less than that of the Greywacke control. The density of the RCA concrete is generally 5% lower than the Greywacke concrete. The reduction in density is attributed to the porous nature of the masonry, cement and concrete paste particles in the RA concretes. The variation in density across the w:bs and RAs is illustrated in Figure 9.7.

A comparison between w:b ratios shows that generally density decreases with increased w:b. Hardened concrete density increases with increased aggregate density as expected. The variation in density between w:b ratios in the RA samples is more noticeable and random than in the control concrete. These occur in the virgin samples, which have a uniform composition, as well as the mixed composition samples. RA concrete properties may vary considerably between RA concrete and RA materials batches.

9.2.2.2 Failure Patterns of RACs

Analysis of the failure mechanisms of the concrete cubes yields shows a distinct difference between the higher strength aggregates (RCAs) and lower strength aggregates (masonry).

Inspection of the BCA-MV sample shows the composition of this RA concrete. From Figure 9.8, various types of clay brick material as well as large pieces of brickwork mortar can be seen in the failure surface of the cube.



Figure 9.8: Failure of BCA-MV concrete cube under compression

Closer inspection of the RA, Figure 9.9, shows clear fractures through the weak clay masonry aggregate pieces as well as the mortar piece. From the rough surface of the mortar piece it is thought that the cube sheared through this weak material upon failure.

This characteristic is repeated in the failure of the NFP concrete. Fractures through the coarse aggregate can again be seen in Figure 9.10. Fractures are represented as the dashed lines. Separation of the concrete paste from the aggregate surface (failure along the ITZ), as is the general failure mechanism in NA concrete, is shown by the red circle in the Figure 9.10. The effect of a rough surface in increasing shear capacity can be seen by the quantity of concrete mortar stuck to the surface of this RA particle. The clean, exposed faces of the coarse aggregate pieces also show a shear failure through the aggregate matrix. This shows that an improved ITZ in clay masonry RAs may result in tension and/or shear failure through the weak coarse aggregate particles rather than failure along the ITZ as is the case in NA concrete.

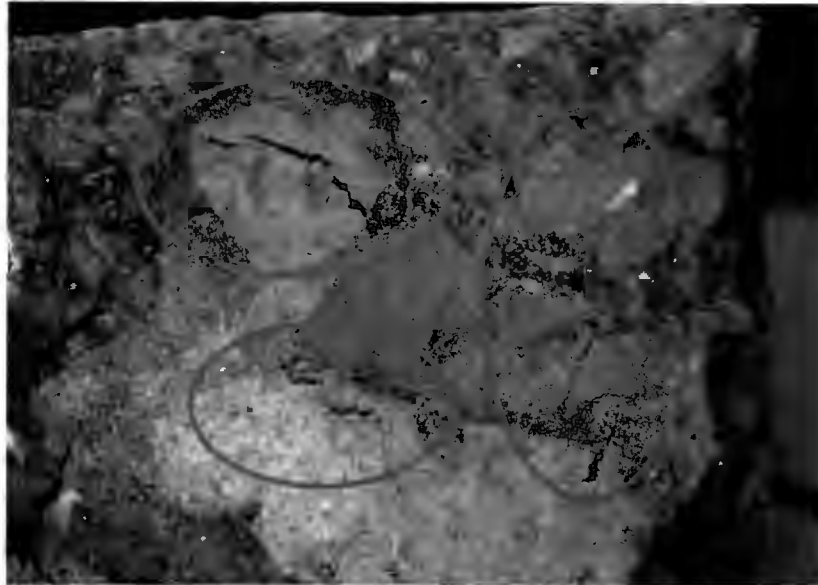


Figure 9.9: Photograph of fractures through weak clay masonry and mortar



Figure 9.10: Photograph of the failure (red lines) in the NFP concrete under compression

This can be compared to the cracks seen in the RCA-45 and RCA-MC samples in Figure 9.11 and 9.12. These cube failures show crack patterns along the perimeter and through perimeter concrete mortar. This shows that these aggregate particles did not fracture but failure through the concrete mortar.

The failure lines do not follow the exact contours of the aggregate particles as can be seen by the dashed red lines in the Figures 9.11 and 9.12. In some cases they follow a path around and perimeter of concrete mortar that surrounds the RA particles. This shows the failure between the old adhered mortar and the new concrete mortar, rather than at the aggregate paste interface. Rough, grey surfaces as well as exposed smooth surfaces can be seen on the coarse aggregate particles. Similarly, this shows where new

The Use of C&DW in Concrete in Cape Town

concrete mortar has bonded to the irregular surfaces of the RCA and either failed at the virgin aggregate interface or at the old mortar interface.

These Figures can be compared to the failure of the Greywacke cube, Figure 9.12, in which smooth defined aggregate faces are exposed and clear cracks are seen at the aggregate paste interface. This illustrates that failure in Greywacke concrete occurs only along the ITZ in the strength range defined in this study. This is dissimilar to the clay masonry that fails through the aggregate.

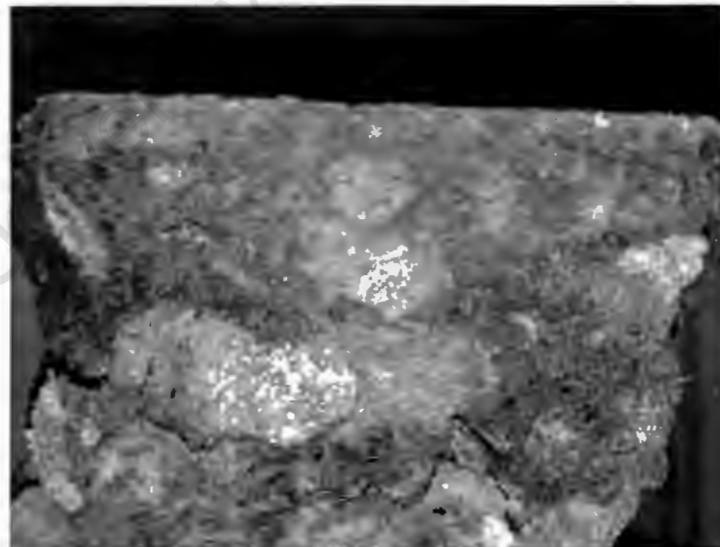
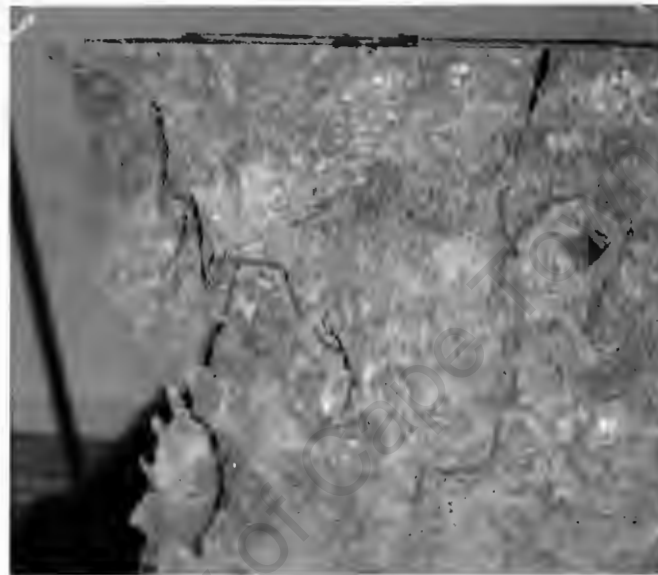


Figure 9.11: Red lines showing failure cracks in RCA-45 (Top) and RCA-MC (Bottom) concrete cubes under compression

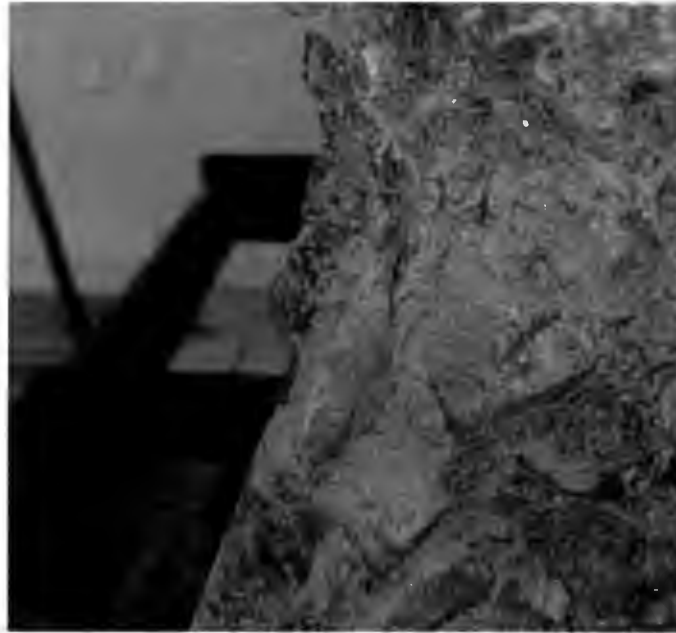


Figure 9.12: Red lines showing failure of Greywacke concrete cube under compression

9.3 Shrinkage

Concrete undergoes volume changes throughout its existence. Shrinkage is the time-dependant volume change in both fresh and hardened concrete. Concrete shrinkage is predominantly due to volume changes in the cement paste. The factors effecting shrinkage include w:b, binder type, moisture content of concrete, admixtures and aggregate properties. Member geometry and size, curing and drying conditions such as relative humidity and temperature also affect the degree of shrinkage. The parameters varied between concretes in this study are course aggregate type and w:b.

There are various types of concrete shrinkage such as plastic, autogeneous, carbonation and drying shrinkage. Drying shrinkage is measured by this experiment as samples are cured for 7 days before testing is begun. This is usually of most interest to structural engineers. Drying shrinkage is a result of loss of excess moisture to the environment in normal-strength ($w:b > 0.4$) concrete. The rate of moisture loss is slow creating a time dependant strain response.

The structural repercussions of shrinkage on concrete include detrimental cracking and deflections. Unrestrained concrete will not crack however, this is rarely achieved in practice. Cracking due to shrinkage may result in frequent, random cracks of significant size. This may be aesthetically unpleasing and may cause cracking or popping of tiles, other finishes and jamming of windows and doors. Cracking is also detrimental to achieving concrete durability. Shrinkage may increase deflections in structural concrete by increasing curvature in unsymmetrically reinforced members and may also lead to additional tensile stresses that increase deflections above the load induced deflections (Alexander et. al.

2009). COLTO (1998) specifies a maximum shrinkage value of 400×10^{-6} (400 micro-strain) for concrete structures.

9.3.1 Test Procedure

Drying shrinkage testing was carried out on 100 mm by 300 mm cylinders for 56 days according to SANS 6085:2006, *-Concrete tests- Initial drying shrinkage and wetting expansion of concrete*. BCA-MC and RCA-MC 0.60 w:b concrete data is not available due to equipment failures and materials quantity constraints.

9.3.2 Results and Discussion

Table 9.4 below shows the numerical shrinkage values of each RA concrete across the various w:bs.

Table 9.4: 56-day shrinkage values in micro-strain

56-Day Shrinkage x 10 ⁶ (micro-strain)			
Aggregate	W:B Ratio		
	0.50	0.60	0.80
NFP	260	290	350
NFX	240	280	340
FBE45	240	250	300
CMA	430	560	600
BCA-MV	260	300	340
RCA-45	560	570	610
RCA-MC	490	-	530
Greywacke	340	370	420

Contrasting behaviour is seen when comparing the strain development of the clay masonry concrete when compared to the RCA concrete. Clay masonry aggregates reduce clay masonry concrete shrinkage whereas RCAs increase RCA concrete shrinkage over a 56-day period. This can be seen numerically in Table 9.4 and is also illustrated by Figure 9.13.

The Use of C&DW in Concrete in Cape Town

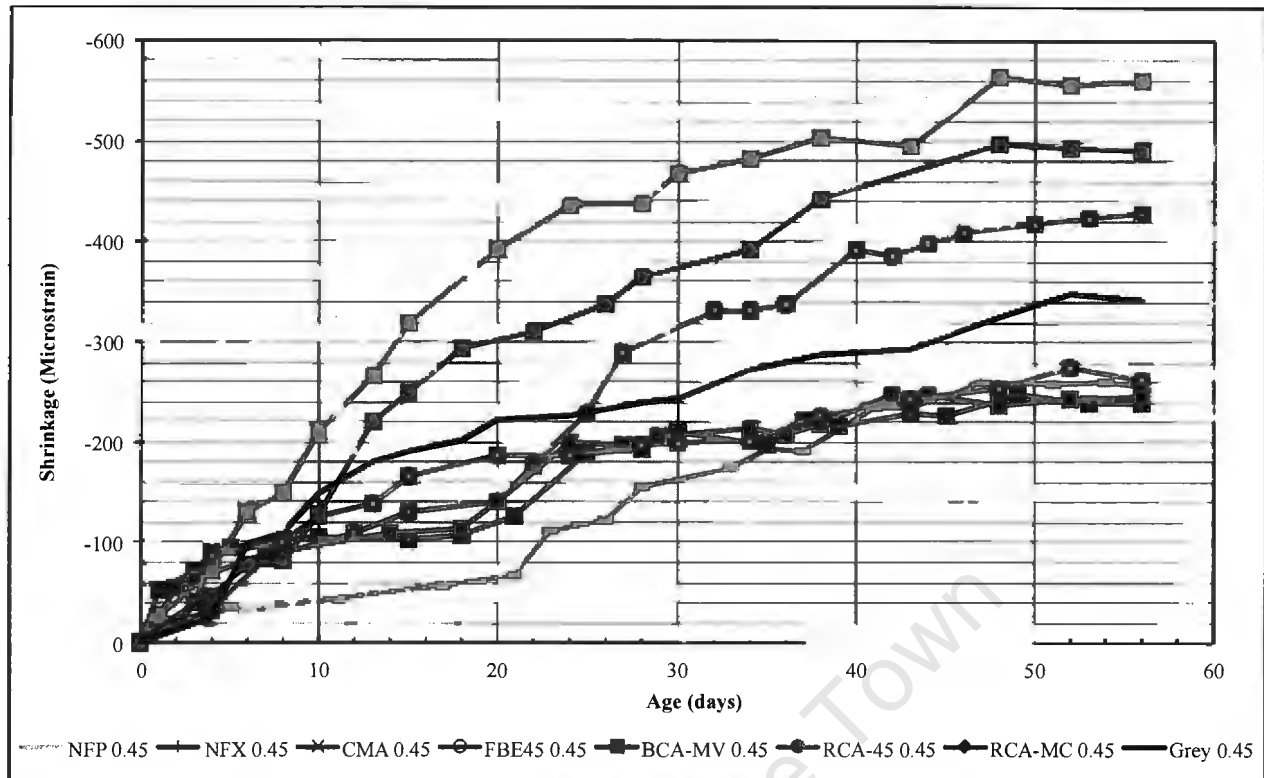


Figure 9.13: Shrinkage chart showing all RA concretes with w:b 0.50

Figures 9.14, 9.15 and 9.16 show that less shrinkage occurs in all the clay masonry aggregate concretes. Clay masonry RAC shrinkage is less than the control Greywacke concrete by an average of 23%. This reduction in shrinkage ranges from 26% in the concrete of w:b = 0.50 to 20% in the concretes with w:b = 0.80. Less shrinkage in masonry aggregate concrete is also reported by Mansur et. al. (1999) and Bektas et. al. (2009). When one compares shrinkage across the various w:b's of the clay RACs. An average decrease in shrinkage of 32% is seen from w:b = 0.80 to w:b = 0.50. The CMA concrete has significantly higher shrinkage across all the w:b's. The Clay masonry concrete all have relatively similar 56-day strain values in each w:b ratio however, the FBE45 concrete can be seen to show the lowest shrinkage in each w:b after 56-days. Shrinkage strain development is erratic but more linear in the clay masonry concretes when compared to the parabolic shape of the CMA, Greywacke and RCA concretes. As discussed in the literature review, drying shrinkage is a result of loss of excess moisture to the environment in normal-strength (w:b > 0.4) concrete. This data shows that absorbed water in RAs replaces the moisture lost to the environment, reducing shrinkage in RA concrete, especially in aggregates with a high absorption potential such as clay masonry aggregates.

The Use of C&DW in Concrete in Cape Town

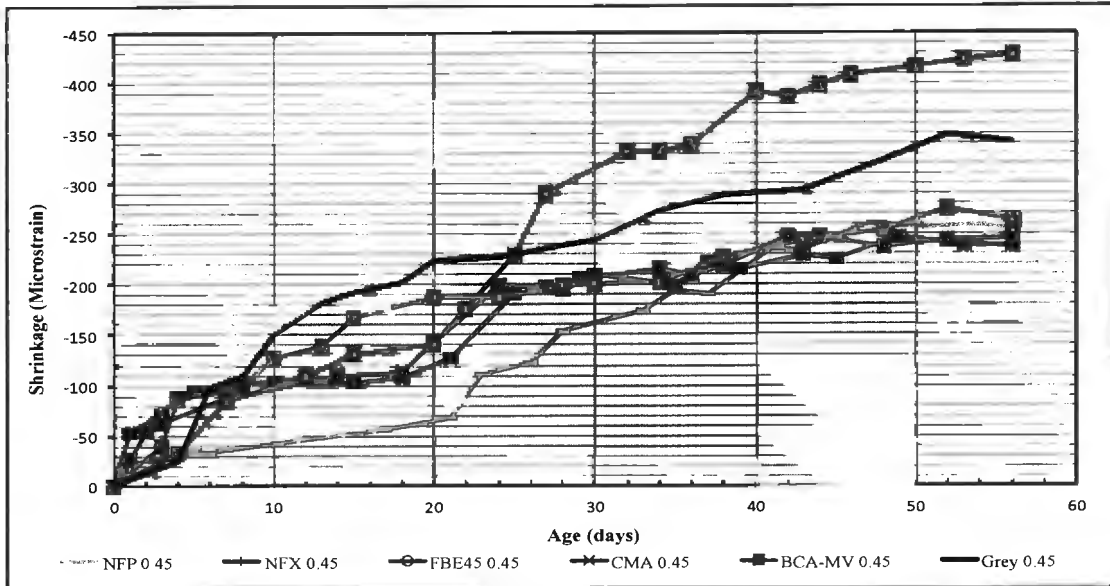


Figure 9.14: Masonry aggregate shrinkage with w:b = 0.50

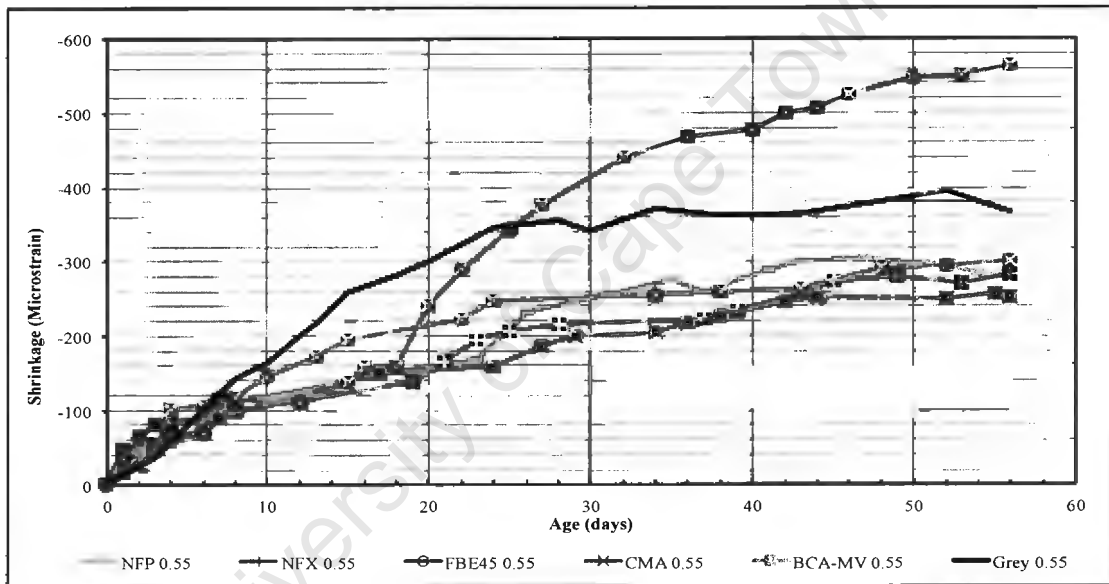


Figure 9.15: Masonry aggregate shrinkage graph with w:b = 0.60

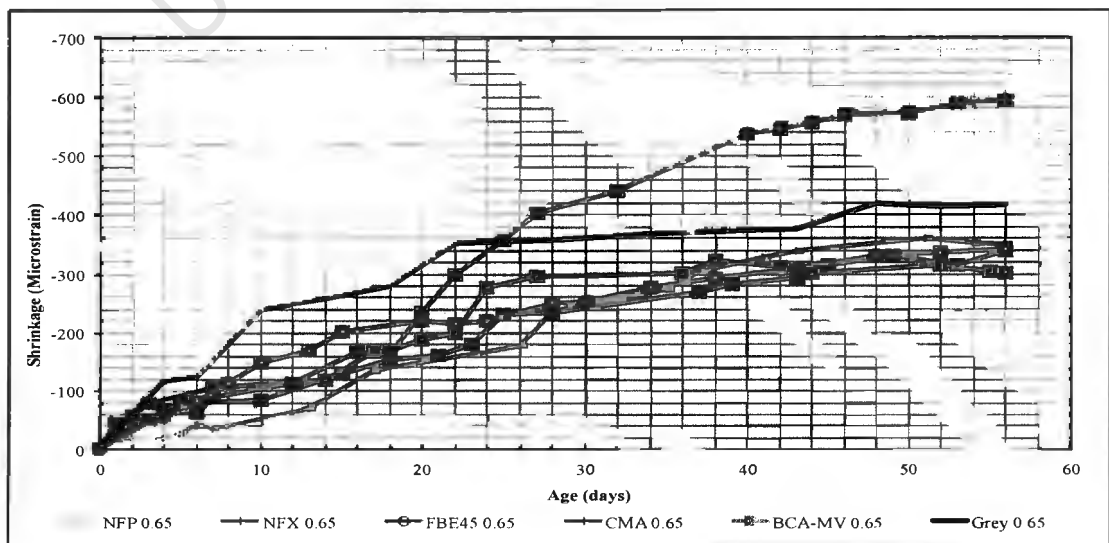


Figure 9.16: Masonry aggregate shrinkage graph with w:b = 0.80

The Use of C&DW in Concrete in Cape Town

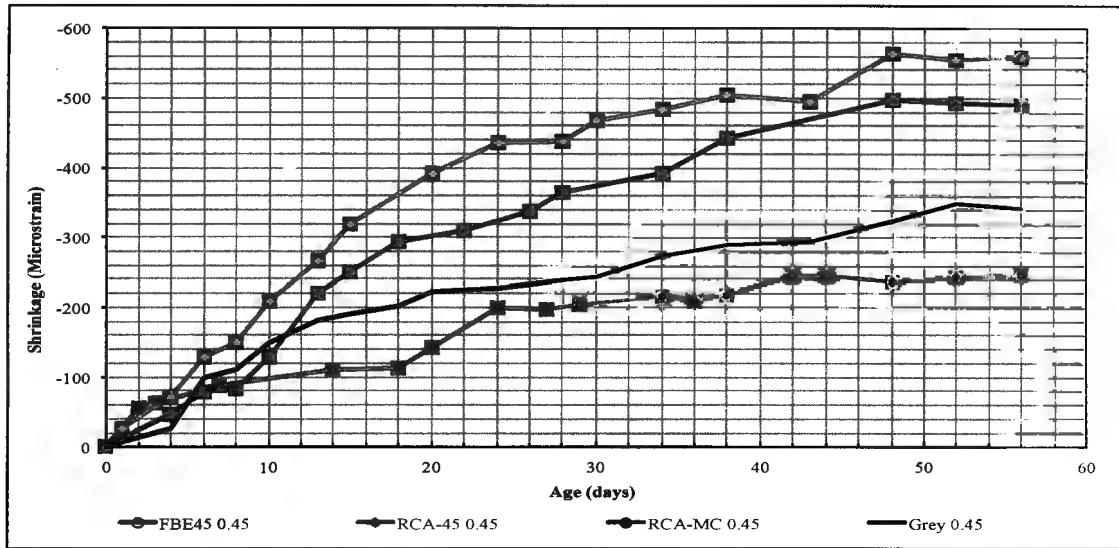


Figure 9.17: RCA shrinkage graph with w:b = 0.50

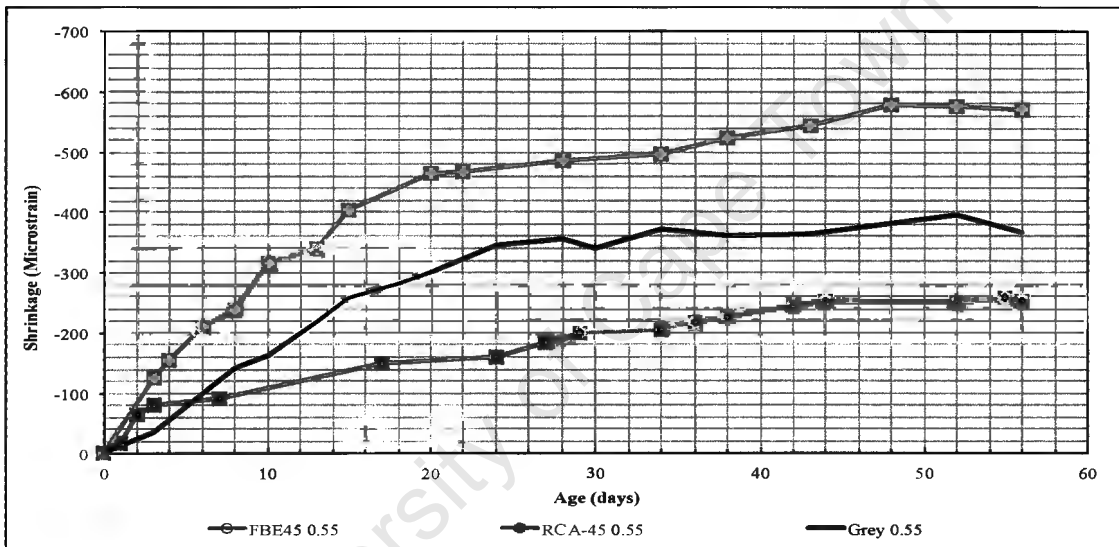


Figure 9.18: RCA shrinkage graph with w:b = 0.60

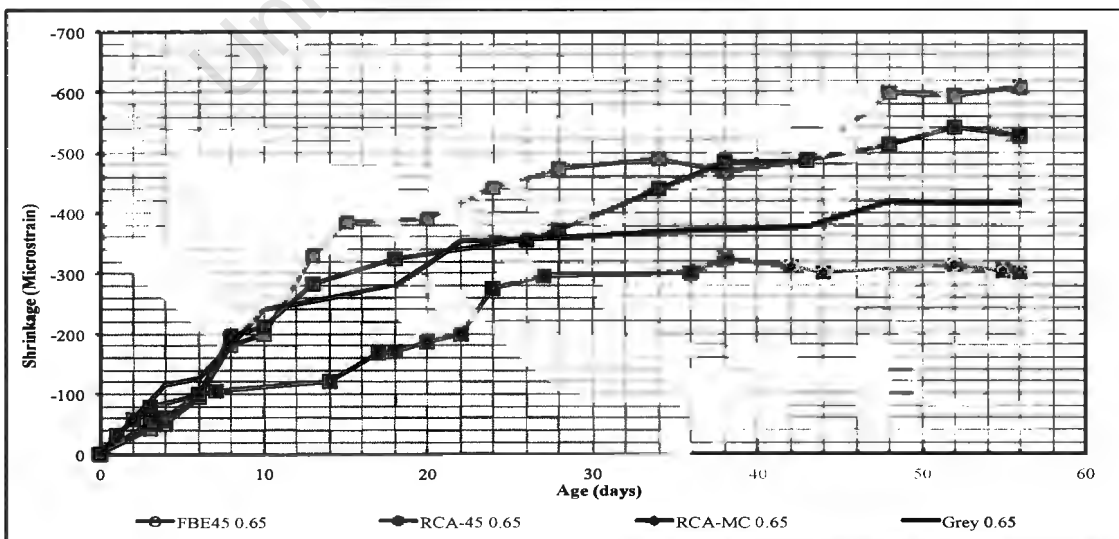


Figure 9.19: RCA shrinkage graph with w:b = 0.80

The Use of C&DW in Concrete in Cape Town

Figure 9.17, 9.18 and 9.19 show the strain progression in the RCA concretes. These are compared to the control Greywacke concrete and the FBE45 clay masonry concrete. These Figures illustrate that 56-day shrinkage increases by an average of 48% in all the RCA concrete when compared to the control Greywacke concrete. This increased shrinkage ranges from 53% in the concrete of w:b = 0.50 to 36% in the concretes with w:b = 0.80. This relates to research done by Eguchi et. al. (2007) who reports increased shrinkage with increased replacement of RCA in concrete.

Shrinkage changes between w:bs in the RCA concrete is less significant than in the masonry aggregate concretes. Shrinkage increase by an average of only 8% between w:b = 0.50 to w:b = 0.80. The RCA-45 concrete shows increased shrinkage when compared to the RCA-MC concrete with w:b = 0.50 and w:b = 0.80. An illustration of the difference between clay masonry shrinkage values and RCA shrinkage can be seen by the inclusion of the FBE45 concrete shrinkage data in Figures 9.17 – 9.19. This shows that clay masonry aggregate concrete shows significantly lower shrinkage than RCA concrete.

Kutugeza (2004) and Bektas et. al. (2009) comment that drying shrinkage may be delayed in RCA concrete since hydration continues due to the presence of internal moisture. This is not evident in this data in w:b = 0.50 and w:b = 0.60 however, slight delayed shrinkage is seen over the 0 to 10 day ages in the concrete with w:b = 0.80. This is seen in Figure 9.19. This delayed shrinkage may be inconsequential as RCA concretes long-term shrinkage is significantly higher than that of the control and clay masonry concretes.

Of further concern is the potential moisture expansion of clay masonry. This is believed to range from 40 to 120 micro-strain (CSIR 1984). From this data this does not seem to be of significant concerns as the clay masonry concrete's shrinkage is lower than that of the control aggregates.

Shrinkage is recommended to fall below 400 micro-strain for use in structural concrete. This parameter is not satisfied across all the w:b ratios in the RCA-45, RCA-MV and CMA concretes. Therefore, shrinkage in RCA and CMA concrete is a concern.

A comparison of individual RA concrete with varying w:b ratio can be seen in Appendix K.

9.4 Elastic Modulus

Elastic Modulus (MOE) is a representation of concrete's stiffness under an imposed stress. A material is considered elastic when it deforms under loading and then recovers completely and immediately to its original form. Concrete is not elastic and its stress-strain relationship is not linear. This is mainly due to response of the concrete paste, the ITZ and to micro-cracking in the matrix under stress. However, the initial portion of concretes stress-strain relationship, approximately 30% - 40% of ultimate strength, may

be regarded as effectively linear (Alexander et. al. 2009, Kutugeza 2004). The ratio of applied stress to longitudinal strain in this region therefore represents the Elastic Modulus or Young's Modulus of concrete.

Elastic modulus is directly proportional to the stiffness of the concrete components and their interfacial affects. The most influential factors are therefore the stiffness of the aggregate and the nature of the aggregate paste interface. This said stiffer aggregates might not result in a greater elastic modulus, especially in concrete of higher strengths. Concrete strength has a lesser influence on the stress-strain relationship when compared to aggregate influence. Therefore, elastic deformation and hence elastic modulus is highly specific to the aggregate elastic properties, content and type (Alexander et. al. 2009, Dittmer et. al. 2012).

9.4.1 Test Procedure

Elastic modulus in this study is derived from static testing and is therefore referred to as static elastic modulus. There is no prescribed SANS test method to determine static elastic modulus. The test method used therefore is based on BS 1881-121:1983 or the ASTM C 469-02 procedures. Static elastic modulus testing is carried out at 28 day and 56 days on cylinders of 80 mm x 150 mm in length. A load is applied to the sample in a Zwick testing machine at two intervals below 40% of their ultimate compressive strength. The stress-strain ratio between the two intervals is used to calculate the elastic modulus of the sample.

28 day Greywacke elastic modulus data is estimated using the SANS 10100-1:2000 expression based on the BS 8110 equation (Alexander & Beushausen 2009):

$$E_{c,28} = K_u + \alpha f_{cu,28}$$

Equation 2: Elastic modulus equation as per SANS10100-1:2000

Where: $E_{c,28}$ is the concrete elastic modulus at 28 days
 K_u is the aggregate stiffness factor (24 GPa for Greywacke stone)
 α is the co-efficient based on aggregate type (0.25 for Greywacke stone)
 $f_{cu,28}$ is the 28 day characteristic cube strength

This expression is used due to equipment failures during the testing period that did not allow 28 day tests to be performed. The 56 day Greywacke test data compares favourably to 56 day values calculated

The Use of C&DW in Concrete in Cape Town

with this equation. Virgin brick aggregate data in the NFX, NFP and FBE45 concretes is also not available due to the same equipment difficulties.

9.4.2 Results and Discussion

MOE results are tabulated in Table 9.5.

Table 9.5: MOE results

Elastic Modulus (GPa)						
Aggregate	28 Days			56 Days		
	W:B Ratio					
	0.50	0.60	0.80	0.50	0.60	0.80
CMA	15.1	12.5	10.3	17.0	15.1	14.9
BCA-MC	20.2	18.4	14.7	21.7	20.8	16.2
BCA-MV	19.7	18.6	17.7	22.4	21.1	19.7
RCA-45	27.9	26.5	19.8	32.2	30.0	22.9
RCA-MC	24.0	21.1	19.1	24.8	24.1	22.5
Greywacke	37.0	34.4	32.4	38.8	35.8	31.5

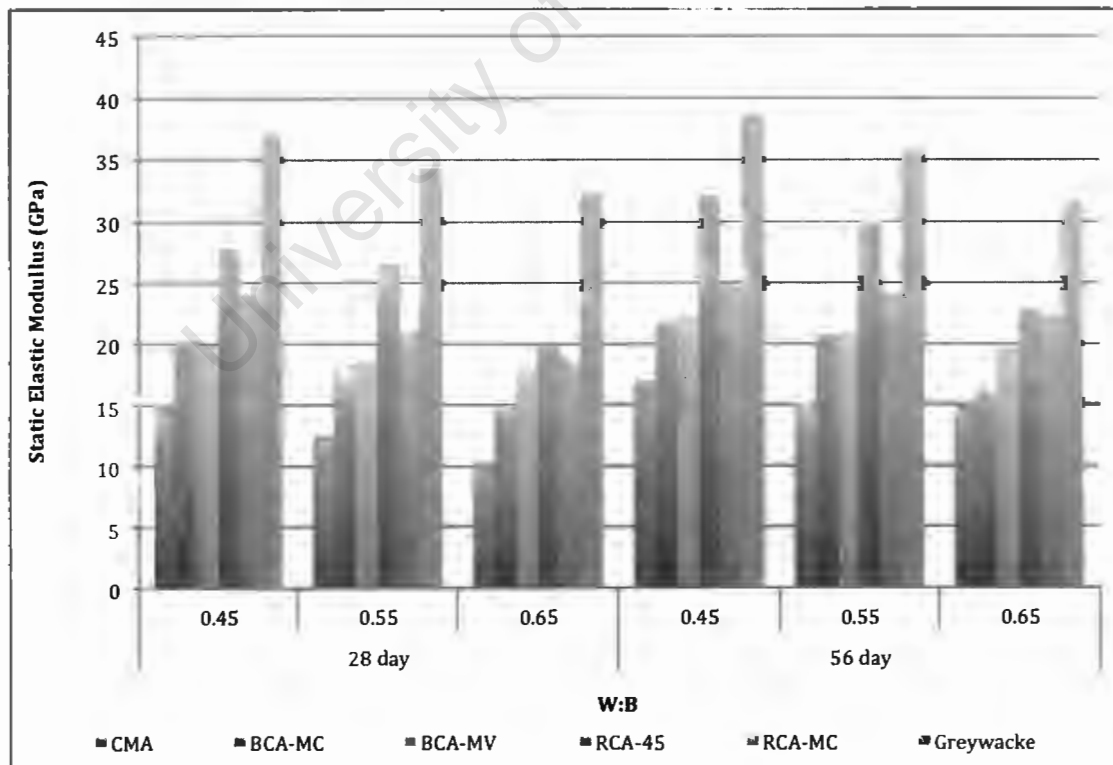


Figure 9.20: Modulus of elasticity with w:b ratios 0.50, 0.60 and 0.80 (the bars follow the order of the legend)

The Use of C&DW in Concrete in Cape Town

Figure 9.21 shows the elastic modulus results for both the control and RA concretes in this study. MOE increases from 28 to 56 days in all the ¹⁶concretes (the bars follow the order of the legend below). The elastic modulus in the clay brick samples is on average 46% lower than the Greywacke at 28 day and 56 day ages. The RCA sample's elastic modulus is on average 33% lower than the Greywacke at 28 day and 56 day ages. This corresponds to a 30% - 50% reduction in elastic modulus for clay brick aggregates from Poon & Chan (2000) and a 20%-30% reduction by RCAs by Agrela et al. (2011). The CMA concrete reached only 40% of the elastic modulus of the control concrete.

The BCA-MC aggregate has a dry aggregate strength, in the ACV test and 10% FACT, and concrete compressive strength that is greater than the BCA-MV aggregate and BCA-MV concrete. However, there is not a significant difference between the elastic moduli of these aggregates. Similarly, the RCA-45 has a lower aggregate strength but has a substantially greater elastic modulus than the RCA-MV in the lower w:bs.

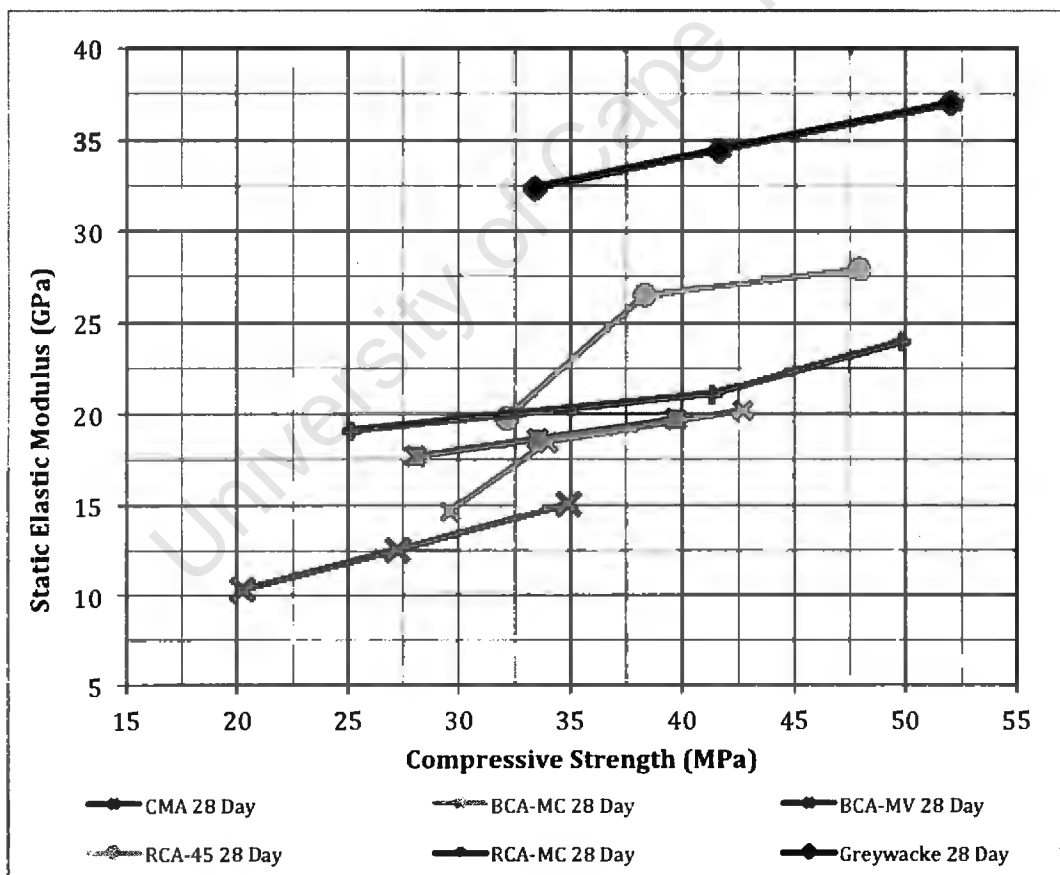


Figure 9.21: Relationship between static elastic modulus and concrete cube strength at 28 day age

¹⁶A slight decrease in MOE in the Greywacke, w:b = 0.80 is seen as 28 day values were calculated numerically and 56 day values are from experimental data.

The Use of C&DW in Concrete in Cape Town

The elastic modulus of the BCA-MV may be improved by excess water being sealed and stored within the porous clay brick aggregate. This may be a result of the higher absorption and therefore added water content in this aggregate. This may create a more elastic response and increase the elastic modulus of this concrete. Evidence of this is seen in Figure 9.21 where the BCA-MV concrete has a higher elastic modulus than the BCA-MC concrete, at both 28 days and 56 days, at a higher water content (w:b of 0.80). This pore water may be detrimental at higher strengths as under increased stress the pore water pressure may cause the relatively weak BCA-MV aggregate to fail. This is illustrated in Figure 9.22 and 9.23. The trend line of the BCA-MC concrete is steeper than the BCA-MV concrete showing that at higher stresses this aggregate is stiffer. It is possible that this stiffening effect would have been seen in the other clay masonry aggregate concretes had they been tested

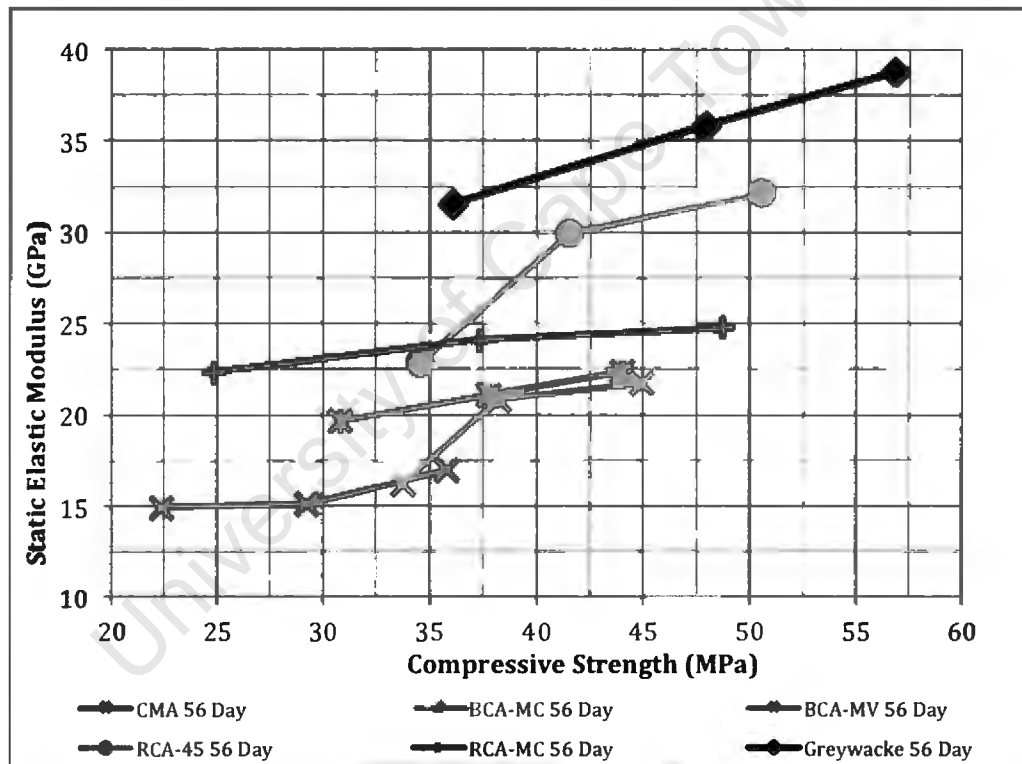


Figure 9.22: Relationship between static elastic modulus and concrete cube strength at 56 day age

The RCA-45 virgin aggregate is made up solely of granite whereas the RCA-MC virgin aggregate is comprised of varying stone materials. This is illustrated in Figure 9.23. The Figure on the left shows the RCA-45's granite virgin aggregate. The Figure on the right shows the RCA-MC virgin aggregate, which is made up of variable virgin aggregate such as granite and greywacke.

Granitic aggregates are known to not enhance the stiffness of concrete even though they may be stiffer than other stone aggregates. This is due to variability in this material's quality but also because the stiffness of this aggregate leads to greater micro-cracks and failure of the ITZ in concrete when put

under stress. However, other ‘stiff’ aggregates such as andesite and dolerite have shown have significant stiffening affects in concrete (Alexander et. al. 2009, Dittmer et. al. 2012). It is thought that the large quantity of high strength concrete mortar surrounding the granite RCA may reduce the stiffening affects of the virgin aggregate and increase the elasticity of the RCA-45 concrete. The ITZ of the RCA-45 is thought to be enhanced due to the rough nature of the surrounding old concrete paste on the RCA. The increased elastic modulus in the RCA-45 may also be a result of the highly variable virgin aggregate in the RCA-MC.

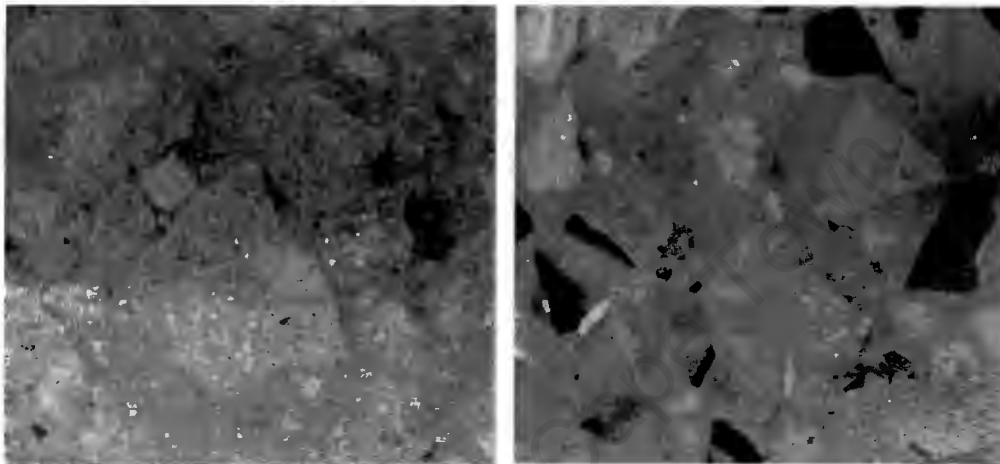


Figure 9.23: Granite virgin aggregate in the RCA-45 concrete (Left) and variable virgin aggregate in the RCA-MC concrete(Right).

9.5 Conclusions

Compression

- Masonry RACs have approximately 90% of the density of Greywacke concrete.
- RCA concretes achieve approximately 95% of the density of Greywacke concrete.
- Low strength masonry RA concrete strength is not proportional to the virgin masonry strength and may fluctuate considerably. This is illustrated by the NFP and NFX concrete in this study.
- The FBE45 concrete has slow strength development at early ages. Therefore high strength virgin masonry may develop in strength at a slower rate than NA concrete.
- BCA-MC and BCA-MV concretes develop in strength at a late age. 28 day and 56 day strengths of these samples are similar indicating that mixed masonry RAs may not reach strengths that are proportional to their crushing strengths.
- Increased added water content in w:b above 0.80 may adversely effect the compressive strength of RA concretes.
- RAs with greater absorptive capacity have more favourable strength development characteristics at higher w:bs.

The Use of C&DW in Concrete in Cape Town

- All of the RA concrete except for the CMA achieved exceeded their mix design compressive strengths.
- Multi-stage mixing is effective and adding 80% of the 24-hour absorption water value as a added water quantity during mixing does no adversely effect the w:b of RA concrete.
- Weak clay masonry RAs fails through the fracture and shearing of the weak aggregate particles as well as failure of the ITZ. This is dissimilar to NA concrete.
- RCAs fail through fracture of the ITZ between the old adhered concrete mortar and the aggregate paste interface. This is similar to NA concrete.
- Binder content needs to be increased with RACs to achieve similar NAC compressive strengths. For a 28-day target strength of 35 MPa, a 12.7% binder increase is required of NFP, NFX and FBE45, 14.3% and 15.9% in BCA-MC and BCA-MV, 28.6% in CMA, 9.5% in RCA-MC and 3.2% in the RCA-45 sample. With increasing w:bs this relationship becomes less pronounced. Therefore RAC is suited to lower grade applications.

Shrinkage

- Clay masonry RA concrete shrinks less than NA concrete. 56-day shrinkage in all the clay masonry aggregate concrete is reduced by an average of 23% when compared to the control Greywacke concrete. This reduction in shrinkage ranges from 26% in the concrete of w:b = 0.50 to 20% in the concrete with w:b = 0.80. FBE45 shows the lowest shrinkage characteristics of all the concretes. CMA concrete has the highest shrinkage of all the RA concretes.
- Shrinkage increases in masonry concrete with increased w:b.
- RCA concrete shrinks more than NA concrete. 56-day shrinkage increases by an average of 48% in all the RCA concrete when compared to the control Greywacke concrete. This decrease in strain ranges from 53% in the concrete of w:b = 0.50 to 36% in the concretes with w:b = 0.80.
- Changes in shrinkage between w:b = 0.50, 0.60 and 0.80 is less significant in RCA concrete compared to masonry RA concrete.
- The absorptive nature and the potential storage of added water within RA pores results in the release, or the internally absorption of this water by the concrete paste over time. This may replace the moisture lost to the environment, especially in aggregates with a high absorption potential such as clay masonry aggregate. Therefore clay brick aggregates may be acting as a self-curing agent reducing overall shrinkage in clay brick aggregate concretes.
- Only the RCA-45, RCA-MC and CMA concretes did not remain below the 400 micro-strain shrinkage benchmark recommended for structural concrete.

Elastic Modulus

- Elastic modulus of RA concrete is less than NA concrete. The elastic modulus of the clay brick samples is on average 46% lower than the Greywacke concrete at 28 day and 56 day ages. The RCA sample's elastic modulus is on average 33% lower than the Greywacke at 28 day and 56 day ages.
- Increased added water and mortar content on RAs may improve RA concrete elastic modulus in w:b above 0.50.
- Increased mortar content and therefore absorption and surface roughness, may increase elastic properties of concrete as is seen in the RCA-45 sample.

University of Cape Town

10 Conclusions & Recommendations

The recycled aggregate industry in Cape Town showed promise around 2001. At that time multiple recycling operations were exploring construction and demolition waste (C&DW) recycling initiatives and the use of recycled materials seemed to be growing as the construction sector found new applications for recycled construction and demolition (C&D) materials. This was mainly in a variety of roadbase and layerwork applications in parking areas and access road applications.

Ten years on (2013), growth in the C&D recycling industry in Cape Town seems to have slowed and recycled products are viewed with suspicion. A major criticism has been the lack of available local codes and standards; however it is suggested that the shortfalls are not within the recycled materials, but in industry's perceptions of these materials as well as current engineering and construction practices. These practices have led to quality control issues, whether perceived by engineers or otherwise, within the production of recycled C&D material and therefore, a disregard for recycled material use within the engineering sector. These quality control issues are linked to recycled aggregate (RA) products that contain varying amounts of C&D materials that are not understood such as masonry, and contaminants such as timber and plastic. The imminent closure of half of the landfill facilities and the subsequent landfill waste management issues in Cape Town, have increased the need for a renewed approach that deals with C&DW. This situation has resulted in an estimated 195 500 tons of C&DW being discarded of and therefore being available for reuse and recycling in the City.

The key to increasing the use of C&D materials is to educate engineers and contractors as to the opportunities and capabilities of multiple C&D materials that can be used individually or can be combined in place of virgin aggregates. Applications for these materials do not lend themselves to high strength concrete, but to the smaller low-grade applications such as housing developments and pavements where concrete of strength below 30 MPa is required. Low-grade applications make up the majority of the concrete construction market, making this approach to material management highly relevant to industry.

Failures to recognise RAs and RA quality control issues are a result of current C&DW management practices. The current approach to C&DW management creates a number of environmental, social and economic repercussions. The largest contributors are the transportation of materials from site either to recycling plants or landfill sites, pressure on the City's landfill facilities and illegal dumping, which is a result of high transportation costs and distances. This research proposes a resource efficient C&D

The Use of C&DW in Concrete in Cape Town

material cycle that involves the identification of C&DWs, the separation of usable materials during demolition, the classification of materials according to their potential use and the processing of recyclable materials on-site. In this approach the contractor performs the role of the commercial C&D recycler. This has the potential to reduce disposal requirements of this waste stream thereby reducing transportation of materials to and from site. Furthermore, by separating C&DWs, opportunities for off-site recycling increase as higher quality, uncontaminated, classifiable materials are made available to the recycling industry.

The development of on-site identification, separation, classification, recycling and re-use protocol relies on two main drivers in:

- Creating an obligation for contractors to identify and separate wastes through updated legislation and enforcement and;
- Providing detailed information to engineers and architects that permits and provides uses for various C&D materials

In the following sections, conclusions and recommendations on material selection, processing, the influence on physical, fresh and hardened properties of concrete and guidelines to the use of RAs in concrete are presented. Lastly recommendations for further research in this field are made.

10.1 Local and International Regulations

In order for a management approach to be successful, positive steps towards developing sound policy and legislative action have to take place. Within this process governmental structures have to develop key initiatives that identify and incorporate specific waste streams. This then creates an environment where a specialist waste-processing sector can develop at local governmental level and practices such as the reuse and recycling of multiple C&D materials can flourish. This process of developing a 'recycling culture' is highly complex as it affects governmental, public and private sector role players.

No single national or provincial Act governs waste per se, however with the formulation of the National Environmental Management: Waste Act (NEM:WA), waste streams can be prioritised through national regulations. NEM:WA requires provincial government to compile Integrated Waste Management Plans (IWMPs) and review municipal waste management programs. The City of Cape Town's Integrated Waste Management (IWM) Policy is a 'response' to NEM:WA. This IWM Policy has led to the passing of the IWM By-law of 2009. This By-law deals with C&DW specifically and gives clear direction to dealing with C&DW management.

The Use of C&DW in Concrete in Cape Town

Currently the IWM planning approach is in an early development stage and is therefore very basic. It is aimed at ensuring that C&D materials are not illegally dumped or stored on City property (i.e. the sidewalk). There is an emphasis on separation, however this is limited to liquids and 'components for recycling'. In short, the By-Law discloses basic obligations of waste generators (owners/developers) to submit an IWMP to the City that deal with storing, transporting and disposing of C&DW at a crushing plant, landfill site or licensed building waste facility.

The requirement of waste generators to separate C&DW at source is key to increasing the use of recycled C&DW in Cape Town. This obligation creates a need for detailed pre-construction/demolition planning to cater for the generation and separation processes. The use of IWMPs that promote C&D separation practices are widespread in California, Australia and Japan. This has been achieved through negotiations with major construction companies and the creation of guideline documents. These documents highlight planning practices in the project planning phase, pre-construction phase, off-site and on-site activities and provide checklists and report templates to be completed by the waste generator that contain information such as company details, site details, materials on site, quantities and persons responsible for disposal, etc. This creates an environment where further stakeholder co-ordination, C&DW targets and goals, detailed characterisation of the C&DW stream, and regulatory actions can be developed. This prerogative can only be fully realised if the C&DW materials that are being produced in Cape Town are fully understood, and applications for these materials are established.

10.2 Processing C&DW into RA

C&DW materials can consist of multiple material components including brick, concrete, plaster, mortar, ceramics, stone, asphalt, plastics, timber, paper and soil. This study analyses virgin clay and concrete masonry, mixed clay masonry and waste concrete. These materials are processed into 19 mm coarse aggregate for concrete and compared to a recognised industry aggregate in 19 mm Greywacke stone. These materials are summarised in Table 10.1:

The Use of C&DW in Concrete in Cape Town

Table 10.1: Summary of materials analysed in study

Summary of Materials Analysed				
Material	Notation	Source	Description of Material	Nominal Grade/ Comp. Strength (MPa)
Virgin clay brick	NFP	Corobrik	Stock/general purpose, virgin burnt clay brick masonry aggregate	7
	NFX	Corobrik	Stock/general purpose, virgin burnt clay brick masonry aggregate	14
	FBE45	Corobrik	Engineering/ paving, virgin burnt clay brick aggregate	45
Virgin concrete brick	CMA	CapeBrick	Virgin concrete masonry aggregate	7-14
Mixed clay brick	BCA-MC	CapeBrick	Burnt clay brick aggregate, mixed with mortar, plaster and soil contamination, CapeBrick sample	Unknown /Variable
	BCA-MV	Illegally dumped rubble, Voortrekker Road, Koeberg Interchange Bridge	Burnt clay brick aggregate, mixed with mortar, plaster and soil	Unknown /Variable
Recycled concrete	RCA-45	Concrete Units, precast yard	Recycled concrete aggregate, granite virgin aggregate	45
	RCA-MC	CapeBrick	Recycled concrete aggregate, mixed concrete and virgin aggregate	Unknown /Variable
Virgin Stone	Greywacke	Peninsula Quarry (AfriSam)	19 mm Greywacke stone (Malmesbury Shale)	-

The Use of C&DW in Concrete in Cape Town

The materials summarised above were processed or what is referred to as recycled into the aggregate analysed in this study. Of importance is an appreciation of the term recycling. Crushing C&DW into aggregate for various applications can be described as downcycling. Downcycling converts waste materials into products of lesser quality and reduced functionality. Downcycling should be the last resort to managing waste before disposal. This study refers to crushing as recycling; however strictly speaking this approach is classified as downcycling.

It is evident that the scale of a crushing operation and the crushing equipment used to process C&DW materials had a significant effect on the properties of RA products. Materials in this study were processed through three basic actions that can be reproduced easily on-site. This consisted of splitting the materials in 'fist-sized' particles, single-stage hand-fed crushing with a small jaw crusher, and manual sieving to remove materials smaller than 4.75 mm in size to yield nominal 19 mm coarse aggregate. This process was efficient with an average yield rate 82% from the waste materials.

Crushing revealed that RA properties were defined more by the type of crusher and stages involved in the crushing process than by their virgin material characteristics. This was especially true of recycled concrete aggregates (RCAs). Large-scale commercial operations pulverise weaker masonry wastes and the concrete mortar surrounding RCAs. Smaller single-stage operations produced less fines material and increase the yield of weaker masonry materials. Therefore simple, labour intensive 'on-site' crushing and sieving was efficient in producing 19 mm coarse aggregate products and removing fines. It is noted that jaw crushing produced flaky clay masonry materials with sharp edges that may not conform to SANS 1083:2006 shape requirements. However, the particle shape of these materials was not dissimilar to that of Greywacke stone.

Of further interest was the consistency of the aggregates that are produced by this method. Physical properties such as grading, fines content and particle shape were similar in materials of the same origin (i.e. clay masonry, mixed masonry, recycled aggregate) even though material strengths may have varied considerably between the samples. This bodes well for contractors/engineers who explore this recycling approach, as technical on-site activities can be inconsistent.

10.3 Influence of RA Materials

10.3.1 Physical Properties

The physical properties analysed in this study included grading, fines content, dust content, chloride content, flakiness index, water absorption, surface saturated density, oven dried density, apparent relative density, bulk density, 10% FACT and ACV.

The Use of C&DW in Concrete in Cape Town

Virgin masonry material's strength had a distinct impact on the physical properties of the RAs. Increased masonry strength resulted in a coarser grading, lower absorption, increased density and increased crushing strength. Increased virgin concrete strength did not affect RCA properties significantly. The crushing equipment used to process this material played a more significant role in dictating its properties.

Mortar content in both masonry and concrete RAs also played a significant role in defining RA physical properties. Increased mortar content led to increased dust content, increased absorption, more rounded RCA shape, lower densities and decreased dry crushing strength. Water absorption was high in the RAs. This was especially true of masonry aggregates. Masonry RAs had absorption values of between 15 – 8% for low and high strength masonry's. RCA's were less absorptive with absorption values between 4 – 5%. Chloride content in RAs may be concern in certain concrete applications and should be established.

The clay masonry aggregates varied in dried density from 1780 kg/m³ to 2120 kg/m³. The RCA-45 and RCA-MV had dry densities of 2230 kg/m³ and 2290kg/m³. The control stone had a dry density of 2690 kg/m³. Apparent relative density was low in NFP, NFX and CMA RAs. Compacted bulk density in the masonry aggregates ranged from 980 kg/m³ to 1200 kg/m³. RCA-45 and RCA-MC had bulk densities of 1310 kg/m³ and 1360 kg/m³. These values were lower than the Greywacke stone at 1535 kg/m³.

Crushing strength may be low for low-strength masonry RAs. Wet crushing results (wet ACV and 10% FACT) in masonry RAs should be viewed with caution, as they tended to show increased crushing capacities. This was due to the compacting together of fine particles when wetted and therefore the reduced ability of materials to pass through fine sieves when dried. Wet sieving would have rectified this outcome. Natural aggregates and RCA showed an inverted trend in this regard with wet testing producing poorer results than dry testing.

Density and absorption potential are of great importance when using RAs, especially in masonry aggregates. The compacted bulk density of low strength masonry aggregates may be below 1000 kg/m³, which may affect concrete properties substantially. Dry density should be established, as surface saturated densities are misleading due to the high absorption potential of these materials. High absorption in coarse aggregates can have deleterious effects on concrete that may not only impact workability but water/binder significantly. It is therefore paramount that this property is established in RA materials. This attribute was also crucial to the multi-stage mixing procedure adopted by this study to mitigate these effects.

10.3.2 Fresh Properties

Fresh properties measured by this study were water requirement, workability and water content. It is important that bulk density, relative density and absorption properties of RAs are carefully determined, as these characteristics may vary substantially between RAs and affect fresh concrete properties. SUREBUILD CEM II/B-M (L-S) binder was used in all of the RACs. A w:b of 0.45, 0.55 and 0.65 to achieve a mix design strength of 20 MPa, 30 MPa and 40 MPa was chosen.

This mixing procedure used in this study was a multi-stage mixing approach. This is described as follows:

- Add 80% of the 24-hour coarse aggregate absorption as added water to the RA to saturate the aggregate. Mix for a minimum 30 seconds.
- Add 50% of the binder and 50% of the fine aggregate, followed by 50% of the mix water to coat the RA with concrete paste. Mix for at least 60 seconds.
- Add the remaining 50% of the binder, fine aggregate and mix water to complete the fresh concrete mix.

This mixing approach was successful, with each mix achieving a slump of 80 ± 20 mm with a mix water quantity of 180 l/m^3 . Masonry RAs required between 32 – 56% and RCA between 22 – 25% increased water (added water) to achieve the desired slump. Total water needed in the mixes ranged from 230 – 275 l/m^3 for masonry RAs and between 219 - 224 l/m^3 in the RCAs. Harsher and less cohesive mixes can be expected from masonry with greater absorption characteristics and recycled aggregate concrete (RAC) with higher w:b.

Multi-stage mixing is the most feasible and accurate, when absorption values are obtained, on-site concrete mixing approach for RA use. It takes into account the absorption potential of each RA with an added water quantity and mitigates the highly absorptive characteristics of RAs. Other approaches such as pre-wetting and pre-soaking are effective in reducing absorption, but they do not provide an accurate understanding of the absorption quantity and therefore water content in a concrete mix. They are also not particularly feasible in on-site operations. Therefore producing fresh RAC, of desired workability, with small mixers or even larger scale on-site batching plants is made possible using the multi-stage mixing procedure. It is noted that larger, high intensity mixers and mixing for long periods of time with this equipment are not recommended as weaker masonry aggregates may be crushed or broken down during the mixing operation.

10.3.3 Hardened Properties

Hardened properties gauged were compressive strength, shrinkage and elastic modulus.

Compressive strength and strength development was variable for masonry RAC particularly at higher w:b. Masonry RAC had late strength development in many cases. All clay masonry aggregates and RCAs reached or exceeded their 28-day mix design (target) strengths; however these strengths were less than the control Greywacke mix. In practice, NAC trial mixes that exceeded their target strength when hardened concrete samples were tested, would be redesigned with a lower cement contents. Therefore cement content may need to be increased with RAC use to achieve similar NAC compressive strengths.

Binder content increased from 4 – 10% in the RCAs, from 13 – 16% in the masonry aggregates and 29% for concrete bricks to achieve the target compressive strengths in this study. With increasing water/binder (decreased target strength) this relationship becomes less pronounced, therefore RACs are suited to lower strength concrete. Binder (cement) content is seen as one of the largest contributors to the environmental impacts of concrete. However, when materials are sourced on-site, thereby mitigating material transportation impacts, and with labour intensive on-site processing, CO₂ emissions and energy usage reductions may prove to be more substantial than the increased binder use. This quantification was beyond the scope of this study.

The RAs in this study performed well in their ability to achieve their target strengths. This was especially evident at water:binder greater than 0.45 (target strength below 40 MPa). These materials should not be specified for concrete above 30 MPa (w:b > 0.55), so this not an undesirable outcome. It is recommended that concrete members, in particular those made with clay masonry aggregates, are not loaded before 14 days as strength development may be slow in these mixes.

The added water aided in reducing 56-day shrinkage in all the clay masonry RAC. Shrinkage was reduced by an average of 23% when compared to the control Greywacke concrete. The absorptive nature and the storage of added water within RA pores resulted in the release of water or the internally absorption of this water by the concrete paste over time. This replaced the moisture lost to the environment and to hydration. Therefore clay brick aggregates act as a self-curing agents reducing overall shrinkage in clay brick aggregate concretes. The opposite is true of RCA concrete as 56-day shrinkage increased by an average of 48% in all the RCA concrete when compared to the control Greywacke concrete.

The reduction in shrinkage found in the concrete made with the clay masonry is a positive outcome. The storage of water within the clay masonry pores and release thereof during the curing process may reduce

The Use of C&DW in Concrete in Cape Town

cracking. The use of these materials may therefore be suited to restrained concrete members and floor slabs. Incorporation of clay masonry aggregate into normal concrete mixes may even present some uses to achieving well cured concrete on-site, as the water released by these aggregates is favourable. The opposite can be said of RCA in which shrinkage should be closely monitored and on-site curing is of importance if cracking is to be avoided.

Elastic modulus was very variable in RACs and lower than that of natural aggregate concrete. Elastic modulus of masonry RAC was on average 46% lower than Greywacke at 28 day and 56 day ages. The RCA sample's elastic moduli were on average 33% lower than the Greywacke at 28 day and 56 day ages.

The reduction and variability in elastic moduli is a concern for the structural use of the RAs. Elastic modulus is used when investigating deflections and cracking in structures. Short-term effects of structures, such as member stiffness are defined by elastic modulus. Long-term effects such as creep also utilise this variable. It is therefore recommended that when designing members for applications in which these properties are of high significance, caution is used in prescribing RCAs in a concrete mix.

10.4 Summary of Major Conclusions

- Limited RA use in Cape Town is not a result of recycled aggregate properties but in industry's perceptions as well as current engineering and construction management practices.
- Creating an obligation to separate C&DW at source (on-site) through updated legislation is paramount. This creates a need for pre-construction/demolition planning to cater for the generation and separation processes. This is being explored by the City of Cape Town in the form of the IWM By-law. The use of IWMPs, such as the City's By-law, are widespread and successful in California, Australia and Japan.
- RA properties were defined more by the type of crusher and stages involved in the crushing process than by their virgin material characteristics. This was especially true of recycled concrete aggregates (RCAs). Simple, labour intensive 'on-site' crushing and sieving is efficient in producing 19 mm coarse aggregate products and removing fines.
- Virgin masonry material's strength had a distinct impact on the physical properties of the RAs.
- Mortar content in both masonry and concrete RAs also played a significant role in defining RA physical properties.

The Use of C&DW in Concrete in Cape Town

- RAs, in particular clay masonry RAs, are extremely absorptive and measures have to be taken to achieve workable fresh concrete.
- Multi-stage mixing is a feasible and accurate, when absorption values are obtained, on-site concrete mixing approach for RA use.
- The RAs in this study performed well in their ability to achieve their target strengths. These materials should not be specified for concrete above 30 MPa ($w:b > 0.55$).
- Concrete members, in particular those made with clay masonry aggregates, should not be loaded before 14 days as strength development may be slow.
- All clay masonry aggregates and RCAs reached or exceeded their 28-day mix design (target) strengths; however these strengths were less than the control Greywacke mix. In practice, NAC trial mixes that exceeded their target strength when hardened concrete samples were tested, would be redesigned with a lower cement contents. Therefore cement content may need to be increased with RAC use to achieve similar NAC compressive strengths.
- Added water quantities aided in reducing 56-day shrinkage in all the clay masonry RAC. Clay brick aggregates act as a self-curing agents reducing overall shrinkage in clay brick aggregate concretes. The opposite is true of RCA concrete.
- Elastic modulus was variable in RACs and lower than that of natural aggregate concrete.

10.5 The Use of RA Materials

Masonry products vary greatly and the classification and use of masonry as aggregate can be problematic if the properties of these products are not fully understood.

This classification of clay masonry by SANS 227:2007 considers aesthetic, strength and durability qualities of clay brick products. The quality of clay bricks with regard to potential for reuse is more easily gauged by understanding the production of clay bricks. Vitrification is the key process whereby clay masonry obtains its strength and durability. In this process clay materials slowly soften and melt. The porosity of the bricks decreases and the strength and hardness increases. The clay masonries used in this study were all coal fired in kilns to reach a phase of adequate vitrification.

Clay masonry can be grouped into sun-baked, also known as green or clinker bricks, 'under-fired' and 'over-fired' bricks. This distinguishes clay bricks into the level of vitrification that they have achieved and therefore their durability, which is of more importance than aesthetic quality for aggregate production.

The Use of C&DW in Concrete in Cape Town

Sun-baked bricks are not suitable for use as aggregates as they deteriorate easily under abrasion and when exposed to water. 'Under-baked' clay bricks have reached a point of vitrification that produces brick strengths of up to approximately 7 MPa, such as the NFP bricks. These bricks are generally used for partitioning walling, non-load bearing walls and internal walls that are to be plastered. They are classified as stock or general-purpose bricks by SANS 227:2007. NFP bricks are very similar visually to NFX bricks and may be difficult to identify. Placing these bricks in water for a period of time and breaking/crushing is a good indicator of their quality. NFP and sun-baked bricks are known to disintegrate in water, may be easily deteriorate under abrasion and produce high quantities of dust and disintegrate when physically broken down. NFP bricks are referred to as 'chalkies' by industry because they will leave surface markings (if used to 'write' with) if dragged along a hard surface unlike NFX bricks. NFX bricks also fall under the stock or general-purpose classification in SANS, however they can be characterised as higher quality, 'over-fired' bricks. NFX products have undergone a higher state of vitrification to the extent that they can be used under damp conditions or below ground level where durability is important. These bricks are used extensively in structures for external, load bearing walling. 'Over-fired' bricks also consist of higher quality facing (FBX, FBS and FBA), paving and engineering bricks (FBE45). SANS 227:2007 classifies these bricks as being exceptionally uniform in shape and of higher strength and durability than general-purpose or stock bricks. These products have been fired at high temperatures, with higher quality clays to achieve extensive fusion and vitrification within their matrices. This allows for the use of these bricks in large structures, in highly impact applications (paving) and to support concrete structural systems.

This study analyses NFP, NFX and a paving/engineering (FBE45) quality clay bricks. NFP and NFX clay masonries are visually difficult to tell apart as their firing temperatures are their main distinction. As mentioned, physically, NFP bricks are softer and produce more fines when crushed or broken than NFX bricks. Higher strength paving and engineering bricks, FBE45, are generally darker in colour, may be larger in size and are denser than NFP and NFX bricks. Paving and engineering bricks break cleanly and produce minimal fines materials when processed. The materials chosen for this study by no means cover all the products available on the market. However, gaining insight into the properties of aggregates made from low/medium (NFP and NFX) to high strength (FBE45) masonry provides a scope of results in which masonry aggregates that are suitable for use in concrete, in the target concrete strength range of 20 – 40 MPa, may fall within. 'Over fired' bricks are more stable and suited for this application.

Moisture expansion may be a concern if relatively new clay bricks are processed into aggregates. Clay bricks undergo an irreversible, 3-dimensional moisture expansion due to absorption of moisture from

The Use of C&DW in Concrete in Cape Town

the atmosphere as soon as bricks leave the kiln. There is a high early-age rate of expansion during the first month of manufacture followed by an almost constant rate after 6 months. Bricks acquired from structures that cannot serve their purpose any longer are therefore recommended for aggregate production. Bricks should be older than 1 year, if they are to be used as aggregate, as by this stage their rate of moisture expansion has reached a relatively dimensionally stable state.

Visual indications of the origin and properties of recycled concrete wastes are harder to establish than that of masonry wastes. Indicators of strength need to be established by scientific methods such as coring and/or use of a Schmidt hammer. The majority of concrete waste that is produced in Cape Town contains Greywacke or Granite virgin aggregate which are of high quality. The amount of attached mortar on virgin aggregate particles after crushing influences the crushing strength and absorption potential of RCAs. This study has established that the performance of RCA's is related more to the processing approach, which removes a varying amount of concrete mortar, than the concrete mortar strength properties.

A major objective in using masonry and concrete waste as aggregate in concrete is to establish the material properties of structural elements from which the materials are derived before they are demolished, and before the materials are crushed.

Both the RCA-45 and RCA-MC aggregates conformed to all the requirements of SANS 1083:2006. These materials can be classified as Class 1A recycled aggregates by the Australian HB 155-2002 guideline. This allows for 30% blending of these RCAs with NA and use in structural concrete up to 40 MPa. Alternatively these RCA's may be used exclusively in concrete up to strength of 25 MPa. It is thought that this recommendation errs on the side of safety and that the RCA materials tested may be 100% substituted for NA in concrete up to a strength of 30 MPa. However, increased shrinkage and reduced elastic modulus should be accounted for in this RAC.

High strength masonry (FBE45) is suited for use as aggregate in concrete. This RA conformed to HB 155-2002 requirements for class 1B RCA however; this material cannot be classified as 1B as it is a clay brick aggregates. It is thought that 100% substitution of this RA in concrete for low-grade structural applications up to 30 MPa is feasible. There are also opportunities for high ratio blending of this material with NA or RCA. Use of this RA reduces shrinkage in concrete substantially however; late age curing, reduced and variable elastic modulus should be accounted for. This RA conformed to most of the requirements of SANS 1083:2006 and only marginally failed the dry ACV, 10% FACT and flakiness index limit. It is noted that the wet 10% FACT and ACV tests are not seen as good reflection of masonry aggregate strength as wet sieving was not used in the testing procedure.

The Use of C&DW in Concrete in Cape Town

Medium strength masonry (NFX) should be limited to non-structural and low-grade concrete applications. As with the high strength masonry, reduced shrinkage can be expected when these RA's are substituted for NAs. Blending may offer opportunities for improved curing and reduced shrinkage in applications where these variables are significant. However, the reduction in elastic modulus and potential reduced strength and strength development that occurs with these materials should be considered.

In this study the mixed masonry samples (BCA-MC and BCA-MV) produced better physical and hardened concrete properties than the medium strength masonry. However, utilising mixed masonry waste is not recommended as variability is high and the effects of components such as mortar aggregate pieces and weak masonry particles may be detrimental to concrete members.

The use of NFP bricks and concrete blocks/bricks (CMA) in concrete is not recommended for use in the target strength range tested in this study. These materials may be suitable for low-grade applications such as low strength concrete, void fillers and fill material.

As international standards have progressed towards prescribing limits for coarse recycled concrete aggregate. SANS 1083:2006 prescribes material property limits for aggregates from natural sources only. These properties include grading, dust content, crushing values (dry ACV and 10% FACT) and flakiness index. SANS 1083:2006 needs to be updated to follow materials guidelines such as the Australian HB 155-2002 document, which includes recycled masonry and concrete materials. Material limits for properties such as materials type, dried and bulk density, absorption, chloride content and contamination level need to be included in SANS to cater for these aggregates. These limits must be prescribed with relevant information on potential applications and mix design protocol in order to ensure safe usage. This would create opportunities for the increased use of waste materials in industry, as engineers would have guidelines for recycled aggregate material usage.

Concrete is not immune to weathering, corrosion and exposure to the natural environment. Durability is associated with the potential deterioration of concrete over its intended service life. Durability is largely defined by the how impermeable concrete is. This is because deterioration mechanisms such as chemical attack, leaching, chloride ingress and/or carbonation are all related to fluid or ion ingress through concrete's microstructure. Abrasion may also be a concern if weak masonry RAs are used in high impact concrete applications. RAs are more porous than NAs. In RCAs this is a consequence of the old surrounding concrete mortar on the parent aggregates surface. Porosity in masonry allows for a capillary effect, which helps regulate temperature and humidity in masonry structures. This increases permeability in RAC's matrix potentially reducing the durability depending on the application of the

concrete member. Of particular concern in Cape Town is the corrosion of steel caused by its depassivation, linked to carbonation or chloride penetration into concrete. Chloride penetration may also be caused by the presence of chlorides in the recycled material as a result of exposure to sea air over a structure's design life. Therefore an understanding of exposure conditions and steel reinforcement requirements are particularly importance when utilising RACs.

10.6 Developing Regulations and Moving Forward

As mentioned, the IWM By-Law of 2009 provides the basis for waste generators (owners/developers) to submit IWMPs to the City that deal with storing, transporting and disposing of C&DW. International IWMPs make use of more complex documents that identify individual C&D materials and require waste generators to specify their uses for them. Through the use of documents such as the *Guidelines for Preparing Waste Reduction: Strategy for Construction and Waste Minimisation Plans for Construction and Demolition projects* created by the Australian WasteWise Construction Program, the City's IWM By-Law needs to be developed and moulded to suit the waste materials being produced and construction industry dynamics in Cape Town.

From this research it can be concluded that IWMPs should aim to identify high and low strength clay masonry, concrete masonry and concrete as elements to be reused and recycled. Through separation protocol and simple processing actions, there is potential for multiple uses of clay masonry and concrete materials in low and higher-grade, non-structural and structural concrete applications. Making the submission of IWMP obligatory promotes awareness as to the potential and capabilities of C&D materials. Regulations that specify safe on-site processing protocol also need to be developed. This can improve the quality of commercially produced RAs as the components of the C&DW stream are more fully understood and materials of low performance can be identified in mixed waste sources. Through this approach, the current resource inefficiencies, economic and social burdens and environmental impacts associated with the construction industry can be reduced.

10.7 Further Research

Recommended further research should cover:

- Investigations into the effects of influence such as chlorides, sulphates and masonry complications such as moisture expansion, wetting and drying and efflorescence in RACs.
- An investigation into durability. OPI, Sorptivity and Chloride Conductivity indices as well as long-term exposure trials are paramount to understanding the long-term performance of these RACs. Of importance to this work is to establish how interconnected the pores are of various RA

The Use of C&DW in Concrete in Cape Town

materials are. This has critical influence on the ability of substances to permeate through to steel reinforcement. The ability of paint and/or plaster to protect internal concrete members that contain porous RA is also of importance.

- Further efforts need to be directed towards updating SANS and providing materials guidelines that specify material properties for recycled masonry and concrete materials that can be used in concrete.
- Life cycle assessment on the true impacts of natural aggregate production, demolishing and construction activities, transportation of virgin and waste materials, off-site and on-site recycling needs to be established.

University of Cape Town

Appendices

Appendix A. Overview of Governmental Structure

This section on governmental structure gives an overview of the basic governmental institutional arrangement in South Africa with regard to waste management. It is a summary of the responsibilities and legislative protocol used currently.

The South African government is constituted as made up three spheres namely:

- National
- Provincial
- Local spheres

The legislative authority of the national sphere of government lies within Parliament. The legislative authority of the provincial sphere rests in provincial legislature and local sphere in Municipal Councils.

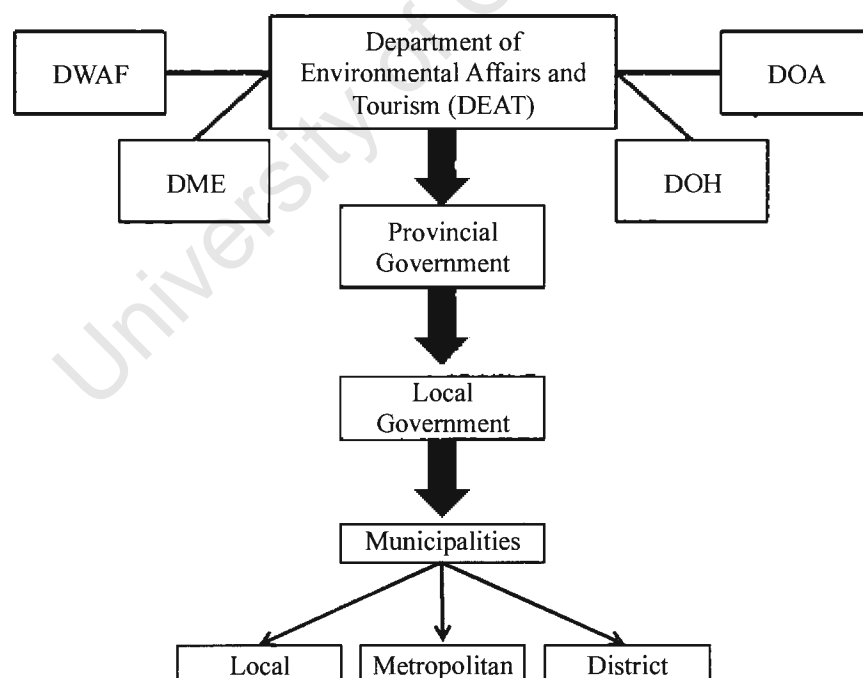


Figure A.1: Illustration of governmental structure

At National level, the Department of Environmental Affairs and Tourism (DEAT) is the lead authority for implementing waste minimisation and recycling plans. They are charged with developing national policy, strategy, action plans, framework, guidelines and national standards (DEAT May 2000). The Department of Water Affairs and Forestry, Department of Minerals and Energy, Department of Health,

The Use of C&DW in Concrete in Cape Town

and Department of Agriculture all deal with the regulations and disposal pertaining to particular waste such as landfilled, mining, medical and agricultural waste (DEAT 2000). The development of national or provincial government follows that draft legislative document are published and made available for public comment before they are introduced. These legislations prevail over provincial and municipal legislation.

Provincial legislation is developed by the provincial sphere in order to maintain provincial administration over municipalities. This legislation is seen as ineffectual unless it follows the lines of national legislation. Provincial Government is responsible for further developments within national regulation. These include provincial guidelines and standards, implementation plans and provincial regulation (DEAT 2000).

Local Governments are then responsible for general waste management through the Local Government Municipal Systems Act. They are required to submit waste management plans and Integrated Development Plans (IDP), which outline strategies in which waste is to be managed in specific municipalities. These can be classified as metropolitan (urban environment), district and local (rural environment) municipalities.

Municipalities may then develop by-laws for effective administration of its communities subject to national and provincial legislation. This involves the co-ordinate refuse removal, refuse dumps, solid waste disposal and municipal planning (Coetzee 2012).

Appendix B. Summary of National Acts and Policies

There is a range of national and provincial ¹⁷acts that relate to the recycling of C&D waste through different national sectors. Considering this extensive body of literature a basic summary of the development of the South African National recycling legislative, which is relevant to the C&D waste stream is seen as adequate.

¹⁷ It is useful to define the role of bills, acts and policy. Simply put, a bill is a proposed legislation (law that has been enacted by a governing body) and can be seen as a draft. Bills are then passed through legislature or congress before being made in law. An act is this adopted law or effective legislation. Policies (or strategies) outline the course of action, guiding principles, or procedure to take which may or may not relate to specific legislation.

The Use of C&DW in Concrete in Cape Town

The promulgation of the Environment Conservation Act (ECA) no 73 of 1989, forms the foundation for the transformation into the developing South African environmental management system of today (Macozoma 2006).

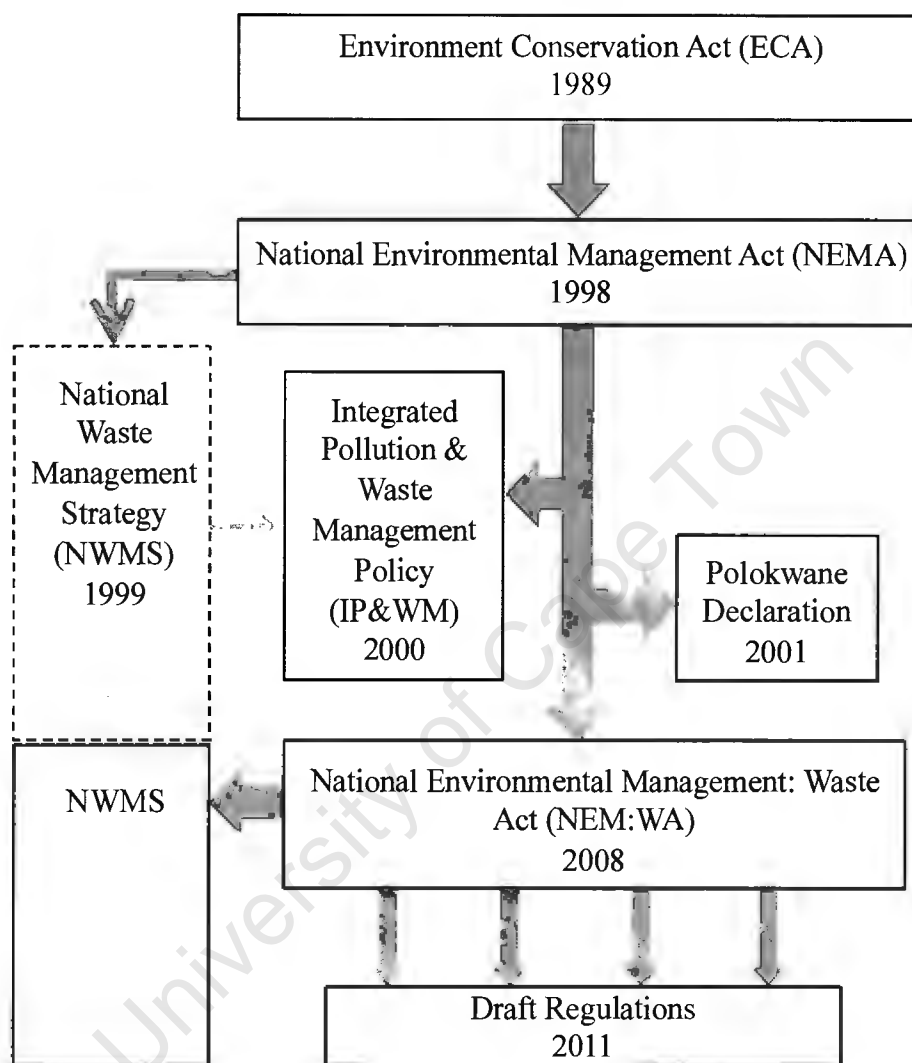


Figure B.1: Interpretation of national regulatory structure

This led to the public release of the National Environmental Management Act (NEMA) no 107 of 1998 (DEAT May 2000). NEMA provides the institutional structures and procedures to follow in order to implement integrated environmental management and specific (recycling) sector legislation. This is based on Environmental Impact Assessment (EIA) regulation. It is a framework Act governing the overall protection of the environment matters.

The policy objectives set out by NEMA were further refined in the National Waste Management Strategy (NWMS) in 1999. This strategy showed a governmental commitment to making recycling more economically viable and to promote these activities in the private sector (DEAT 2000). This early

The Use of C&DW in Concrete in Cape Town

NWMS introduced ideals such as integrated development and waste management plans. However, the development of the NWMS had no bearing at this time, as its priorities were not made mandatory by NEMA. This was seen by the complete disregard by provincial and municipal entities of the proposed (integrated) waste management planning initiatives.

The integration of most of the existing environmental laws relating to pollution and waste management were then developed as a framework policy called the White Paper on Integrated Pollution and Waste Management (IP&WM), promulgated in 2000 (DEAT 2000).

This policy marks a shift from pollution control focused on waste disposal and impact control, to a focus on pollution prevention in integrated waste management over the entire waste cycle from cradle to grave. It is the first regulation to purpose the following of the waste hierarchy in future legislation and policies.

In 2001 representatives from all three government levels, civil society and business met at Polokwane to formulate a declaration on waste management. It was realized that there is an urgent need to reduce, reuse and recycle waste. Furthermore the represented sectors recommitted themselves to the objectives of an integrated pollution and waste management policy. A goal was set to reduce waste generation and disposal by 50% and 25% respectively by 2012 and to develop a plan for zero waste by 2022 (DEAT 2011).

The National Environmental Management: Waste Act No. 59 of 2008 is a more specific environmental management Act that is developed from NEMA (DEAT 2008). It deals specifically with the management of waste in South Africa. One of the most significant aspects of this Waste Act is that it embraces and approaches waste management through the waste management hierarchy. It seeks to put minimum requirements for any person who undertakes a waste generating activity. This includes storage, transportation, processing and recycling activities. This is being enforced by the mandatory submission of Integrated Development Plans (IDP) and Integrated Waste Management Plans (IWMP) by provincial and local spheres.

The NWMS was made a legislative requirement under NEM:WA. The purpose of the NWMS is therefore to achieve the goals set out by the NEM:WA. With this updated NWMS the target of 25% reduction in landfill disposal by 2012 has been moved forward to 2016 (DEAT 2011).

With the NWMS now having bearing with the national legislative environment, individual waste streams can be targeted. This can be seen as a “link” to the development of SANS with regard to the

The Use of C&DW in Concrete in Cape Town

'use' or currently, the avoidance of specific waste materials. This is seen in current SANS standards that provide guidelines that specify details on the storage and disposal of liquids (Coetzee 2012).

The Minister has therefore pursued tyre waste as one of the first priority waste streams and released regulation on tyre waste disposal. In addition three sets of draft Waste Regulations and three waste handling standards were published for comment as of July 2011.

The draft landfill and classification regulations consist of the:

- Draft National Standard for Disposal of Waste to Landfill
- Draft Standard for Assessment of Waste for Landfill Disposal
- Draft Waste Classification and Management Regulations

Two more waste priorities in waste car and waste gas have subsequently been identified. Draft national standards for these are being developed in the:

- Draft National Standard for the Scrapping and Recovery of Motor Vehicles
- Draft National Standard for the Extraction, Flaring or Recovery of Landfill Gas in South Africa

Appendix C. Regulations in The City of Cape Town

The management of waste is traditionally left to local authorities leading to a plethora of by-laws and local regulations covering this topic. This section provides an overview of the development of the IWM By-law, which is the leading legislation with regard to C&D waste in The City. The following section is a brief overview of this development.

NEM:WA requires provincial government to compile integrated waste management plans (IWMP) and review municipal waste management plans. The City of Cape Town's Integrated Waste Management (IWM) Policy is a 'response' to NEM:WA. These plans have been formulated to co-ordinate the waste management process in terms of the Cape Town Councils' governance responsibilities. This process is closely linked to the Municipal Systems Act.

With regard to C&D waste, the purpose of this policy is to introduce, facilitate and encourage waste minimisation and management practices as per the waste management hierarchy. This involves the reuse of waste, promotion of waste separation practices, landfill diversion and public-private partnerships (DEAT May 2000).

The Use of C&DW in Concrete in Cape Town

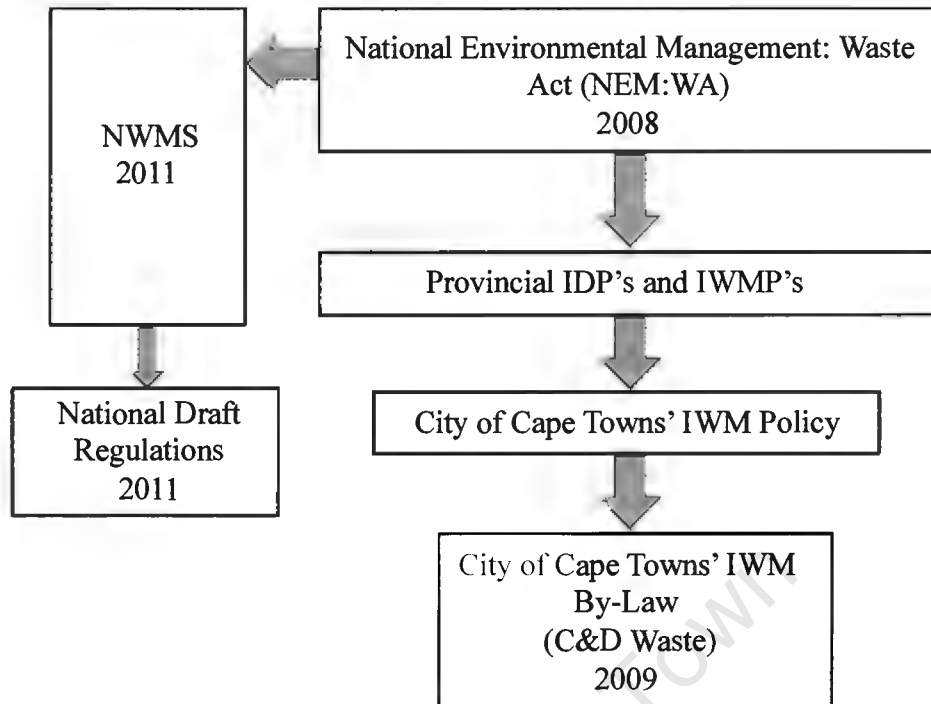


Figure C.1: Interpretation of local regulatory structure

This IWM Policy has led to the passing of the IWM By-law of 2009. This By-law deals with C&D Waste specifically and gives clear direction to dealing with C&D waste management. The details of this management process are discussed in the following section.

Appendix D. Integrated Waste Management By-law of 2009

The City of Cape Town's IWM By-law of 2009 is the leading legislation that controls C&D waste management in Cape Town. The City of Cape Town's approach to waste management has shifted from direct disposal of C&D waste at landfill sites, to minimisation and recycling with the implementation of the IWM By-law. This By-law was amended in 2010 to give specific reference the obligations of waste generators in submitting Integrated Waste Management Plans (IWMP) to the City. It discloses strict obligations to owners/developers in terms of depositing, transporting and disposing of builders waste (Van Vuuren 2012; City of Cape Town 2005)

The IWM By-law makes reference to *building waste*, which in the context of this study, alludes to C&D waste. An overview of the By-Law with obligations and amendments specifically applying to owners/developers generating waste from building and demolition activities is discussed below (Coetzee 2012; The City of Cape Town, Van Vuuren 2012). Section 4 of the by-law applies specifically to building and demolition activities (City of Cape Town 2009):

The Use of C&DW in Concrete in Cape Town

- *“(13) A waste generator generating industrial waste shall submit an integrated waste management plan to the City and comply with the terms and conditions set out by the City for the generation, minimisation, storage, recycling, collection and disposal of such waste.*
- *(16) Any person who directly or indirectly generates building waste or the owner of the property on which such building waste is generated shall not store such waste in containers provided by the City for residential waste and shall remove and dispose of it at a licensed crushing plant or landfill site or any other licensed building waste disposal facility.*
- *(17) When plans are submitted to the City for its approval in terms of the National Building Regulations and Building Standards Act, 1977(Act No. 107 of 1977), the person submitting same must submit simultaneously therewith*
 - (a) an integrated waste management plan setting out what provision is made for collection and disposal of the building and other waste;*
 - (b) what provisions are made to store the waste on their property; or*
 - (c) provide a permit to store the waste on the City's property.*
- *(18) Contaminated building or other waste where the contamination agent is hazardous or dangerous must be deposited at a licensed waste disposal facility for the treatment and disposal of hazardous waste.*
- *(20) The waste generator or the owner of the property on which waste is generated who deposits or stores waste on property of the City may be fined for failure to have or produce a permit for such deposit or storage.*
- *(21) When the building control officer inspects the property where building works have been undertaken to check that it has been built in accordance with the approved plans, he or she shall also check if all building waste has been disposed of.*
- *(22) The owner of the property referred to in subsection (21) will be required to provide the building control officer with proof of a weighbridge certificate that he or she has disposed of the full mass of the building rubble at a licensed waste disposal facility for that category of waste prior to an occupancy certificate or any final approvals being granted.”*

This approach is to be implemented in phases to allow system tweaks and optimisations. The first phase targets small residential developments and was implemented in early 2012. The second phase of this process will target business and industry developments (non-residential) and housing developments (high-rise flats, multiple housing etc.). It is envisioned that this process will be compulsory for all building applicants in the 2013 (City of Cape Town 2009).

This By-law requires waste management issues to be addressed during the pre project-planning phase. This allows for a more efficient analysis of waste generation and generation of waste prevention strategies.

The Use of C&DW in Concrete in Cape Town

This prerogative is facilitated by integrated waste management planning. This marks a major shift in construction and demolition practice within the Cape as waste material has to be identified, separated and disposed off in a certain manner. Details required by the City in these IWMP's are discussed next

Appendix E. The City's C&D Waste Integrated Waste Management Plan

The submission of an Integrated Waste Management Plan (IWMP) to the City by owners/developers generating waste from building and demolition is paramount to the monitoring and implementation of C&D waste recycling initiatives. The proposed plan is in a very early development stage and is therefore very basic. The following details and actions are to be recorded by the owner or developer in the submission of IWMP's to the City for approval:

- *separate industrial waste into liquids, components and materials that can be treated for recycling or re-use;*
- *not store building waste generated in containers provided by the City for residential waste;*
- *store the building waste generated on their property, and to remove and dispose at a licensed crushing plant or landfill site or any other licensed building waste disposal facility;*
- *obtain and provide a permit to store the waste on the City's property where applicable;*
- *contract with an accredited service provider for the disposal of waste' deposit contaminated building or other waste where the contamination agent is hazardous or dangerous at a licensed waste disposal facility for the treatment and disposal of hazardous waste;*
- *provide the building control officer with proof of a weighbridge certificate that he or she has disposed of the full mass of the building rubble at a licensed waste facility for that category of waste prior to an occupancy certificate or any final approvals being granted*

(City of Cape Town 2009)

The submission of this IWMP puts the onus on the owner or developer to carry out the above waste minimization strategy. This process is to be controlled by the right of the City to withhold of the final approval of building plans.

Appendix F. Development of the ANZECC

The Australian and New Zealand Environmental Conservation Council (ANZECC) developed the WasteWise Construction Program in 1995. This was facilitated by a waste reduction agreement through negotiations with five of the major Australian construction companies. The agreement utilised a MoU

The Use of C&DW in Concrete in Cape Town

between government and industry to pursue waste reduction initiatives and recycling targets in an effort to reduce the amount of C&D waste going to landfill sites (Andrews 1998).

Phase I of this program was a 3-year industry funded initiative that identified the best approach to C&D waste reduction within the bounds of their commercial practices. This first phase led to some key imperatives. These included:

- Developing and recognising the 'bottom line' benefits of waste minimisation
- Developing a national approach to waste minimisation
- Conducting waste reduction trials in their operations
- Addressing coordination issues and barriers within their industry
- Using key stakeholders to develop future arrangements
- Accepting, adopting and promoting best practices within their industry

(Australian Bureau of Statistics 2006)

A review of the individual success of the five partners was undertaken followed by the publication of the WasteWise Construction Program Review in 1997. Under the MoU companies agreed to reduce waste going to landfill by 50% by the year 2000 against 1990 per capita levels. The WasteWise Handbook was then published in 1998 (Andrews 1998). This was a 'how to' booklet that outlined the procedures and achievements of the companies involved in the initial phase of this program.

Phase II of this initiative sought to widen participation in waste minimisation to other sectors of the construction industry. Industry sectors invited to sign the MoU and participate in this initiative included (Australian Bureau of Statistics 2006):

- Architects and designers
- Material suppliers
- C&D companies
- Waste collectors
- Industry organisations

Appendix G. CalRecycle Background

Statute AB939 of 1989 laid the foundation for the development of IWMP's for each county with California. This statute required each county to establish a task force and to prepare, adopt and submit a city Source Reduction and Recycling Elements plan by 07/01/1991. This IWMP was to include waste

The Use of C&DW in Concrete in Cape Town

characterisation, source reduction, recycling, composting, solid waste facility capacity, education and public, funding, special waste and household hazardous waste information. Also included was an IWMP that specified areas for transformation or disposal sites. This is to provide capacity for solid waste generated that cannot be reduced or recycled for a 15-year period. Furthermore a Waste Diversion Mandate that requires each city to include an implementation scheme that shows a diversion of 25% of solid waste from landfill by 2005 and 50% by the year 2000 was implemented (California Government 2012).

In order for the California Department of Resources Recycling and Recovery (CalRecycle) to achieve the AB939 goals, legislation was developed to provide information to contractors on methods and activities to divert C&D materials.

The Model C&D Diversion Ordinance requires that waste management plans (WMP) be completed and submitted prior to the beginning of a project. Essentially this plan is estimate how much C&D material will be generated and shows evidence of how the plan is to be achieved, where and how much waste will be diverted. This includes (California Government 2012):

- The estimated volume or weight of project waste to be generated by material type;
- Determine if materials will be sorted on-site or mixed;
- The maximum volume or weight of such materials that can feasibly be diverted via reuse, recycling or salvage for future use or sale by material type;
- The vendor(s) that the applicant proposes to use to haul the materials;
- Facility(s) the materials will be hauled to, and their expected diversion rates (by volume or weight) by material type;
- Estimated volume or weight of construction and demolition waste that will be disposed.

Appendix H. Cumulative Energy Demand

CED is an energy assessment variable that represents primary energy consumed by an action. This can be described as not a measure of energy such as electricity consumed, but the amount of primary energy needed to produce, use and dispose of an electricity supply (Vossberg, C. 2012). This life cycle assessment measure allows for the assessment of a variety of energy categories to be described under a single variable.

Representations of CED output, measured in Megajoules (MJ), are repeatedly used to discuss energy demand in the sections below. Vossberg (2012) uses this quantification to draw conclusions as to the effectiveness of different recycling options within the City.

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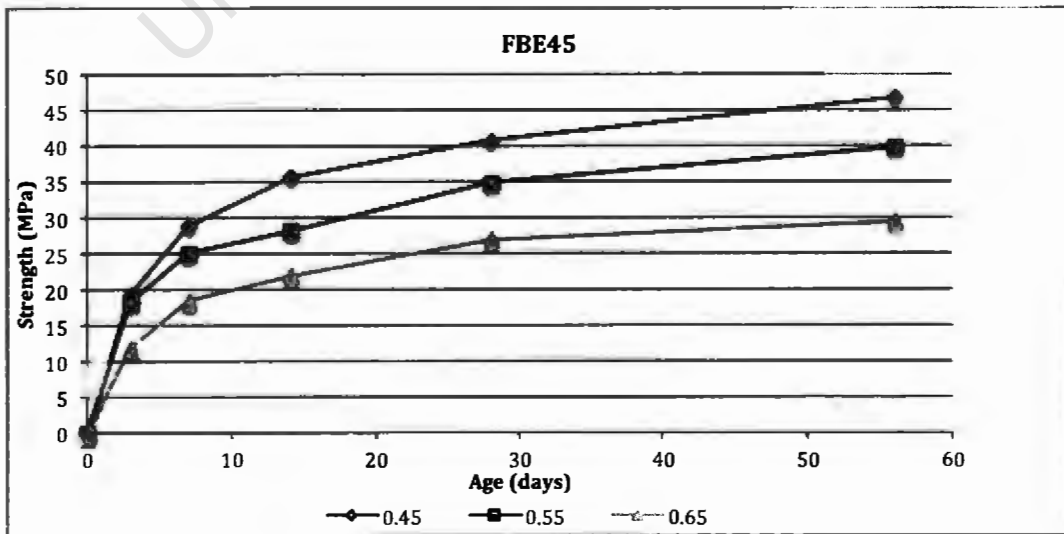
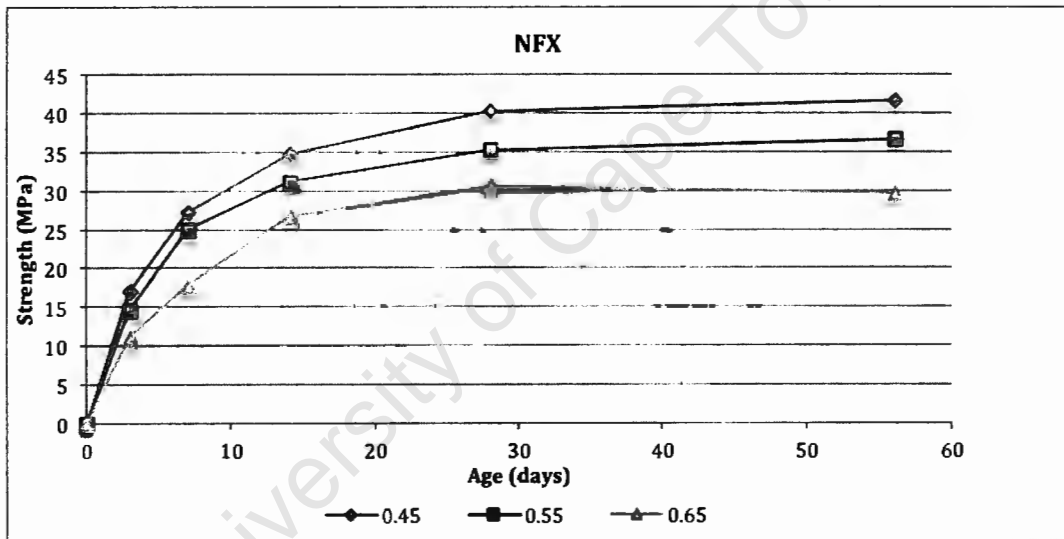
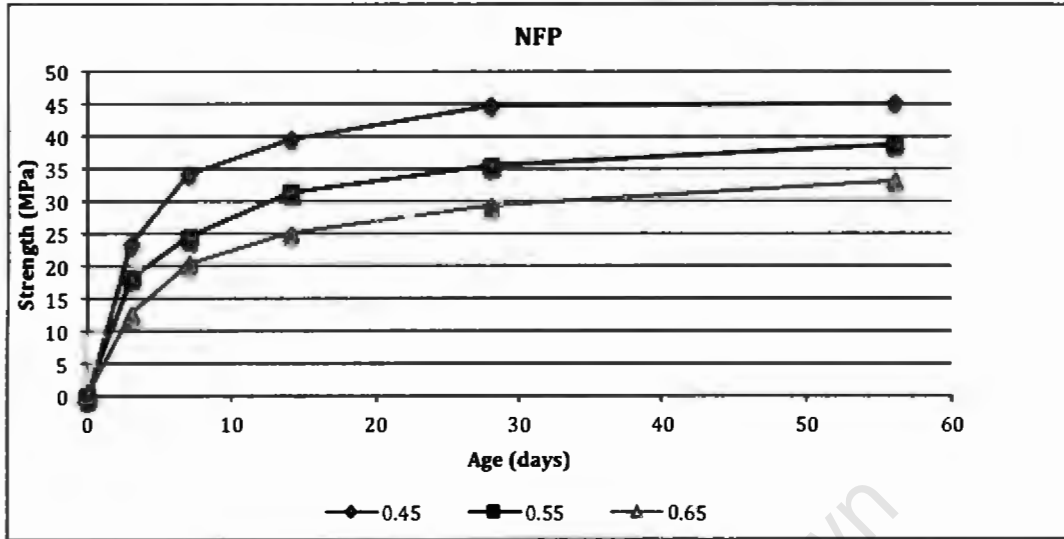
As mentioned, CED is a measure of primary output. This shows a dependence on the national energy production approach used by a country. In South Africa's case, electricity production is characterised by high CED, as our primary energy is supplied by the operation of coal-fired power stations.

The relevance of this, in this study, is that electricity usage is seen as a more sustainable approach to power supply than fossil fuel use. Even though the use of diesel for the transportation and operation of on-site crushers is described as more efficient than electrical crushers. This relates to peak oil supply and the understanding that in the near future, fuel prices and availability will be extremely volatile. Therefore the operation of machinery and vehicles that utilise this energy source will become exceedingly expensive and impractical. It is also noted that electrical supply to off-site crushers is assumed to be the same as supply to virgin aggregate crushers.

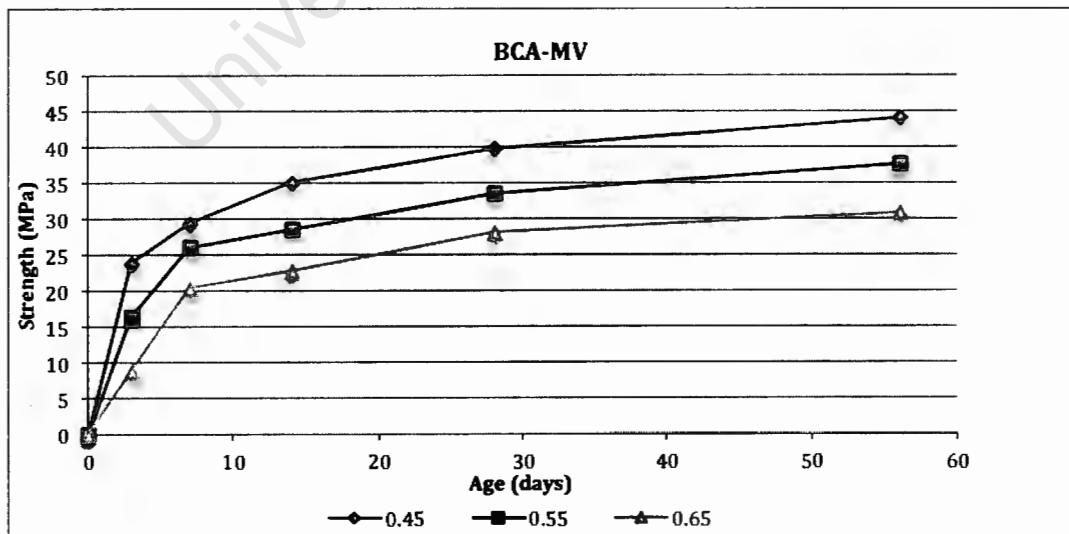
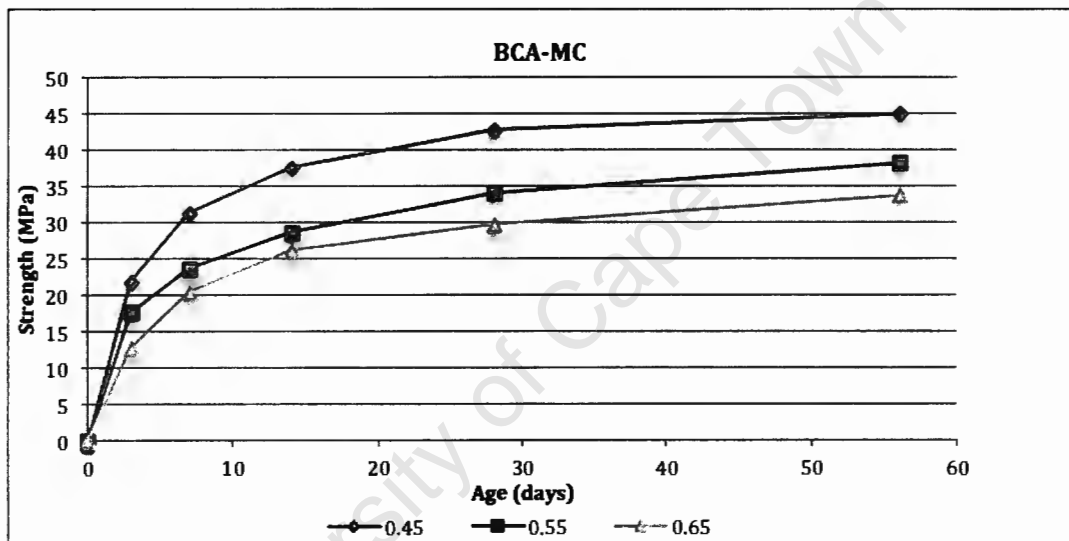
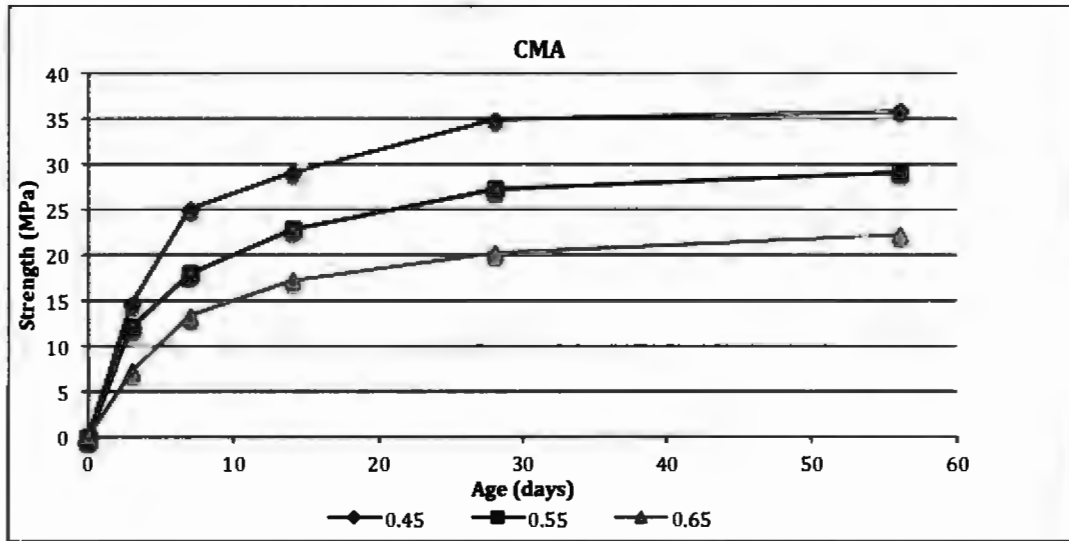
Appendix I. Global Warming Potential

GWP is an assessment parameter that measures the global warming potential of the air emissions from an activity, for a 100-year period. It was developed by the International Panel on Climate Change and converts all air emissions to a common carbon dioxide equivalent or CO₂e (Vossberg 2012).

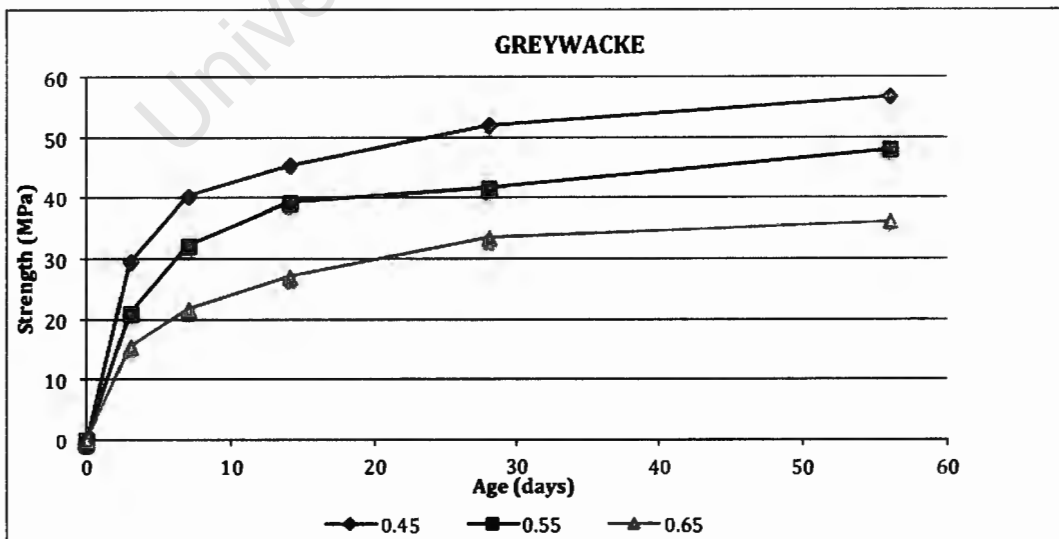
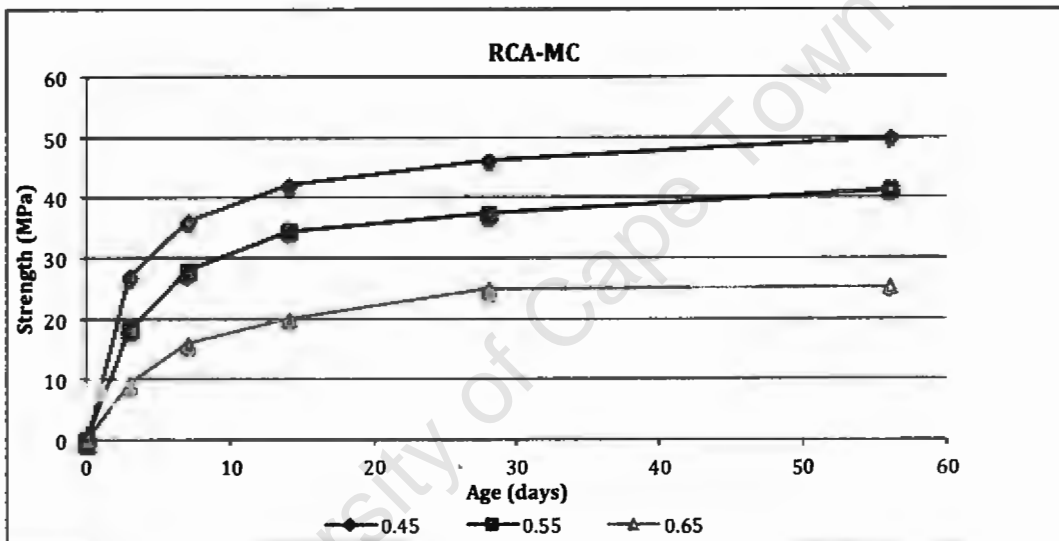
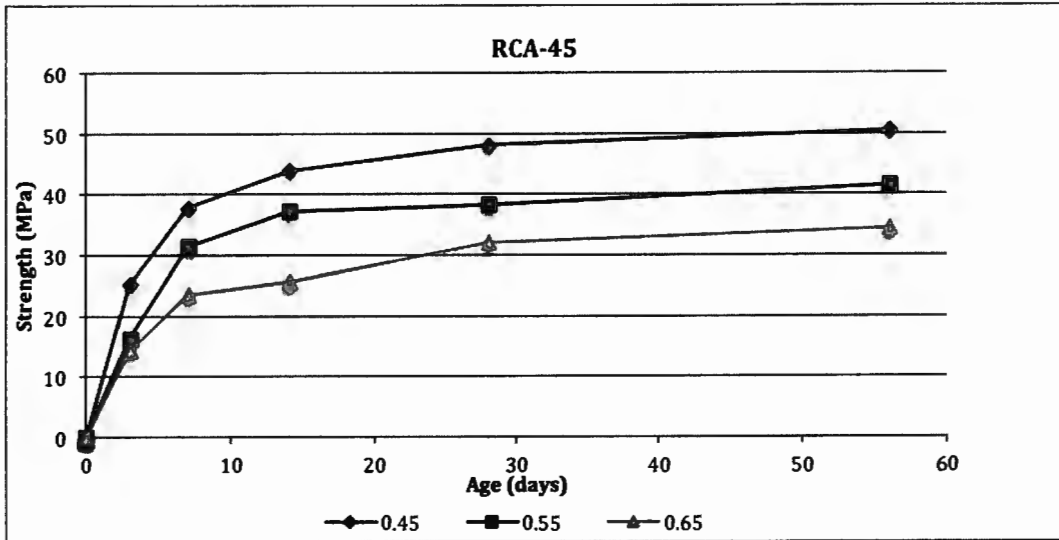
Appendix J. RAC Compressive Strength Development Graphs



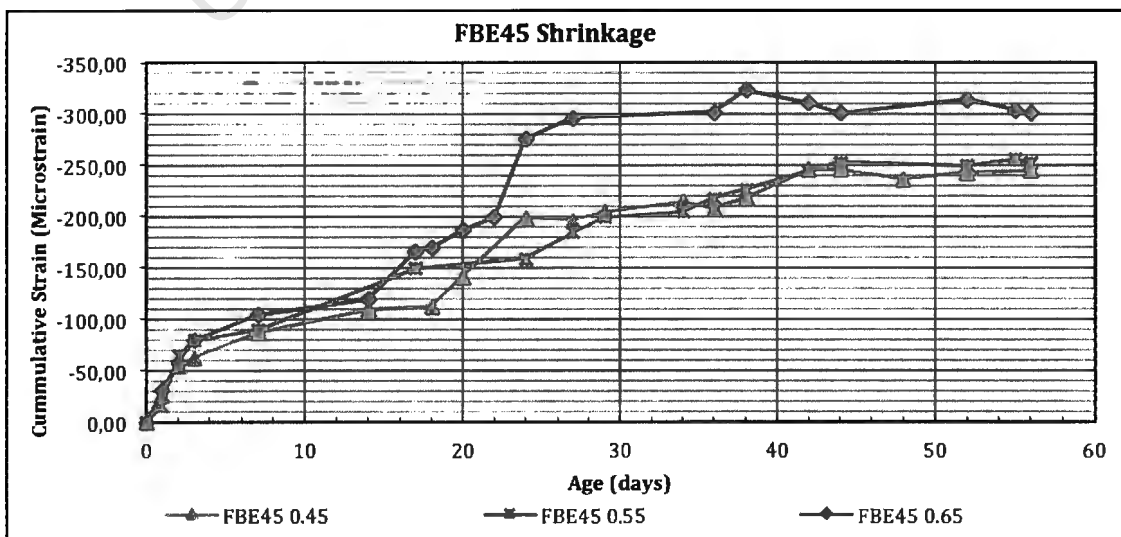
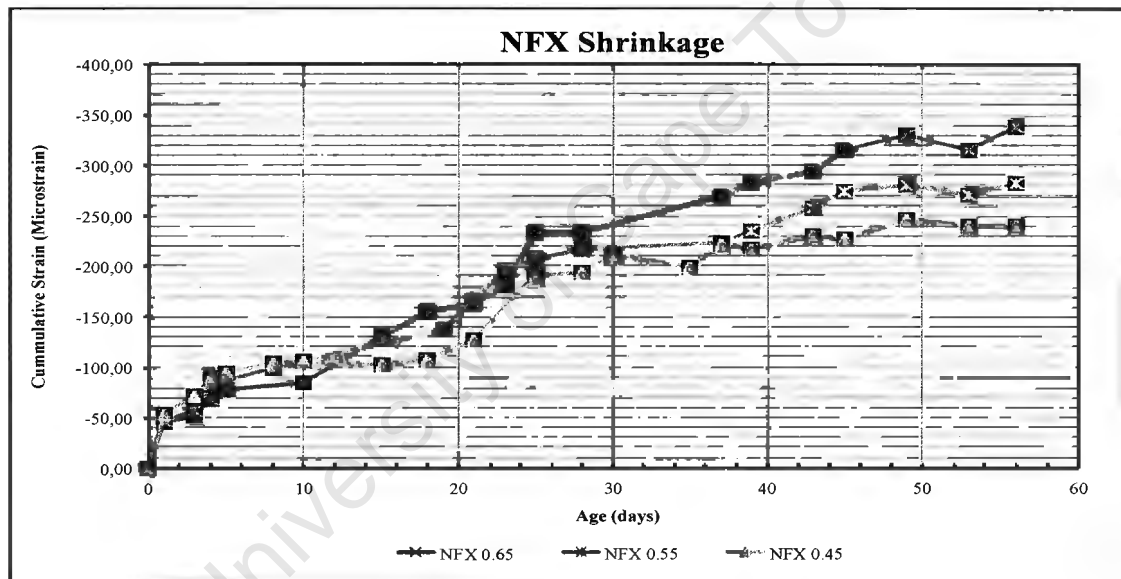
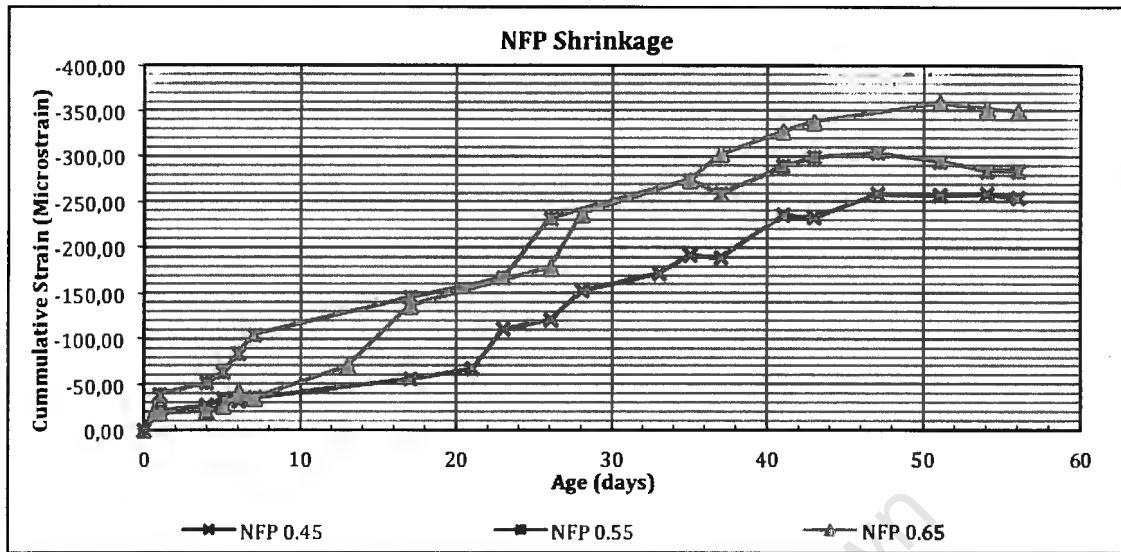
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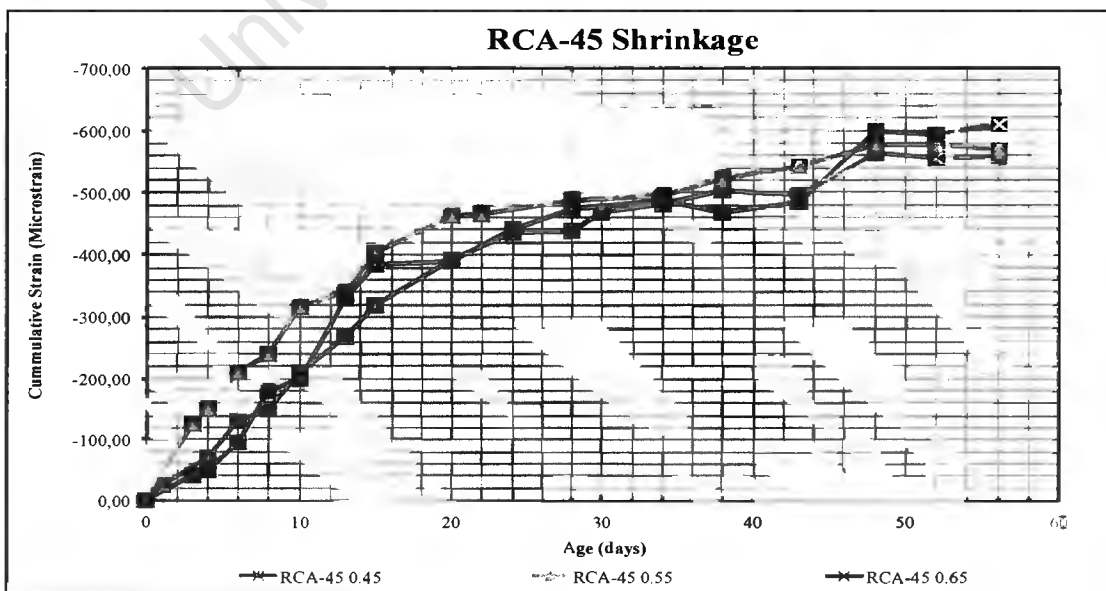
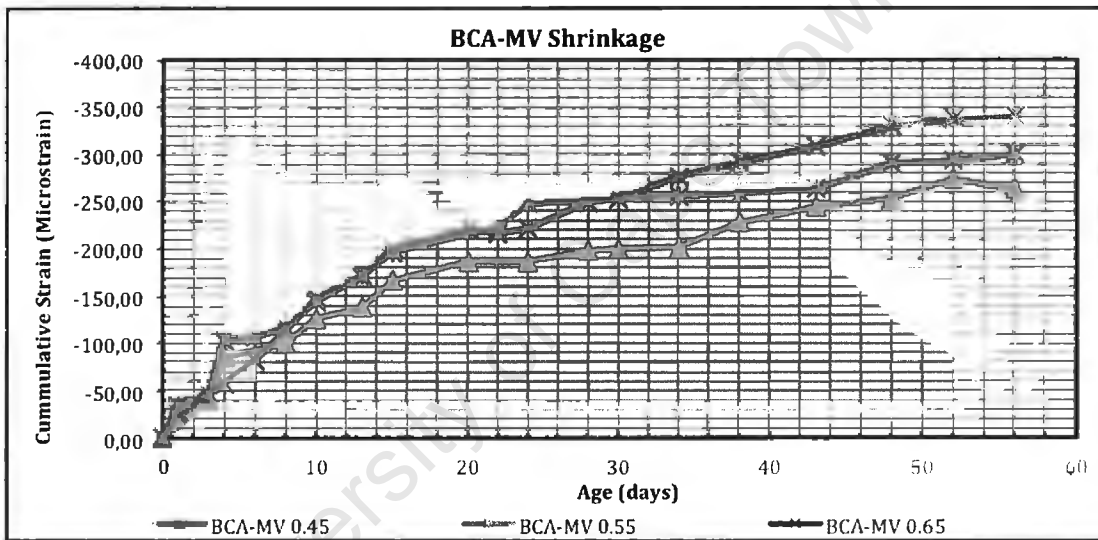
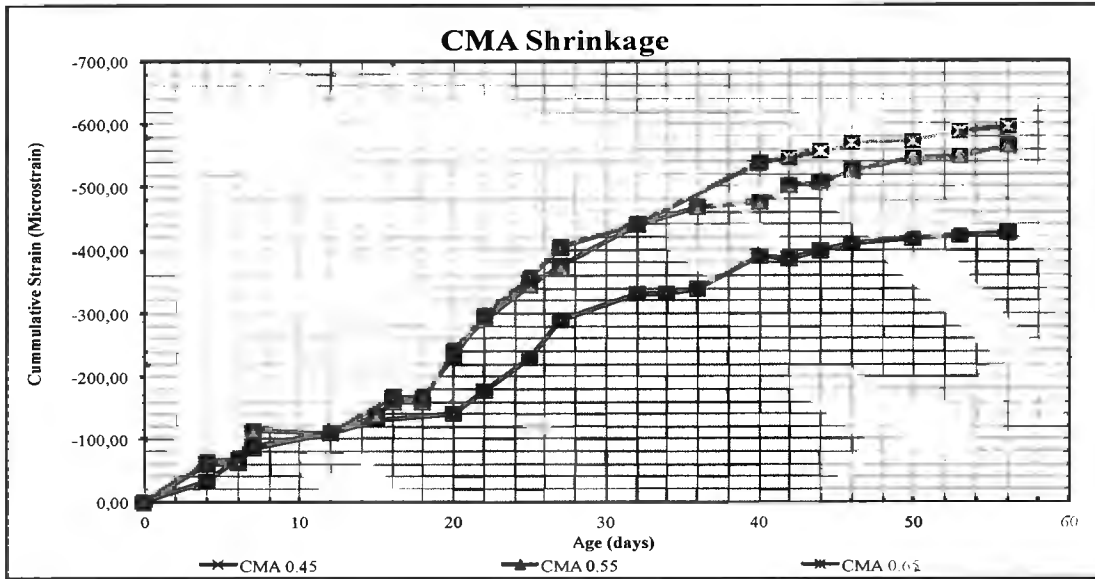
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Appendix K. RA Concrete Shrinkage Graphs



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