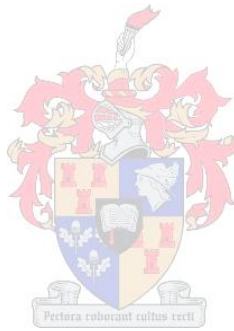


The influence of percentage replacement on the aggregate and concrete properties from commercially produced coarse recycled concrete aggregate

by
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Declaration

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Summary

The aim of this research is to investigate the potential use of coarse recycled concrete aggregate (RCA) as a material in structural concrete. The lack of knowledge and specifications in South Africa are the main reasons for this research of RCA. By increasing the database of research of RCA in South Africa the possibility of specifications for this alternative building material can be initiated. The implications of such specifications would lead to RCA acceptance in concrete design and therefore reducing the amount of construction and demolition (C&D) waste accumulating at landfill sites and decreasing the extraction of depleting natural aggregates.

The objectives that are achieved through this research project are firstly, what is the percentage replacement of RCA to a concrete blend that will produce a material that achieves similar or better results than a concrete blend containing natural aggregates. Secondly, what aggregate properties and limits should be defined in the specification of RCA for it to be accepted as a material in concrete mixtures. The objectives were assessed through examining the geometrical, physical and chemical properties of the aggregate as a material and the fresh and hardened concrete properties of concrete which contains RCA as a constituent.

RCA which was processed by a commercial recycling facility which produces concrete masonry units was collected at three different instances. This material was reprocessed in the laboratory to control the grading and amount of fine material not guaranteed by the recycling process. The RCA is then combined with natural aggregate (NA) at the replacement percentages: 0, 15, 30, 50 and 100% which is then used to examine the aggregate properties. It was determined that the physical properties of RCA were dependent on the geometrical properties, while taking into consideration that the geometrical properties are dependent on the source and method of recycling of the original C&D waste. The chemical properties were established as dependent on the physical properties of the RCA.

The RCA is then mixed with NA at the same replacement percentages together with other concrete constituents to produce the concrete used to examine fresh and hardened concrete properties. The fresh concrete properties investigated were: slump, slump loss, air content and fresh compacted density. The hardened concrete properties studied were: compressive strength, tensile splitting strength, oxygen permeability, water sorptivity, chloride conductivity, modulus of elasticity, shrinkage and creep. The concrete properties were not significantly influenced by the inclusion of RCA.

According to the aggregate and concrete properties examined in this investigation, the full replacement of NA in structural concrete is possible and will improve the sustainable development of the construction industry.

Opsomming

Die doel van hierdie navorsing is om ondersoek in te stel na die potensiele gebruik van growwe herwonne betonaggregaat (RCA) as 'n materiaal in betonstruktuurontwerp. Die gebrek aan kennis en spesifikasies in Suid Afrika is die vernaamste rede vir hierdie navorsing van RCA. Deur die vermeerdering van die databasis van hierdie navorsing van RCA in Suid-Afrika kan die moontlikheid van spesifikasies vir hierdie alternatiewe boumateriaal geïnisieer word. Die implikasie van sodanige spesifikasies sou lei tot RCA aanvaarding in betonontwerp en dus die vermindering van die hoeveelhede konstruksie en slooping (C&D) van afvalversameling by stortterreine en om die ontginning van natuurlike aggregate te verminder.

Die doelwitte wat deur hierdie navorsingsprojek bereik word is eerstens, wat is die vervangingspersentasie van RCA in 'n betonmengsel wat produseer word wat dieselfde of beter resultate sal lewer as 'n betonmengsel wat uit natuurlike aggregate bestaan. Tweedens, watter aggregate eienskappe en beperkings moet gedefinieer word in die spesifikasie van RCA sodat dit aanvaarbaar is as 'n materiaal in betonstruktuur ontwerp. Die doelwitte word geassesseer deur die ondersoek van die geometriese, fisiese en chemiese eienskappe van die aggregate as 'n wesentlike materiaal en die vars en verharde betoneienskappe van RCA as 'n bestanddeel in struktuur betonontwerp.

RCA monsters was geneem by 'n kommersiële herwinningsfasiliteit wat RCA gebruik om betonsteen eenhede te vervaardig, is op drie verskillende tydperke ingesamel. Hierdie materiaal is herverwerk in die laboratorium om die gradering en die hoeveelheid van fyn materiaal wat nie deur die herwinningsproses beheer is nie. Die RCA was dan gekombineer met NA teen vervangingspersentasies van: 0, 15, 30, 50 en 100 % wat dan gebruik was om die eienskappe van die aggregate te ondersoek. Daar is vasgestel dat die fisiese eienskappe van die RCA afhanklik van die geometriese eienskappe, met inagneming dat die geometriese eienskappe afhanklik is van die bron en metode van die herwinning van die oorspronklike C&D afval. Dit is gestig dat die chemiese eienskappe is afhanklik van die fisiese eienskappe van die RCA.

Die RCA is toe gemeng met NA teen dieselfde vervangingspersentasies saam met ander beton bestanddele om beton te produseer wat dan vergelyk kan word met vars en verharde beton eienskappe. Die volgende vars betoneienskappe is ondersoek: insinking, insinking verlies, luginhoud en vars gekompakteerde digtheid. Die volgende verharde betoneienskappe is bestudeer: druksterkte, trek die splintsing van krag, suurstofpermeabiliteit, water sorptiwiteit, chloride geleidingsvermoë, modulus van elastisiteit, krimp en kruip. Die beton eienskappe was nie beduidend beïnvloed deur die insluiting van RCA nie.

Volgens die aggregate en beton eienskappe wat in hierdie navorsing ondersoek is, blyk dit dat die volle vervangingswaarde van NA in strukturele beton moontlik is en die volhoubare ontwikkeling van die konstruksiebedryf sal verbeter.

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List of Abbreviations

10% FACT	10% fines aggregate crushing value
ACV	Aggregate crushing value
AD	Air-dry
ASR	Alkali-silica reactivity
C&D waste	Construction and demolition
CAF	Central Analytical Facilities
CBD	Compact bulk density
DI	Durability Index
FA	Fine aggregate
FI	Flakiness Index
FM	Fineness modulus
GGCS	Ground granulated Corex® slag
hcp	hardened cement paste
ITZ	Interfacial transition zone
LBD	Loose bulk density
LOI	Loss on ignition
LVDT	Linear variable differential transducers
MarR100C	March – Recycled – 100% replacement – OPC
MarN100S	March – Natural – 0% replacement – slag
NA	Natural aggregate
NAC	Natural aggregate concrete
OD	Oven dry
OPC	Ordinary Portland cement
OPI	Oxygen permeability index
PPC	Pretoria Portland cement
RA	Recycled aggregate
RAC	Recycled aggregate concrete
RCA	Recycled concrete aggregate
RD	Relative density
SABS	South African Bureau of Standards
SSD	Surface saturated dry
UCT	University of Cape Town
WA	Water absorption
XRF	X-ray florescence

Chapter 1

Introduction

Recycling of materials is not a recently developed practice. The need for recycling became apparent when the increasing demand for raw resources placed pressure on countries to become more conscious of the use of materials in all sectors. The construction and civil works industries account for 60% of worldwide consumption of the earth's raw natural resources (Bribian et al, 2011). The concrete industry is one of the largest consumers of earthly resources and energy. In 1995 global concrete production was in the region of 10 billion tonnes and was set to reach 16 billion tonnes by 2010 (Lui & Chern, 2008). Van Zijl (2010) stated that the concrete production worldwide was estimated at 12 billion tonnes per year and the construction and demolition (C&D) waste, excluding industrial waste, accumulated to 2 billion tonnes per year. This C&D waste is mainly sent to land fill sites, however a minority of C&D waste is reused and generally in low grade applications in the construction industry. South Africa's C&D waste sent to land fill is said to be over 1 million tonnes, which was derived from limited data (van Zijl, 2010). With such immense stress placed on natural resources and landfill sites worldwide the need for the development of alternative uses for C&D waste has led many countries to explore the possible uses to include more construction applications. According to Tam (2009) Japan is the leading country in the use of recycled concrete aggregate (RCA). Countries such as Germany, Switzerland, Netherlands, Denmark, Great Britain, USA and Russia all have established standards or specifications for the use of RCA in concrete (Dehn, 2007). These countries have created guidelines and specifications that make the addition of RCA in construction mandatory, thus reducing the impact on land fill sites and natural aggregate extraction. Currently South Africa does not have similar specifications and therefore there is a reluctance to use RCA in concrete mix design due to the uncertainty of its properties. There are companies such as Cape Brick which produce products using percentages of recycled aggregate; however these products have not been accepted because many engineers do not perceive that the products can meet the standards that natural aggregate can deliver. This leads to the necessity for the development of guidelines or specifications specifically for RCA so that the reliability of such a commodity can be ensured.

1.1 Research Aims

The aim of this research is to make recommendations and specify the potential use of coarse RCA as a material in structural concrete with possible guidelines and/or specifications. The shortage of knowledge and lack of specifications in South Africa are the main reasons for this research of RCA. By increasing the database of research of RCA in South Africa the possibility of specifications for this alternative building material can be initiated. The implications of such specifications would lead to RCA acceptance in concrete design and thus reducing the amount of C&D waste accumulating at landfill sites and decreasing the extraction of depleting natural aggregates from the earth.

1.2 Research Objectives

The objectives that are achieved through this research project are firstly, what is the percentage replacement of RCA to a concrete blend that will produce a material that achieves similar or better results than a concrete blend containing natural aggregates. Secondly, what aggregate properties and limits should be defined in the specification of RCA for it to be accepted as a material in a concrete mixture.

These objectives will be accomplished by assessing the aggregate properties of RCA at predetermined percentages mixed with natural aggregate as well as the properties of fresh and hardened states of concrete. A literature review of RCA and C&D waste will provide knowledge and guidelines to assess the outcomes of the tests performed in this research.

The objectives can be summarized as follows:

- An overview of the use of recycled materials in modern construction and the influence thereof on sustainable development.
- A comprehensive literature study into the aggregate, fresh and hardened concrete properties to gain an understanding of the possible outcomes from the experimental programme.
- A study into the current standards and specifications applicable to recycled materials for the recommendation of RCA in South Africa.
- A well-defined experimental programme to ensure all the necessary methods and testing procedures are utilised.
- An investigation into the aggregate properties and the influence of RCA replacement on these properties.
- The influence that the RCA will have on fresh concrete.
- Examining the impact which RCA will have on the mechanical, durability and dimensional properties of hardened concrete.

- Finally, conclude and recommend limits and specifications for the aggregate properties, as an inclusion into the current South African standard for aggregates.

1.3 Research Scope

This research will focus mainly on coarse RCA because the inclusion of fine RCA is not recommended in concrete mixtures as noted in Chapter 3. The RCA samples were collected at intervals over a 5 month period and sourced from the company Cape Brick. Cape Brick receives sorted and sized RCA from various construction and demolitions sites within the greater City of Cape Town. This material is processed through various crushing and sorting stations to produce both coarse and fine aggregates.

The main focus of this research is on the aggregate properties and their influence on the fresh and hardened concrete properties. The aggregate properties to be investigated included grading, dust content, fineness modulus, particle shape and surface texture, flakiness index, loose bulk and compacted bulk density, relative density, water absorption, aggregate crushing value, constituents of coarse RCA, chemical analysis for water soluble cations and anions and the chemical mineralogy through an XRF analysis.

The aggregates were mixed with other concrete constituents at replacement percentages of: 0, 15, 30, 50 and 100%. The natural aggregates used in the experimental programme was 19mm Greywacke as coarse aggregate and Malmesbury sand as fine aggregate. The binders include: CEM I 52.5 N cement and Corex® slag (GGCS), both available from the same cement producer. A water:binder ratio of 0.6 was used for all the concrete mixes and no admixtures are used.

The fresh concrete properties examined after mixing the relevant constituents once combined with water were the workability and loss of workability, fresh density and the air content. The fresh concrete is cast into the relevant mould and cured for a specified period at which point the hardened concrete properties were inspected. The hardened concrete properties investigated included the: compression strength, tensile splitting strength, oxygen permeability, water sorptivity, chloride conductivity, modulus of elasticity, shrinkage and creep. These properties are divided into mechanical, durability and dimensional properties to isolate the possible effects that the aggregate may have.

1.4 Research Layout

Chapter 2 describes the sustainability of construction materials and the issues surrounding the consumption of natural resources and the damaging effects of the construction industry. Construction and demolition waste and the methods of recycling this material to produce recycled aggregates are discussed in general. The applications of recycled concrete aggregate (RCA) are briefly described. The waste management in South Africa and the amounts of resources utilised (recycled and natural) are provided, with reference to a brick manufacturing company which uses recycled aggregates.

A comprehensive review of aggregate, fresh concrete and hardened concrete properties is given in Chapter 3. Research and investigations into the influence of RCA on above mentioned properties are reviewed from various sources. The South African and international standards and specifications used to classify aggregates for concrete are finally covered with particular relevance to RCA.

The experimental programme is explained in Chapter 4. The details outlining the materials used and tests for the aggregate, fresh and hardened concrete properties are provided. The concrete mixture design, mixing procedure and concrete production required to produce the test specimens for the relevant tests are defined.

Chapter 5 details the test methodologies necessary to examine the aggregate properties. The results from the various tests according to the geometrical, physical and chemical properties are analysed and studied with reference to the information found in Chapter 3.

The fresh concrete properties test methodologies and results relating to the workability and consistency of concrete are covered in Chapter 6. The slump, slump loss with time, air content and fresh density are evaluated and compared to the investigations dealt with in Chapter 3.

In Chapter 7 the hardened concrete properties from this investigation are examined. The test methodologies are described in detail with the inclusion of the design and manufacture of creep testing apparatus (creep frame) which was completed during this investigation. The results for the mechanical, durability and dimensional properties are analysed and deliberated according to the research found in Chapter 3.

Finally, Chapter 8 covers the general conclusions and discussions reviewing the information and results found in the previous chapters. From the knowledge and information gained from this investigation a proposal for possible guidelines and/or specifications for RCA properties in concrete are provided. To finish, recommendations for further research into various aspects of RCA are discussed and proposed.

Chapter 2

State of the Art

2.1 Sustainability of Concrete Construction Materials

According to the United States Environmental Protection Agency (EPA) (n.d.), the direct and indirect balance between the natural environment and human existence is dependent on the sustainability in which the two can coincide. Furthermore, sustainability develops and maintains the conditions amongst nature and humans, which allow the requirements of the present and future generations to be achieved. The term sustainable development was first introduced in 1987 at the United Nation's Brundtland Commission which stated that "development which meets the needs of the present without compromising the ability of future generations to meet their own needs" (Mihelcic & Zimmerman, 2010, p.7). The growing demand on natural resources due to social and economic development of all nations has led many to question whether the above statement was considered sufficiently. This steered the creation of the Millennium Development Goals (MDGs) in 2002 at the World Summit on Sustainable Development.

The MDGs consist of eight main goals with targets based on 1990 global figures for achievement by 2015 (Mihelcic & Zimmerman, 2010), one of which was Goal 7: Environmental Sustainability. One of the targets set under Goal 7 was to integrate the principles of sustainable development into country policies and programs and reverse the loss of environmental resources. In the Millennium Development Goals Report 2012, one of the greatest indicators of sustainable development is the ever growing greenhouse gas emissions. The 2012 report showed that there was a decrease since 1990 among developed countries; however developing countries showed an increase in carbon dioxide CO₂ emissions. The total global CO₂ emissions in 1990 were 21.7 billion metric tonnes compared to 30.1 billion metric tonnes in 2009 (Millennium Development Goals Report, 2012). The reason for the increase in emissions of developing countries is largely associated with infrastructure needs and lack of clean technologies related to energy requirements, whereas developed countries have sufficient infrastructure and can focus on cleaner technologies to meet energy requirements.

The energy consumption per sector can be seen in Table 2.1. From this data it is clear that the industrial sector is generally the leading consumer of energy worldwide with buildings consuming nearly 20 to 40% of this energy demand.

Table 2.1 Percentage energy consumption per major sector (Van Zijl, 2010 adapted from IEA (2007);¹ Perez-Lombard et al. (2008);² DME (2006);³ CIDB (2007) and ⁴ CO₂ emission per sector (CIDB,2007))

Sector	World		EU	RSA	
	1973	2004	2004	2006	
Industry	39	30	28	⁴ 40	
Manufacturing				37	
Mining				9	⁴ 11
Transport	25	28	32	31	⁴ 16
Other	36	42	40		
Buildings		¹ 20-40	¹ 37	² 16	⁴ 23
Other				³ 8	⁴ 10
Total	100	100	100	100	⁴ 100

Energy is needed to support both developed and developing countries to meet the requirements in each sector, however with the concept of sustainable development incorporated within each of the sectors included in Table 2.1 the impact on the environment may be lessened. Sustainable development is divided into three elements: economic prosperity, environmental awareness and social responsibility. Figure 2.1 demonstrates how when each of the elements is considered, sustainable development is possible.

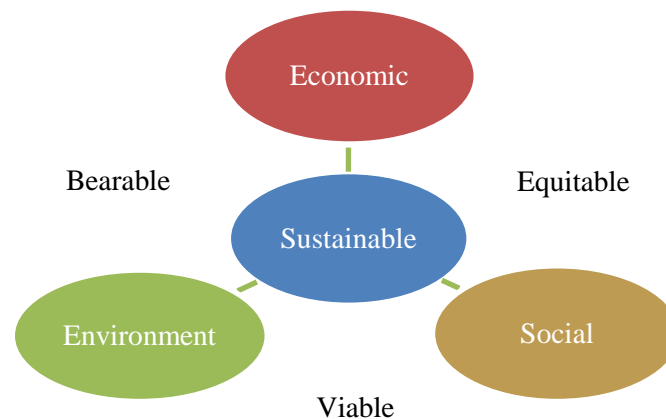


Figure 2.1 Elements of sustainable development (adapted from IzReaL (n.d.))

Concrete is the most widely used construction material globally and is contributing to the extraction of natural resources and energy usage, thus responsible for large quantities of CO₂ emissions (Lui & Chern, 2008). Concrete usage is based on the fact that the material is generally readily available, affordable and has proven durability properties (Van Zijl, 2010). Concrete is formed through a

mixture of aggregates, binders and water, where various environmental issues are associated with concrete production. To manufacture 1 tonne of cement, about 4 GJ of energy is used and 1 tonne of CO₂ is emitted, where overall cement production accounts for roughly 7% of CO₂ emissions (Lui & Chern, 2008).

The demand for concrete is challenged by the following global trends (Lui & Chern, 2008):

- Population growth is projected to be nearly 10 billion by the year 2050;
- Pressure on infrastructure to meet the needs of the growing population will increase;
- The available non-renewable resources, such as materials and fossil fuels are decreasing.

The extraction of natural/virgin resources from the earth is another significant environmental hurdle that the concrete industry faces in terms of sustainability. The figures differ amongst the various sources. Listed below are some typical figures related to construction and concrete production:

- Worldwide, the civil and building construction consumes 60% of raw materials from the earth (Bribian et al, 2011);
- Since 1995 concrete production was expected to rise from 10 billion tonnes to about 16 billion tonnes by 2010 (Lui & Chern, 2008);
- An estimated 12 billion tonnes of concrete was produced per year (van Zijl, 2010).

The impact that this has on each country is individualised, as each country's available natural resources may differ. Although some countries may have a sufficient supply of natural resources, this has not resulted in countries such as these exploring other options for constituents in concrete. Construction and demolition (C&D) waste is one of the most notable options which could have an influence on decreasing the need for virgin materials.

2.2 Construction and Demolition Waste

Construction projects can be separated into three phases, namely; pre-use, use and end-of life. Table 2.2 provides a breakdown of the occurrences within each phase. The impact that each phase has on the sustainability of a project is dependent on the construction methods provided and carried out by the relevant parties involved.

Table 2.2 The different phases of a construction project (adapted from Nushi & Bejtullahu, 2011 and Dias & Ilomäki, 2011)

Pre-design/Conceptual Design	
Design	
Extraction of Raw Materials	Pre-use Phase
Production	
Construction	
Use	Use Phase
Maintenance	
Demolition	End-of-Life Phase
Disposal , Reuse, Recovery and Recycling	

The pre-use phase has high importance by reason of the fact that it dictates how a project will start and possibly how a project will end. The source of materials needed for a project, the way in which the materials are utilised and manner in which the materials will be dealt with in the final phase can be determined within this phase. The highest demand for energy could be associated with the first and second phase of a project life-cycle, whereas material handling can be linked to all of the phases, with possibly higher volumes in the first and last phase. Many organisations have focused on reducing the energy demands of a building through the use of advanced building and architectural techniques, but much attention has also been given to the final phase where a project's life-cycle concludes.

The end-of life phase occurs when a project has either reached its durable life-span, is damaged or destroyed due to natural or man-made disaster or must make way for a new project. This usually means that a building is demolished and therefore has to undergo one of a few waste management options. These waste management options may be ranked according to environmental impact which Brits (2010) noted from Peng et al. (1997) as seen in Figure 2.2.

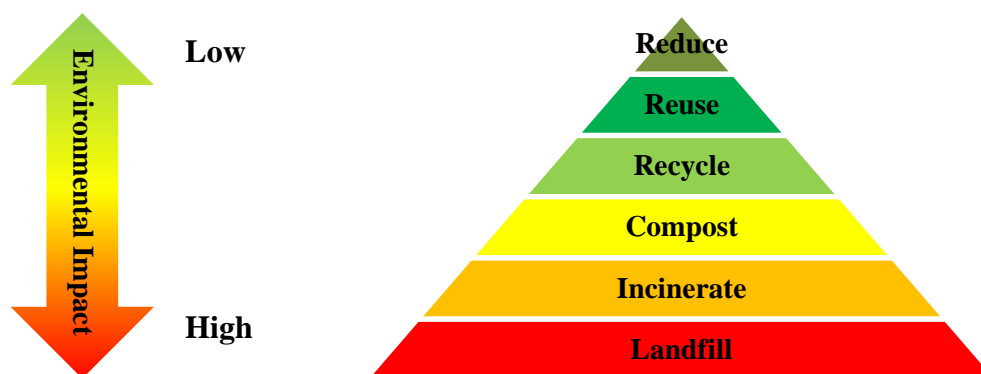


Figure 2.2 Hierarchy of waste disposal options adapted from Brits (2010)

The three most important waste minimization strategies of these options would be to reduce, reuse and recycle. The waste materials that are accumulated during a project life-cycle have been defined as C&D waste. C&D waste can be accumulated within any of the three phases, with the majority of this waste formed in the final phase. Within the first and second phases C&D waste can be generated in the following manners described by Tam (2009) from various sources: over ordering, damage during transportation, loss during construction and maintenance, poor workmanship and change in design. The amount of C&D waste generated each year is estimated by different sources to be in the region of 1-3 billion tonnes (Lui & Chern, 2008, Mohammend, 2007 noted by Chandra Paul (2011), and Van Zijl, 2010). Disposal via landfill has been the norm for most countries until more recently, with pressure from society to meet sustainable methods of disposal.

C&D waste may be derived throughout the various stages of construction, but determining what constitutes C&D waste is not clearly defined, as each project uses a selection of different materials. Franklin Associates & EPA (1998) defined C&D waste as material produced in the process of construction, maintenance and renovation, or demolition of structures. These structures include roads, bridges and buildings of all types (residential and non-residential) and are generally non-hazardous. The material may consist of the following sub-materials: concrete, wood, asphalt, gypsum, metals, glass, bricks, plastics, building components, rocks and organics.

The concern which develops from the accumulation of C&D waste is the decreasing availability of landfill space. This development has been driven by many factors for example available recovery methods, low landfill costs and lack of control and management. Generally 40% of a country's waste stream is associated with C&D waste, while 15-30% of this amount will end up at landfill as determined by the California Integrated Waste Management Board (Macozoma, 2006). Many built-up countries cannot accommodate large volumes of waste material and thus have resorted to specific waste management techniques, with recycling being the dominant method of choice.

2.3 Recycling of Concrete

The recycling of waste material has generally been driven by material which is expended on a regular basis, such as glass, metals, plastics and paper. These materials are easy to separate and thus require less input by the secondary manufacturer to process. C&D waste is a much more complex material as many individual materials can be recycled from a project. The contents of the overall waste material depend largely on the manner in which a project is demolished. The recycling of components from a project will require less processing if the recyclables are separated at the source and particular demolition methods are followed. Macozoma (2006) summarises several demolition procedures derived from a background study along with methods prescribed in the ACI 555R-01 noted in Table 2.3.

The demolition of these structures in an efficient manner can be done by first removing small building components through manual procedures, after which more rapid and vigorous approaches such as heavy machinery and/or explosives can be used. This will ensure separation of different materials before recycling and therefore reducing the amount of C&D waste not viable for recycling.

Table 2.3 Various demolition techniques (adapted from ACI 555R-01 & Macozoma, 2006)

Demolition Techniques	Examples of equipment
Hand Tools	Chisels, Pry bars, Sledgehammers
Hand-operated Power tools	Jackhammers, Drills, Saws
Pulling	Wire rope, Vehicle
Impact	Wrecking ball, Impact breakers
Abrasion	Hammer drill, Diamond cutters
Heating	Thermal cutting, Electrical conductors
Freezing	Cryogenic
Expansion	Gas, Chemical
Explosion	High detonation, Low detonation
Bending	Jack up (point loads)
Hydro	Water jet blasting
Mechanical splitters	Steel wedge

Concrete rubble resulting from C&D waste has been investigated for its potential as a secondary material. This secondary material, namely RCA, is generated from the recycling of concrete materials within C&D waste. RCA is then used as an aggregate in new concrete to partially or completely replace natural aggregates (NA) to form recycled aggregate concrete (RAC).

The process of recycling C&D waste to produce RCA generally involves the same machinery and processes utilised in the mining of virgin aggregate (Rotter et al, 2010 and ACI 555R-01). The recycling method and production process similarly play an important role in determining the amount of RCA which can be used in secondary markets and specialised applications. Rotter et al. (2010) states that two main recycling methods exist, fixed/permanent recycling facilities or mobile/on-site recyclers. The notable difference between the two methods is the fact that mobile recyclers are essentially crushers, whilst permanent facilities are a combination of crushers and sorting equipment. The unit operations that can be found within a permanent recycling are described in Table 2.4, while in Figure 2.3 an example of a production process is explained.

Table 2.4 Unit operations that may be found in a C&D waste recycling facility (adapted from Rotter et al, 2010)

Technique	Function
Manual separation	Separate or discard recoverable materials
Crushers	Size reduction
Wind-sifting	Separate light and heavy weight particles
Screening	Size differentiation
Shaking table	Separate light and heavy weight particles
Magnetic separation	Remove ferrous metals
Eddy current separation	Remove non-ferrous metals
Flotation	Use buoyancy to disperse hydrophobic particles

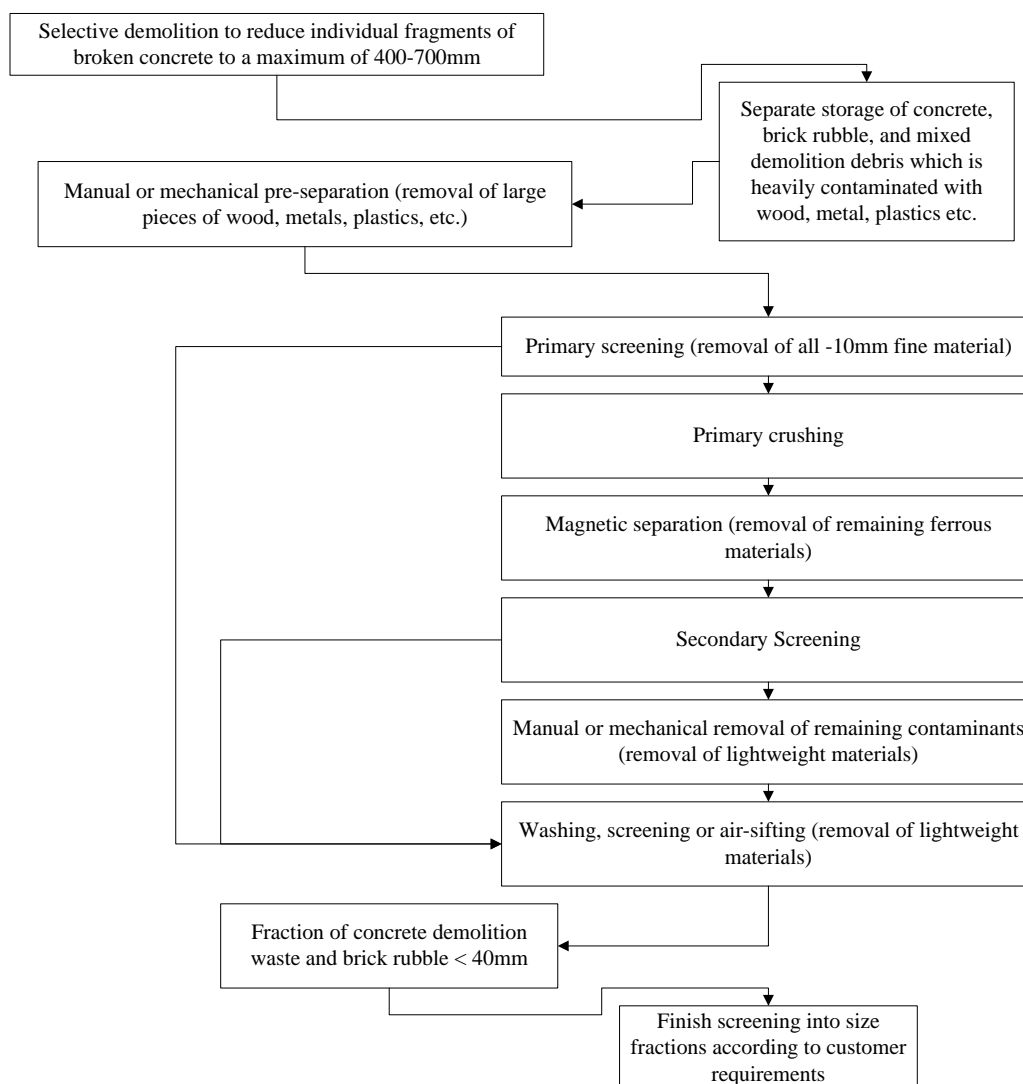


Figure 2.3 Typical recycling production process that would be applicable in a permanent facility (adapted from ACI 555R-01)

To achieve a secondary material of higher quality than normal practices, many recycling facilities include specialised crushers such as gyro-crushers and vertical impact crushers as well as refining the production process. The issues relating to the recycling process can be weighed up by exploring the benefits and difficulties. Tam (2009) examines the implementation of concrete recycling in the Australian and Japanese construction industries through a questionnaire survey. The four focus areas were surveyed: awareness, benefits, difficulties and effective methods of concrete recycling. In terms of benefits and difficulties the following was questioned in Table 2.5.

Table 2.5 Benefits and difficulties associated with recycling of C&D waste adapted from Tam (2009)

Benefits	Difficulties
<ul style="list-style-type: none"> • Reducing the need for new landfills • Saving natural materials • Reducing project costs by using recycled materials • Saving cost in transportation when recycling done on-site • Stimulating improvement in recycling methods • Rising recycling awareness, such as selecting suitable resources, techniques and regulations • Increasing overall business competitiveness • Improving management and communication of concrete recycling information and commitment 	<ul style="list-style-type: none"> • High cost investment • Difficult to place recycling machines on-site • Poor quality of recycled materials • Time consuming procedure • Lack of support from industry • Mixed attitude between different stakeholders, policies and regulatory requirements • Limited applications • Lack of technologies, resources, training, component staff and expertise

Tam (2009) concluded that reducing the need for new landfills and saving natural resources were considered key benefits and the prices of recycled products were costly and limited applications were among the main difficulties.

2.4 Applications of Recycled Concrete Aggregate

The applications of RCA have been largely driven by the reluctance of construction industries and stakeholders to utilise this material in all aspects of construction projects. Due to the quality issues surrounding RCA much of the material has been limited to low grade applications. With more recent studies and research the prospects for its use in higher grade applications have been investigated and established.

RCA has been used in roads, civil works, structural and landscaping regions of projects, mostly as a fill material. Majority of the low-grade applications are related to road works such as unbound road base, fill and hardcore (Tam et al, 2005). Although the amount of RCA being deposited at landfills is relatively high, some C&D waste is needed as a capping material (Coetzee, 2012). Other specific applications include drainage for embankments, brick/block manufacturing and base foundation material in parking areas (Kutegeza, 2004).

The structural applications and concrete applications have improved, largely driven by research at universities and construction agencies worldwide. The countries that have made notable progress to the recommendation for the use of RCA in new concrete are: Japan, Australia, Netherlands, China and most of Europe. Specifications and standards developed by individual countries have provided a platform by which the implementation of RCA can be controlled, henceforth providing relevant stakeholders with knowledge and confidence related to RCA.

2.5 Waste Management in South Africa

The South African construction industry and governing bodies are displaying an increasing interest into improved waste management techniques and minimising the deposit of C&D waste at landfills (Macozya, 2006). For this interest to be translated to implementations means that the correct policies and legislation need to be in place, with the aim of regulating the relevant stakeholders and providing concerned parties with documentation for accountability. Of this legislation the Constitution of South Africa of 1996 states in Section 24 that:

*“Everyone has the right
(a) to an environment that is not harmful to their health or well-being; and
(b) to have the environment protected, for the benefit of present and future
generation through reasonable legislative and other measures that -
(i) prevent pollution and ecological degradation;
(ii) promote conservation; and
(iii) secure ecologically sustainable development and the use of natural
resources while promoting justifiable economic and social development.”*

This section of the Constitution reflects the Brundtland Commission’s definition of sustainable development as set out by the United Nations. The White Paper on Integrated Pollution and Waste Management was introduced as South Africa’s national policy on pollution and waste management. This paper is set to inform the public of the government’s objectives and how these will be achieved and to inform the stakeholders of their roles in these objectives. Further, the government provides specific national legislation for the environment and subsequently the management of waste through the National Environmental Management: Waste Act (NEMWA) (Act No. 59 of 2008). Resulting from The Waste Act is the National Waste Management Strategy (NWMS) (2011), which is a strategy

defined around eight goals set out to achieve the objectives as defined in the Waste Act. The eight goals are described in Table 2.6 along with targets to be met by 2016. The Constitution, NEMWA and NWMS form the spearheads for subsequent provincial and local legislation and strategies.

Table 2.6 Eight goals and targets set according to the NWMS (2011) of South Africa

Goal 1:	Promote waste minimisation, re-use, recycling and recovery of waste.	25% of recyclables diverted from landfill sites for re-use, recycling or recovery. All metropolitan municipalities, secondary cities and large towns have initiated separation at source programmes. Achievement of waste reduction and recycling targets set in IndWMPs for paper and packaging, pesticides, lighting (CFLs) and tyres industries.
Goal 2:	Ensure the effective and efficient delivery of waste services.	95% of urban households and 75% of rural households have access to adequate levels of waste collection services. 80% of waste disposal sites have permits.
Goal 3:	Grow the contribution of the waste sector to the green economy	69 000 new jobs created in the waste sector 2 600 additional SMEs and cooperatives participating in waste service delivery and recycling
Goal 4:	Ensure that people are aware of the impact of waste on their health, well-being and the environment.	80% of municipalities running local awareness campaigns. 80% of schools implementing waste awareness programmes.
Goal 5:	Achieve integrated waste management planning.	All municipalities have integrated their IWMPs with their IDPs, and have met the targets set in IWMPs. All waste management facilities required to report to SAWIS have waste quantification systems that report information to WIS.
Goal 6:	Ensure sound budgeting and financial management for waste services.	All municipalities that provide waste services have conducted full-cost accounting for waste services and have implemented cost reflective tariffs.
Goal 7:	Provide measures to remediate contaminated land.	Assessment complete for 80% of sites reported to the contaminated land register. Remediation plans approved for 50% of confirmed contaminated sites.
Goal 8:	Establish effective compliance with and enforcement of the Waste Act.	50% increase in the number of successful enforcement actions against non-compliant activities. 800 EMIs appointed in the three spheres of government to enforce the Waste Act.

IndWMP = Industrial Waste Management Plan

SME = Small medium enterprises

IWMP = Integrated Waste Management Plan

SAWIS = South African Waste Information System

WIS = Waste Information System

EMI = Environmental Management Inspectorate

At a local government level the City of Cape Town (2006) has developed an Integrated Waste Management (IWM) Policy. This policy applies to the demarcated municipal boundaries of Cape Town and aims to:

- Manage and minimise waste that will be collected, streamed, diverted, processed/treated or recycled;
- Manage waste ending up at a licensed and regulated landfill or waste management site;
- Regulate all service providers operating in the waste management industry;
- Control and regulate waste crossing the municipal boundaries to ensure proper management, recycling and control of all types of waste.

Nationally, provincially and locally the issue of managing waste, particularly waste disposed at landfill is of great concern. The problem that arises in South Africa is the implementation of these overarching policies, managing the objectives and regulating the stakeholders (Nahman & Godfrey, 2009). For example, information concerning the amounts of waste deposited at landfill nationally is not accurately monitored on a regular basis, due to the lack of available data. Of concern is the increase in illegal dumping, which according to the City of Cape Town will cost over R100 million across 2-4 years to clean-up (Coetzee, 2012). Larger construction and demolition companies are easy to monitor, whereas smaller companies try to avoid transport and disposal costs (Kutegeza, 2004).

The amount of C&D waste deposited at South African landfill sites was estimated by Macozoma (2006) in 2002 to be over one million tonnes per annum which formed part of the estimated 5-8 million tonnes of C&D waste generated by the construction and demolition industry (Table 2.7).

Table 2.7 only takes into account landfills that receive over 50 000 tonnes of municipal solid waste and the C&D waste referred to, is defined in the broad sense. As seen in the comments of Table 2.7 C&D waste is not clearly defined, and therefore keeping record of C&D waste that is non-recyclable that which is recyclable cannot be achieved. Also evident is the high occurrence of illegal dumping within each province. A noticeable trend is that provinces with the highest C&D waste deposited at landfill sites each have metropolitan districts. The high economic growth and continuous infrastructure development associated with these metropolitan areas directly correlate to higher volumes of waste accumulated.

Table 2.7 Estimated amounts of C&D waste ending at landfill in 2002 (Macozoma, 2006)

Province	Amount (tonnes)	C&D Classification	Recycling	Illegal Dumping
Gauteng	700 000	Not detailed	On-site & SM	Extensive
Kwa-Zulu Natal	380 000	Not detailed	On-site & SM	Extensive
Western Cape	240 000	Not detailed	On-site & SM	Extensive
Eastern Cape	64 000	Not detailed	On-site & SM	Extensive
Mpumalanga	minimal	Regarded as rubble	On-site & SM	Extensive
North West	minimal	Regarded as rubble	Less extensive	Less extensive
Free State	minimal	Not detailed	Less extensive	Less extensive
Northern Cape	minimal	Not detailed	Less extensive	Less extensive

SM = secondary markets

The extraction of natural resources for the purposes of construction projects shows increasing trends. South Africa is considered a developing country, where the growing population and increasing need for economic infrastructure places a heavy burden on the environment. Table 2.8 is an extract report by the Department of Minerals and Energy (DME) with assistance from the Aggregate and Sand Producers Association of Southern Africa (ASPASA) for the amount of aggregate by classification sold in 2004 and 2005.

Table 2.8 Amounts of natural resources utilized in South Africa for 2004 and 2005 (adapted from DME, 2006)

Classification	2004			2005		
	Mass	Value		Mass	Value	
	kt	R'000	R/t	Kt	R'000	R/t
Calcrete	12	106	9	19	169	9
Gravel	298	6 998	23	179	4 328	24
Slag blast furnace	96	3 708	39	101	5 048	50
Sand	8 347	136 721	16	12 046	221 034	18
Shale	15	289	20	11	263	23
Aggregate (4.75-13mm)	2 735	161 154	59	2 784	182 678	66
Aggregate (13-26mm)	10 578	633 390	60	11 591	722 266	62
Aggregate (>26mm)	2 827	135 187	48	2 617	123 292	47
Base (G1-G3)	3 781	200 100	53	3 601	198 835	55
Sub-base (G4-G7)	4 846	154 584	32	5 050	164 635	33
Crusher sand	9 357	434 869	46	9 726	495 310	51
Crusher run	835	38 869	47	813	38 811	48
Aggregate (Others)	3 656	179 388	49	1 432	65 344	46
TOTAL	47 382	208 5364	39	49 970	222 2019	40

From this data it can be seen that aggregate (13-26mm) and sand are the natural resources of which the highest amounts are extracted each year. These materials are usually associated with concrete production and therefore the amount of potential C&D waste is increasing concurrently.

The City of Cape Town’s Department of Solid Waste Management manages and regulates the flow of waste material within and out of the municipal boundary. The department estimates that currently 19-20% of the total waste is C&D waste (Figure 2.4) (City of Cape Town (2012)). Builders rubble or C&D waste was only differentiated in the solid waste stream from mid-2010. Figures 2.5 and 2.6 give a perspective on the amount of waste generated by the City of Cape Town from 2011 until mid-2012. A report by the Sustainability Institute of Stellenbosch compiled by Engledow (2007) found that in 2006, C&D waste totalled 15% of the solid waste deposited at landfill sites and a total of 2.6 million tonnes of waste was generated.

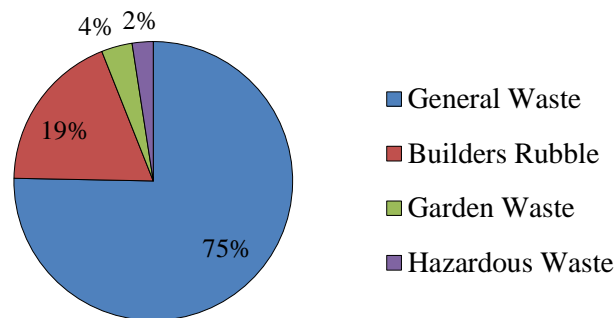


Figure 2.4 Estimation of solid waste % accumulation at landfills in the City of Cape Town 2011(adapted from City of Cape Town, 2012)

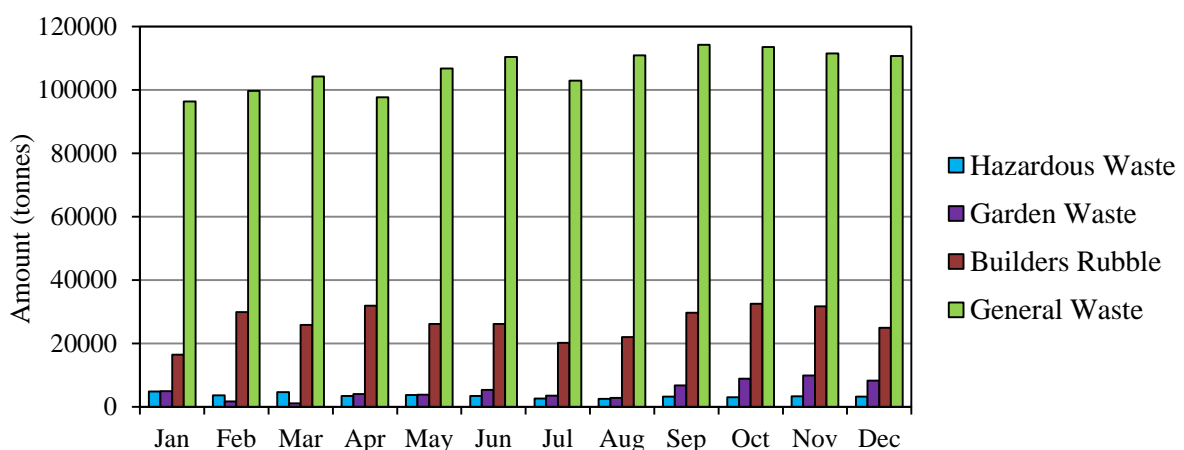


Figure 2.5 Solid waste amounts accumulated at the City of Cape Town landfills in 2011(adapted from City of Cape Town, 2012)

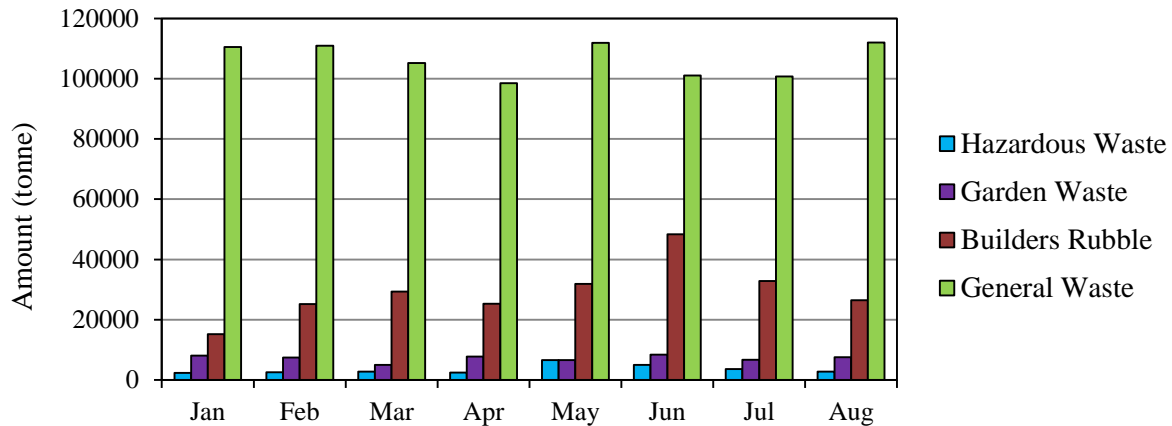


Figure 2.6 Solid waste amounts accumulated at the City of Cape Town landfills in 2012(adapted from City of Cape Town, 2012)

Reflecting on more recent data shows that Macozoma (2006) C&D waste estimations for the Western Cape were relatively correct and that the C&D waste deposited at landfill sites has increased from approximately 240 000 tonnes in 2002 to 315 000 tonnes in 2011 and possibly over 350 000 tonnes in 2012. This means that the amount of C&D waste dumped at landfills increases roughly by 2-3% per year.

The City of Cape Town (n.d.) allows for 1.3 tonnes of builders rubble per load/day/resident to be discarded at landfill sites without charge. The City of Cape Town only provides three landfill sites whereby C&D waste recycling facilities are available, one of which is a drop-off facility. The City of Cape Town recognises the need to help implement initiatives for the creation waste management facilities which will enable the recycling, recovery, repair, treatment and/or re-use of waste materials, public or privately owned.

Cape Brick is one such initiative, where C&D waste generated from projects within the greater Cape Town area is recycled and used to produce new concrete products. The company was founded in 1938 and was originally contracted to transport waste ash out from a nearby power station (Cape Brick, n.d.). In 2001, after relocating in 1996, the company became one of the first manufacturers to utilise waste material in the production of concrete products (Cape Brick, n.d.). The products include: concrete bricks, concrete masonry units (CMU), retaining wall blocks and wet cast paving products (EcoSpecifier, 2011). The amount of recycled material included into the products ranges from a minimum of 70% in the CMU's and retaining wall blocks and up to 95.6% in the 14MPa concrete plaster brick (EcoSpecifier, 2011). The company also replaces 50% of the cementitious materials with Corex® slag from PPC.

Cape Brick partnered up with Ross Demolition, which is a recognised demolitions company in the Western Cape, to provide a continuous supply of C&D waste. Apart from reducing the amount of C&D waste ending up in landfill sites, Cape Brick also reduces both the CO₂ emissions resulting from concrete products and embodied energy needed to produce concrete products. EcoSpecifier (2011) estimates that the 14 MPa concrete brick has an emission of 0.13 kgCO₂/block, compared to 0.15 kgCO₂/block from bricks produced from virgin materials. This figure does not include the reduced transportation benefits; however the embodied energy (which takes transport into account) is 1.43 MJ/14 MPa concrete brick, compared to 2.72 MJ/14 MPa standard concrete brick with virgin materials (EcoSpecifier, 2011).

Kutegeza (2004) recounted data from a questionnaire conducted by Ayers in 2002 for the amount of recycling occurring at private companies in the Cape Town area (Table 2.9). Cape Brick (2004) reported in 2004 that the total amount of RCA utilised was approximately 42 000 tonnes. In 2012 the amount of RCA produced and utilised by the company was estimated at 70 000 tonnes, which shows a large increase since 2002 (Cape Brick, n.d.).

Table 2.9 Amount of recycled C&D waste produced in 2002 in the City of Cape Town (Kutegeza, 2004)

Company	Demand/Year (tonnes)	Produced/Year (tonnes)	Applications
Malan Quarries	> 200 000	> 150 000	Road works General site fill
Bradis (Pty) Ltd	> 100 000	> 55 000	Road works Concrete works Brick manufacturing General site fill
Ross & Sons Demolition	> 20 000	> 15 000	Road works General site fill
CapeBrick (Pty) Ltd	> 2 000	> 2 000	Brick manufacturing
Total	> 222000	> 320000	

In August of 2010, the cooling towers of Cape Town's old Athlone power station were demolished by method of implosion (Figure 2.7). Cape Brick along with Ross Demolition were contracted to remove and recycle the C&D waste from this site, which yielded 16 000m³ of rubble amounting to roughly 20 000 tonnes (Cape Brick, 2011). The C&D waste from this project took about 4 months to recycle and produced nearly 6 million bricks (Cape Brick, 2011).



Figure 2.7 Demolition of Athlone cooling tower in 2010 by implosion (Athlone Towers Demolition (left), 2010 and Athlone Towers Demolition (right), 2010)

Gracie (2011) Managing Director at Cape Brick stated that although their products met the specifications according to SANS 1215:2008 *Concrete Masonry Units*, there is still however a reluctance from project stakeholders and engineers to use the products in many projects. The products have been used in low – medium rise residential structures in the Cape Town area seen in Figure 2.8.



Figure 2.8 Cape Brick (n.d.) products used in residential structures in the City of Cape Town

The recycling industry will benefit from the specifications and/or standards for the use of RCA in concrete construction projects, because the project stakeholders and respective engineers will be more confident in the RCA material. The potential benefits for the use of RCA will include:

- Reduced material deposited at landfills;
- Reduced transportation impact of C&D waste;
- Reduction in the extraction of natural/virgin materials, and;
- Therefore a lower embodied energy and emissions of CO₂ when using RCA;
- Meeting the sustainable development goals and targets for individual countries and international partnerships.

Chapter 3

Recycled Concrete Aggregates in Concrete: A Review

In Chapter 2 the current applications of recycled concrete aggregate (RCA) are discussed as well as the interest of relevant stakeholders to promote further research into recycling and use of recycled materials. Of interest is the use of RCA in new structural projects specifically concrete, where the majority of applications are limited to non-structural concrete elements. Extensive research has been done internationally with regard to RCA in structural concrete. However, many researchers have noted that an inclusion of 100% RCA in concrete could result in concrete of a lesser quality than those containing only natural aggregates. Similarly, many of the investigations have involved crushing the C&D waste under laboratory conditions, where the RCA composition is better controlled. The need to determine the influence of raw RCA or commercially produced RCA on the concrete properties from a practical point of view should be investigated. This chapter reviews the aggregate, fresh concrete and hardened concrete properties when RCA has been used.

3.1 Aggregate Properties

Aggregates are a key constituent of concrete along with water, air, cement and other additives. Their addition to concrete provides a more dimensionally stable product, greater strength and a reduction in the cost of concrete. Aggregates in general account for 65 to 80% of the total volume of concrete (Domone & Illston, 2008). Aggregates are sourced from natural materials such as rocks which are crushed or deposited gravels from natural formations.

The mineralogical, physical and chemical properties of aggregates or more specifically the rocks from which they originate depend on the geological location and history (Grieve, 2009a). Table 3.1 shows the geological type for various rocks used in construction are chosen from the region from which they can be sourced. The rocks in each of these regions are classified by the method of formation. The methods of formation are natural processes that occur on earth by which the characteristics of rocks are determined. The formation method for rocks may be igneous, metamorphic or sedimentary.

Table 3.1 Widely used sources of South African stone and crusher sand (Addis, 2008)

Geological type	Source
Quartzite	Witwatersrand Supergroup (Reef quartzite): mainly waste dumps of gold mines Table Mountain Group: along southern and eastern seaboard Pretoria Group: vicinity of Pretoria
Sandstone and Quartzitic sandstone	Karoo Supergroup: interior of South Africa Beaufort Group: East London area Ecca Group: Natal Midlands
Dolerite	Karoo Sequence: widespread throughout Southern Africa
Basalt	Karoo Eruptives: Drakensburg, Lebombo, Springbok Flats Venterdorp Eruptives (Andesite): Gauteng, Vaalharts
Granite	Halfway House, Cape Town area, Kwa Zulu-Natal Mpumalanga
Greywacke	Cape Town area
Tillite	Dwyka Formation of Karoo Supergroup: Durban area, Kwa Zulu-Natal coastal regions
Dolomite	Transvaal Sequence: Gauteng Province Griqualand West Sequence: North West Province, Northern Cape Province

All rocks originate as igneous rocks (Alexander & Mindess, 2005) and form from the solidification of molten material beneath the crustal zone of the earth. Two types of igneous rocks exist depending on the rate of cooling and manner in which it reaches the Earth's surface, they are: intrusive/plutonic (coarse) and extrusive/volcanic (fine). Intrusive rocks solidify slowly and in cases under high pressure at great depths. Intrusive rocks are fully crystallized with little or no glassy material (Alexander & Mindess, 2005) and are chemically highly stable and are preferred in concrete production. Extrusive rocks form at the earth's surface and solidify rapidly, where partial crystallization occurs and the material is glassy. These rocks are not as stable as intrusive rocks and in the case of concrete manufacturing may result in processes such as alkali reactivity.

Sedimentary rocks are formed from natural degradation processes by either chemical or physical processes from other rocks. These rocks usually collect as deposits and in most cases under water. The fragments of rocks are bound together by cementing agents from precipitation and accumulation such as siliceous, argillaceous, calcareous or ferruginous (Grieve, 2009a). Their properties rely largely on the original or parent rock. The transportation and weathering of the rocks over long periods

provide a material that is well-shaped and useful in concrete. The material properties can be altered where the different layers of various minerals are cemented together.

Aggregates are considered inert material particles, which do not hydrate, shrink or swell. However, in some exceptions, processes may occur which may be detrimental to the concrete as a whole. Aggregates in concrete are divided into two classes namely coarse and fine aggregate. Both of these aggregates have certain properties and specifications which determine their addition in a concrete mix. Also the type of aggregate derived from sources throughout the country may differ in terms of the properties and specifications.

Aggregate properties play a role in the fresh and hardened states of concrete. It is therefore necessary to look at the different properties of aggregates to determine their specific influence in concrete.

3.1.1 Particle shape (angularity and flakiness) and surface texture

The shape of aggregates plays the most important role in the fresh concrete properties (Grieve, 2009a). The workability and water requirement of fresh concrete is related to the shape of aggregates, both the fine aggregate (sand) and coarse aggregate (rock). The particle shape can be assessed and described by three geometric properties; “sphericity”, “roundness” and “form” (Alexander and Mindess, 2005). The first describes how spherical a particle is, while the second defines how sharp the edges of a particle are while the “form” is a measure of the particle’s axial proportions (Figure 3.1). These definitions depend highly on the manner in which the aggregate is sourced. Naturally occurring particles deposited by natural processes tend to be more spherical and have smooth edges, while mined/crushed aggregates have angular and flaky (flat) particles as described in Table 3.2.

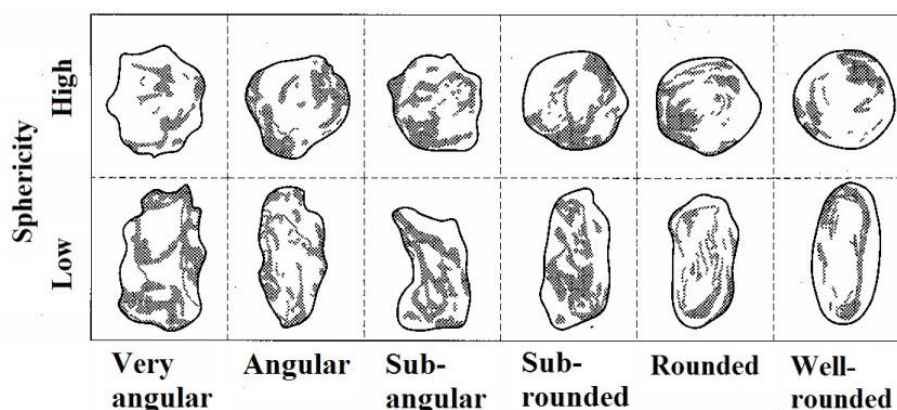


Figure 3.1 Classifying the particle shape by “sphericity” and roundness
(Alexander & Mindess, 2005)

Table 3.2 Description of particle shape as specified by BS 812: Part 102: 1989(Alexander & Mindess, 2005)

Particle Shape	Description	Examples
Rounded	Fully water-worn or completely shaped by attrition	Gravels and sands derived from marine, alluvial, or windblown sources.
Irregular	Naturally irregular, or partly shaped by attrition and having rounded edges	Other gravels, typically dug from pits
Angular	Possessing well-defined edges formed at the intersection of roughly planar faces	Crushed rocks of natural or artificial origin, talus rocks
Flaky	Material in which the thickness is small relative to the other two dimensions	Poorly crushed rocks, particularly if derived from laminated or bedded rocks, other laminated rocks
Elongated	Material, usually angular, in which the length is considerably larger than the other two dimensions	Poorly crushed rocks, as above. Poor processing techniques can exacerbate the undesirable shape, and vice versa
Flaky and elongated	Material having the length considerably larger than the width, and the width considerably larger than the thickness	

Flakiness is one of the indirect measures of coarse particle shape and is calculated as the Flakiness Index (FI). A high FI value or percentage means that the majority of the particles from a sample are flatly shaped, whilst a low FI value indicates particles which are chunkier or have a more even form. The British Standard 12620:A1:2008 limits the FI of coarse aggregate to 50 and the SANS 1083:2006 limits the FI to 35. Aggregates for concrete with a high FI value are likely to be harsh and less workable in the fresh state and are prone to segregation (Chandra Paul, 2011). Hardened concrete would benefit from aggregates which are more angular and not flaky, because internal cracking would struggle to develop along a single crack due to higher friction (Alexander & Mindess, 2005).

The surface texture of a particle plays a similar role in concrete to that of particle shape. Surface textures can be categorised by the descriptions as seen in Table 3.3 and depend largely on the parent rock properties such as hardness, grain size, pore structure and texture (Mehta & Monteiro, 2006). The surface texture of RCA depends on the crushing process, by matter of how much attached mortar is removed. Rough surface texture will decrease the workability of fresh concrete; however it increases the internal friction between aggregates and the cement paste of hardened concrete.

Table 3.3 Description of particle surface texture as specified by BS 812: Part 102: 1989 (Alexander & Mindess, 2005)

Surface Texture	Characteristics	Examples
Glassy	Conchoidal (curved fracture)	Glassy or vitreous materials such as slag or certain volcanics.
Smooth	Water-worn or smooth due to fracture of laminated or fine-grained rock	Alluvial, glacial or windblown gravels and sands; fine grained crushed rocks such as quartzite and dolomite
Granular	Fracture showing more or less uniform size rounded grains	Sandstone, coarse grained rocks such as certain granites.
Rough	Rough fracture of fine- or medium-grained rock containing no easily visible crystalline structure	Andesite, basalt, dolerite, felsite and greywacke
Crystalline	Containing easily visible crystalline constituents.	Granite, gabbro and gneiss
Honeycombed	Visible pores and cavities	Brick, pumice, foamed slag, clinker and expanded clay

Kutegeza (2004) and Alexander & Heiyantuduwa (2002) found that coarse RCA is a mixture of rounded, irregular and sub-angular particles with a rough and porous surface texture due to attached mortar. The FI of RCA has been found to be lower than that of NA (Chandra Paul, 2011).

3.1.2 Sieve analysis (grading, dust content and fineness modulus)

Conducting a sieve analysis on a sample of fine and/or coarse aggregate can define three physical properties, namely; the grading, dust content and the fineness modulus. Each of these properties has an influence on the fresh and hardened states of concrete.

Grading of an aggregate sample will determine the particle distribution by the percentage passing the relative sieve sizes. Aggregates are divided into two categories: fine and coarse aggregate. Aggregates are divided by the 4.75mm sieve, where nearly all the particles of fine aggregate pass through this sieve and coarse aggregate is retained above it.

The particle distribution has a significant influence on the workability of fresh concrete and the water requirement, as well as the packing density or voids content. The grading of aggregates can be classified into three groups: single-sized, gap graded and continuously graded. Single-graded aggregates contain a high percentage of one particle size and low to zero percentage of other particles sizes, whereas continuously graded material has a moderate percentage of one particle size and distributed percentages of the other sizes (Figure 3.2). Gap graded material occurs when one or more intermediate size fractions are not included.

Fine aggregate grading will have a greater influence on the workability, cohesiveness and bleeding, whereas coarse aggregate is less significant, but may impact the water requirement of fresh concrete (Grieve, 2009a). A well/continuously graded aggregate will have less voids and higher packing capacity as illustrated by Figure 3.2, which may reduce the air content in fresh concrete.

The most commonly used stone is 19mm (Grieve, 2009a) and is usually a nominally sized stone which has a less continuous stone grading with limited amounts of particle sizes specified by country specific standards.

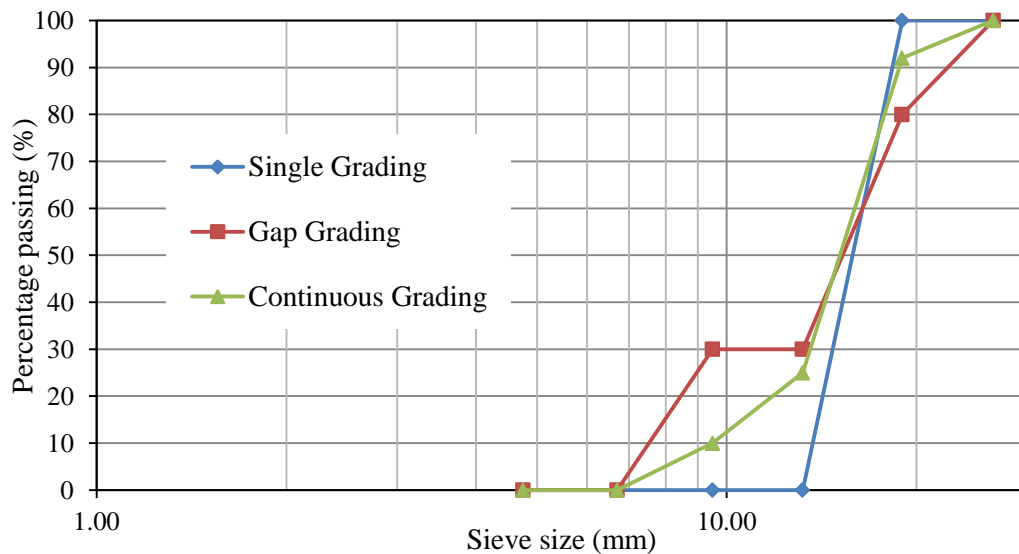


Figure 3.2 Grading examples from a sieve analysis (single, gap and continuous grading)

The dust content is defined as material passing the 75 μ m sieve. The dust content of aggregates is limited because of its relation to possible contamination by clay minerals (Grieve, 2009a). The Cement and Concrete Institute (C&CI) of South Africa conducted tests which showed that the compressive strength increased with increasing dust content (Grieve, 2009a). High dust content will reduce bleeding but if contaminated with active clays it could lead to high shrinkage. Coarse RCA commonly has a higher dust content, due to the crushing of attached mortar to aggregate, however in most cases is still able to meet specified limits. Gutiérrez & Juan (2004) found that coarse aggregate generally has a low fine content of (0.3 to 1.2%) and that the coarse RCA sampled through industrial processes had a fine content of 0.6% which was below 2% as set by the appropriate standards. Alexander & Heiyantuduwa (2002) found that RCA from a crushing facility had a relatively high dust content of 0.59%.

The fineness modulus (FM) is a dimensionless parameter for the measure of average fineness or coarseness of aggregates (Kutegeza, 2004). It is normally used for describing the fineness of sand and less than that for stone. The sand material's FM can be categorized as seen in Table 3.4 where coarser

sand would decrease the water requirement and vice versa. Chandra Paul (2011) notes that for good concrete the FM value of sand should be between 2.25 and 3.25, and for stone in the region of 5.50 and 7.50. The coarse RCA in the investigation by Alexander & Heiyantuduwa (2002) had a FM value of 7.45 after dry sieving which was attributed to the continuous grading of the material.

Table 3.4 Description of fineness modulus of sand (Alexander & Mindess, 2005)

FM	Sand Fineness
< 1.0	Very Fine
1.0 - 2.0	Fine
2.0 - 2.9	Medium
2.9 - 3.5	Coarse
> 3.5	Very Coarse

3.1.3 Loose bulk, compacted bulk and relative densities

According to Domone & Illston (2008) the aggregate type depends on the aggregate density. The possible densities of aggregate from natural sources or manufactured are normal, lightweight and heavy. Normal density aggregates include igneous rocks such as basalt and granite and stronger sedimentary rocks such as limestone and sandstone. Normal density aggregates have a relative density (RD) range from 2.55 to 2.75 and the actual density of the concrete is 2250 to 2450 kg/m³ depending on mix proportions (Domome & Illston, 2008).

Lightweight aggregate which occurs naturally, such as pumice, a volcanic rock, has a lower density and thus reduces the self-weight of a structure. Artificial lightweight aggregates are also now available for use in construction, as noted by Domone & Illston (2008), and mainly include:

1. Sintered pulverised fuel ash, derived from pulverised coal from power stations;
2. Expanded clay and shale, formed by heating suitable sources of clay and shale;
3. Foamed slag, derived from molten slag from blast furnaces.

Lightweight aggregates are highly porous and weaker than normal density aggregate and the density range is highly varied.

Heavyweight aggregates have a much higher density range compared to that of normal density aggregates, in the region of 3500 to 4500 kg/m³, due to the aggregates containing metallic ores (Domone & Illston, 2008).

The aggregate density influences the hardened concrete by the contribution to the weight and therefore the denser the aggregate particle the heavier the concrete. The particle density is measured in most cases as the relative density. The RD of an aggregate is mass of that material divided by the

mass of an equal volume of water (ACI E1-07, 2007). By definition this means that an aggregate with a RD of 2 is twice as heavy as water. The relative density of aggregates may vary due to composition, but also because of the moisture state. The internal pores of an aggregate particle may be filled with air or water. The moisture conditions may be either one of the following; oven dry (OD), air dry (AD), surface saturated dry (SSD) or damp/wet (Figure 3.3). A particle which is in an AD state will be less dense than particle in an SSD state, because the former has internal pores which are filled with air, which is less dense than water.

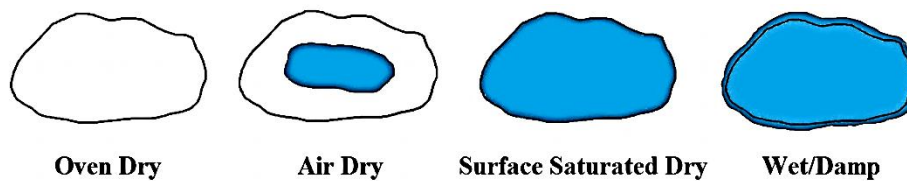


Figure 3.3 Moisture states of an aggregate (OD, AD, SSD and Wet)

The bulk density of an aggregate is the mass of that material occupying a certain volume. The bulk density is influenced by the characteristics of an aggregate, such as, the shape, texture, grading and relative density. For example, an aggregate may have a high RD, however if the aggregate has a single-size grading, the bulk density will be lower compared to an aggregate with a lower RD and a continuous grading. This is largely as a result of the void content, where more voids are filled by combined particle sizes. Two categories of bulk density are measured; loose bulk density (LBD) and compacted bulk density (CBD). The LBD has a lower value to that of the CBD as the particles are loosely packed. The LBD is used in most cases to determine the storage volume of a batch of aggregate, while the CBD is used in concrete mix proportioning. Typical bulk densities range between 1300 to 1750 kg/m³ for aggregates in normal weight concrete (Mehta & Monteiro, 2006).

According to Alexander and Mindess (2005) the strength and stiffness of hardened concrete are indirectly influenced by the density of its aggregate. A lower void content related to a high CBD would mean that less cement paste is required to fill a concrete volume which has an economical benefit. Alexander & Heiyantuduwa (2002) investigated aggregates in the Western Cape including RCA and Table 3.5 gives information on the respective densities. The RCA has a lower RD value and a reasonably similar CBD to that of the natural aggregates, attributable to the continuous grading.

Table 3.5 Comparison of relevant densities for NA and RCA (Alexander & Heiyantuduwa, 2002)

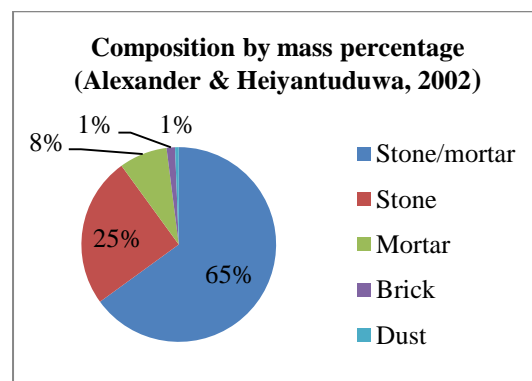
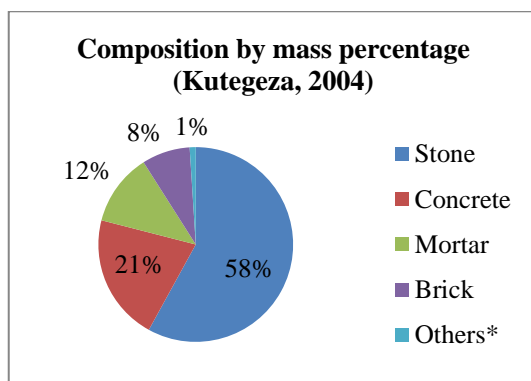
Aggregate Type	RD	LBD (kg/m ³)	CBD (kg/m ³)
Granite	2.63	1280-1365	1460
Greywacke (Malmesbury Shale)	2.65	1400	1525
Quartzite (Ortho-quartzite)	2.65		1480
Recycled aggregate	2.57	1257	1392

The relative density of RCA is typically lower compared to natural aggregates as noted by most researchers. The adhering mortar is the leading cause for the lower relative density, because of the porous nature (CC&A Australia, 2008, Alexander & Heiyantuduwa, 2002 & Sagoe-Crentsil, 2002). The presence of low density materials such as brick, wood and plastics may also lower the respective densities.

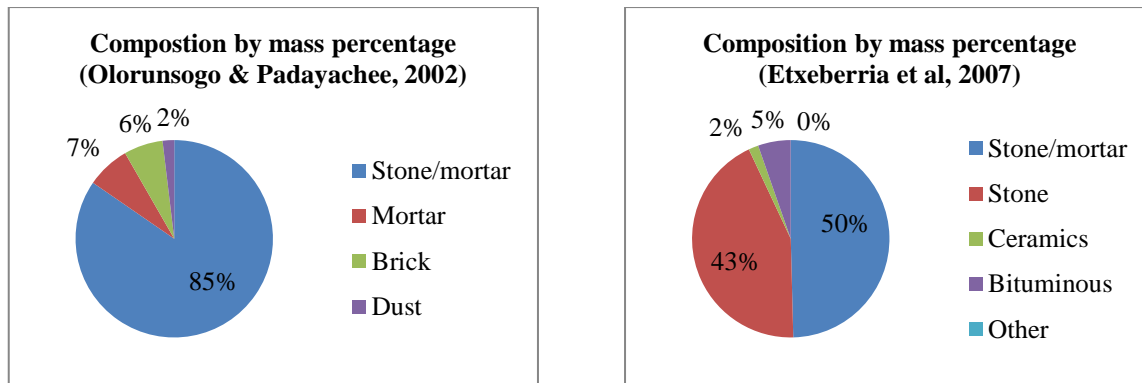
3.1.4 Constituents of recycled aggregates

Concrete properties are negatively affected by the inclusion of foreign materials or substances. Natural aggregates for the most part, do not contain foreign material; however they may contain impurities, such as organics, and other deleterious substances or weak physical characteristics. These impurities may affect the concrete either physically or mechanically. For example, aggregates which are soft or have marked cleavage planes will reduce strength, while organics such as sugars retard the setting of concrete mortar (Grieve, 2009a).

These concerns are heightened in the case of RCA as the material generally has large foreign materials as well as impurities and weak physical characteristics. The foreign materials contained within a sample of RCA will depend on the factors mentioned in Chapter 2. Listed below are some compositions of RCA:



Others* = wood, chipboards, tiles, plastics and bitumen



All of the RCA materials mentioned above were obtained from C&D waste recyclers. The foreign materials including the mortar, brick, dust and others constituted between 10 to 20% of the total mass. Alexander & Mindess (2005) comment that the original concrete strength of RCA has relatively little effect on the strength of the new recycled aggregate concrete (RAC). Standards and specifications from various countries and institutions are described in detail in Section 3.4 and provide limits of the amounts for specific foreign materials. For example, BS 8500-2:2006 specifies the limits for coarse RCA and recycled aggregate (RA) as seen in Table 3.6.

Table 3.6 Limits for the amount of foreign materials that may be derived for RCA adapted from BS 8500-2:2006

Type of aggregate	Requirement (%)				
	Max masonry content	Max fines	Max lightweight material	Max asphalt	Max other foreign material e.g. glass, plastics, metals
RCA	5	5	0.5	5	1
RA	100	3	1	10	1

With the proposal of these specifications, the relevant parties involved will have confidence that the recycled material will not affect the performance of the specified strength class. Classifying the RCA composition is of critical importance. The presence of high percentages of foreign materials may increase the potential for carbonation with metals and lightweight materials such as wood which may swell when in contact with water causing spalling if close to the surface of the concrete. The durability concerns of the concrete containing RCA then becomes apparent.

3.1.5 Water absorption

The water absorption is directly related to the porosity of an aggregate (Alexander & Heiyantuduwa, 2002; Grieve, 2009a; Alexander & Mindess, 2005). The South African National Standard (SANS) for aggregates does not require the water absorption to be specified; however it may have a significant influence on the fresh and hardened states of concrete. The absorption or porosity of an aggregate may

negatively influence the workability, compressive strength and durability as in the case of aggressive environments (Grieve, 2009a). Mehta & Monteiro (2006) define the absorption capacity as the total amount of moisture required to bring an aggregate from an OD to SSD state, while the effective absorption is the moisture amount required, except initially in an AD condition. A water absorption of less than 1% will have negligible effects on concrete shrinkage and creep, however 2 to 3% becomes more critical when used in concrete (Alexander & Mindess, 2005).

RCA aggregates in almost all cases have higher water absorption (Kutegeza, 2004; Chandra Paul, 2011; Sagoe-Crentsil et al, 2001 and Poon et al, 2004). This is directly related to the adhering mortar, which is highly porous as noted by these researchers. Consequently, when using RCA in concrete most researchers prepare the aggregates to an SSD condition. In doing so the effects of the high water absorption are reduced. Domone & Illston (2008) state that when aggregates are in an OD or AD condition, some of the free mixing water will be absorbed, however an SSD condition is desirable, but difficult to achieve outside of laboratory conditions. In a damp or wet state the free surface water will contribute to the mixing water (Domone & Illston, 2008). The amount of binder/cement used in a concrete mix is determined based on the mixing water amount and water:cement (w:c) ratio. The w:c ratio will be altered if the available mixing water is reduced or increased, whereby the strength of the concrete will increase or decrease respectively.

Alexander & Heiyantuduwa (2002) showed that RCA obtained from a recycling quarry had relatively high water absorption values when compared to natural aggregates found in the Western Cape (Table 3.7). Kutegeza (2004) notes the different absorption percentages for varying particle sizes in Table 3.8. The water absorption increased with decreasing particle size, indicating the influence that fine recycled aggregate may have on concrete.

Table 3.7 Water absorption percentages for Western Cape aggregates and RCA (Alexander & Heiyantuduwa, 2002)

Rock Type	Typical Water Absorption
Granite	0.85%
Greywacke (Malmesbury shale)	0.41%
Quartzite (Ortho-quartzite)	0.52%
Recycled concrete aggregate	4.16%

Table 3.8 Water absorption percentages for various stone sizes (Kutegeza, 2004)

Sieve Size	26.5	19	13.2	9.5	6.7	4.75	2.36	<2.36
Sample 1	1.87%	2.46%	3.09%	3.31%	3.72%	4.38%	7.48%	10.10%
Sample 2	1.38%	2.37%	3.42%	3.42%	3.52%	4.41%	8.42%	10.40%
Sample 3	1.60%	2.63%	3.12%	3.27%	4.00%	4.56%	8.77%	9.85%

Kearsley & Mostert (2010) obtained recycled aggregates from four different streams of construction waste, which were subsequently crushed with a laboratory jaw crusher. Three of the waste streams came from strong, medium and weak 28 day concrete, with strength classes in the regions of 100 MPa, 50 MPa and 20 MPa respectively. The final waste utilized was building rubble and consisted of clay brick masonry. The natural aggregate used in this research was crushed dolomite and the relevant water absorption percentages are shown in Table 3.9. The presence of clay brick will significantly increase the water absorption in RCA and therefore should be limited.

Table 3.9 Comparison between the relative density and water absorption for sample of RCA adapted from Kearsley & Mostert (2010)

Sieve Size	Dolomite	Strong RCA	Medium RCA	Weak RCA	Rubble RCA
Water Absorption	0.30%	0.80%	1.10%	1.50%	11.20%
Relative Density	2.86	2.70	2.60	2.54	2.29

3.1.6 Aggregate strength

The aggregate strength has little effect on the strength of conventional concrete within the range of 20 to 40 MPa (Addis, 2008) provided the aggregate specifications are met. The unconfined compressive strength of natural aggregates in South Africa ranges between 70 to 540 MPa (Grieve, 2009a). Mehta & Monteiro (2006) reported that the typical crushing strength and dynamic elastic modulus for most basalt, granite, flint, quartzitic sandstone and dense limestone are in the region of 210 to 310 MPa and 70 to 90GPa, respectively. Consequently the aggregate strength is several times greater than that of the concrete.

The weakest link in concrete is the interfacial transition zone (Domone & Illston, 2008, Mehta & Monteiro, 2006), while the aggregate is the strongest (Perrie, 2009). The failure mechanisms of concrete are discussed in conjunction with the mechanical properties of hardened concrete in Section 3.3.1. Two tests exist for determining the crushing strength of an aggregate, mainly coarse aggregate, the 10% fines aggregate crushing test (10% FACT value) and the aggregate crushing value test (ACV). The ACV and 10% FACT values are a measure of the granular strength according to Alexander & Mindess (2005), compared to Unconfined Compressive Strength (UCS) measuring the strength in rock form.

The ACV test is generally not used, owing to the test limits for weak aggregates. The 10% FACT test is more commonly used as the scope of the test is not limited by the aggregate in question. The ACV test measures the percentage fine material lost under a compressive load, while the 10% FACT test measures the force required to produce 10% fine material loss from the original sample. Both tests are conducted on the same sample and the ACV values range is between 14 to 30% and the 10% FACT values in the range of 100 to 300 kN (Grieve, 2009a).

The authors in some publications (Alexander & Mindess, 2005 and Grieve, 2009a) make note of the correlation between the two different tests. If the aggregate falls within the ranges as stated above the correlation is given by Equation 3.1.

$$ACV = 38 - 0.08 \times (10\% \text{ FACT}) \quad [\text{Eq. 3.1}]$$

where the ACV is measured as percentage and 10% FACT is measured in kN. These tests are not an indication of abrasion or hardness of an aggregate, as these properties are done according to other tests.

RCA has been reported as having a lower strength when compared to natural aggregate. Sagoe-Crenstil et al, 2001 reported a 7.4% difference in the ACV test between RCA and natural basalt. An investigation by Teranishi et al (2007) into the comparison between laboratory production and crushed RCA and RCA retrieved from a building of a turbine in a power plant showed that various properties of aggregates did not meet country specific specifications. The ACV and 10% FACT values from the building and laboratory crushed specimens are provided in Table 3.10. The E series block are laboratory cast specimens with strength and specimen size indicated by the 20 – 200, respectively. The D series block represents RCA removed from different parts of the structure. There is relatively no difference between the various samples, which is interesting as the building was 37 years old at demolition.

Table 3.10 Data for various combinations of RCA from laboratory and external sources adapted from Teranishi et al (2007)

Test	E series blocks					D series block		
	20-200	30-100	30-200	30-400	40-200	US	T/G	BS
Maximum size (mm)	20	20	20	20	20	20	20	20
Fineness modulus	6.49	6.46	6.57	6.70	6.82	6.18	6.42	6.60
Density (SSD) g/cm ³	2.42	2.40	2.37	2.38	2.41	2.40	2.38	2.46
Water Absorption %	6.42	5.69	7.92	6.99	6.34	7.30	7.66	6.22
Aggregate strength								
ACV % (400 kN)	25.10	23.90	25.30	24.10	23.00	25.70	28.40	22.20
10% FACT kN	13.70	14.00	13.40	14.20	16.60	11.80	9.30	15.20

Alexander & Heiyantuduwa (2002) compared the 10% FACT values for various aggregates found in the Western Cape, which indicated that RCA had acceptable values exceeding the minimum value of 110 kN, however were relatively lower than the natural aggregates (Table 3.11).

Table 3.11 Comparison in Western Cape aggregates and RCA for 10% FACT value adapted from Alexander & Heiyantuduwa (2002)

Rock Type	10% FACT (kN)
Granite	280
Greywacke (Malmesbury shale)	299
Quartzite (Ortho-quartzite)	244
Recycled aggregate	190

Kutegeza (2004) shows how the 10% FACT value is determined by interpolation or visual interpretation from Figure 3.4. The results for three RCA samples ranged between 175 kN and 188 kN which was greater than the specified 110 kN according to SABS 1083:2006.

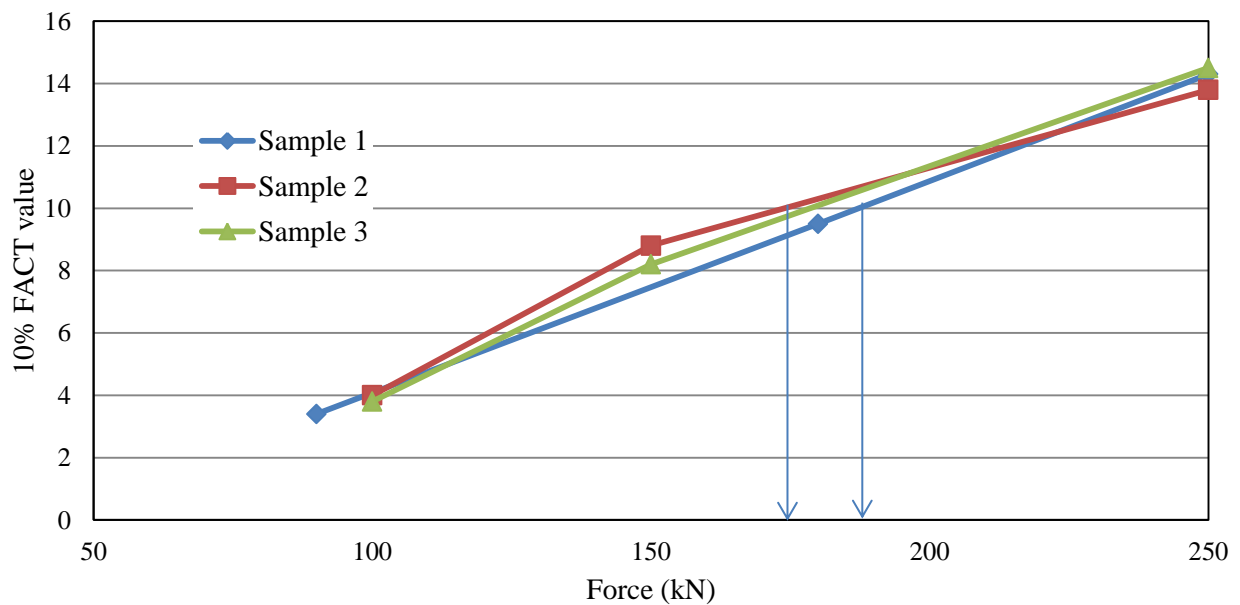


Figure 3.4 Visual interpretation of the 10% FACT value adapted from Kutegeza (2004)

3.1.7 Chemical and mineralogical characteristics of aggregates

The chemical and mineralogical properties of aggregates are important to assess, as the durability of concrete is generally compromised by chemical reactions that take place due to the presence of detrimental substances. Chemical reactions within concrete due to higher than normal concentrations of chemical constituents or impurities may lead to weakened concrete. The durability of concrete is one of the key reasons for its use as a construction material. If the durability of concrete is compromised, the structural integrity of a project can be questioned.

Aggregates are for the most part chemically inert, but may contain substances or minerals that negatively impact the concrete. Grieve (2009a) describes five broadly defined chemically deleterious groups:

1. Substances which are water-soluble, which are leached from the aggregates;
2. Soluble substances or substances which become soluble in the cement matrix and affect the hydration process;
3. Substances that react with the binder and destroy its properties, as is the case with sodium sulphate;
4. Substances which may react with the alkali constituents of cements;
5. Substances that cause corrosive and/or carbonation effects, for example chlorides.

The four main compounds of cement clinker consist of the principal oxides CaO, SiO₂, Al₂O₃ and Fe₂O₃ with shorthand notation, C, S, A and F, respectively. Ordinary Portland cement (OPC) consists of clinker mixed with a small percentage of gypsum and the presence of small amounts of sodium, magnesium and potassium oxides from the cement clinker (Table 3.12). The four main compounds (C₃S, C₂S, C₃A and C₄AF) react with water to form cementitious compounds discussed in Section 3.3.1.

Table 3.12 Compound composition of South African CEM I (OPC) cements adapted from (Grieve, 2009b)

Compound	Formula	Abbreviation	% by mass in cement
Tricalcium silicate	3CaO.SiO ₂	C ₃ S	60 – 73
Dicalcium silicate	2CaO.SiO ₂	C ₂ S	8 – 30
Tricalcium aluminate	3CaO.Al ₂ O ₃	C ₃ A	5 – 12
Tetracalcium aluminoferrite	3CaO.Al ₂ O ₃ .Fe ₂ O ₃	C ₄ AF	8 – 16
Magnesia	MgO	M	1.9 – 3.2
Gypsum	Raw material	-	4.4 – 6.7
Free lime	CaO	-	0.2 – 2.5

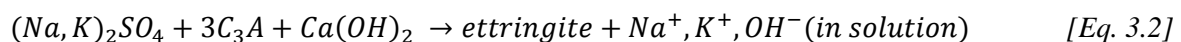
These compounds and hydration products of the cement paste undergo chemical reactions with certain substances present in concrete constituents such as aggregates causing deleterious effects. Some of these reactions are discussed below and in Section 3.3.2 the reactions relating to the corrosion of steel in the presence of chlorides are discussed.

Alkali – aggregate reaction

The alkali-aggregate (AAR) reactions take place between the alkalis cement matrix and reactive components of aggregates (Alexander & Mindess, 2005). The reaction usually produces a gel which, in the presence of enough moisture, swells and causes internal expansion forces which results in cracking (Alexander & Mindess, 2005). There are three types of alkali-aggregate reactions which may occur depending on the composition of the aggregates: alkali-silica reaction (ASR), alkali-silicate reaction and alkali-carbonate reaction (Alexander & Mindess, 2005).

The alkali-silicate reaction term was introduced to separate the ASR from the reaction involving the alkaline pore solution with aggregates such as greywacke (Oberholster, 2009). The aggregates contained strained quartz, microcrystalline quartz or cryptocrystalline quartz in rocks such as quartzite, greywacke, granite and grandiorite (Oberholster, 2009). There was no reason not to use a general term such as ASR for both reactions as the reactions were similar (Oberholster, 2009). The ASR reaction is of particular interest due to the aggregates from the Malmesbury Group used in the Cape Peninsula (Oberholster, 2009).

The alkalis are initially present in the unhydrated cement as sodium and potassium oxides (Na_2O and K_2O) in the form of soluble sulphates (Na_2SO_4 and K_2SO_4) or a salt $(\text{Na,K})_2\text{SO}_4$ (Domone & Illston, 2008). During the hydration of the cement, these sulphates react with compounds of the cement to produce strength forming ettringite and Na^+, K^+ and OH^- ions with low concentrations of Ca^{2+} , SO_4^- and Cl^- which raise the pH of the pore solution (Equation 3.2) (Domone & Illston, 2008 and Oberholster, 2009). Alkalis may also be derived from outside sources such as mixing water, sea water and aggregates containing salts (Oberholster, 2009).

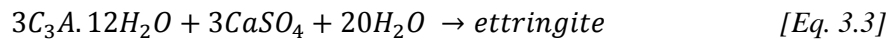


To minimize the ASR risk a combination of measures can be employed to control the possibility of the reaction taking place. The amounts of alkalis can be reduced by using low alkali (less than 0.6% equivalent Na_2O) cement and/or a cement content below 350 kg/m^3 (Oberholster, 2009). The use of cement extenders such as fly ash (FA) and GGCS lower the pore water alkalinity and mobility of ions

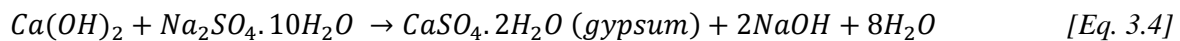
(Oberholster, 2009 and Alexander et al, 2003). Alexander et al (2003) notes that 50% GGCS is recommended to effectively reduce the ASR risk when using reactive greywacke aggregate (Malmesbury shale). Concrete with an ASR risk should not be exposed to environments with high humidity and temperature which promote the rate of expansion (Oberholster, 2009).

Sulphates

Sulphates in solution (water-soluble) react with the calcium hydroxide ($\text{Ca}(\text{OH})_2$) and aluminate compounds in the hardened cement paste (Addis, 2008). The sulphates can be present in concrete from contaminated aggregates and/or from sulphates from clay soils, fertilisers or industrial waste penetrating the concrete through ground-water in the form of sodium, potassium, magnesium and calcium sulphates (Domone & Illston, 2008). When the sulphates react with the hydrated aluminate compounds, ettringite is formed causing an expansive reaction where the solid phases more than triple in volume (Equation 3.3) (Domone & Illston, 2008).



Other sulphates react with the $\text{Ca}_2(\text{OH})_2$ forming gypsum which retards the setting of cementitious compounds also causing expansion of cement paste. The reaction between sodium sulphates (Na_2SO_4) is given as an example in Equation 3.4 (Domone & Illston, 2008).



The effect of this reaction is only significant if the sulphate concentration relatively high (3000 ppm) (Oberholster, 2009). The reaction between magnesium sulphate (MgSO_4) and $\text{Ca}_2(\text{OH})_2$ is similar to the above reaction but is particularly aggressive (Oberholster, 2009). The MgSO_4 is rather aggressive because of the reaction with alumina-bearing hydrates (Mehta & Monteiro, 2006).

The sulphate reactions discussed may occur simultaneously depending on the concentrations of specific sulphates (Mehta & Monteiro, 2006). The overall effect of the reactions between sulphates results in expansion due to the formation of products from hydration processes and loss of strength due to the destruction of binding agents (Oberholster, 2009 and Mehta & Monteiro, 2006). Sulphate concentration can be controlled by classifying the exposure conditions applying the necessary measures to restrict exceeded concentrations. Table 3.13 is an example of exposure conditions depending on sulphate content provided by the ACI Building Code 318 (Mehta & Monteiro, 2006).

Table 3.13 Exposure conditions depending on sulphate content provided by the ACI Building Code 318 (adapted from Mehta & Monteiro, 2006)

Exposure Class	Sulphate conc. (%) in soil	Sulphate conc. (mg/l) in water
Negligible exposure	< 0.1	< 150
Moderate exposure	0.1 - 0.2	150 - 1500
Severe exposure	0.2 - 2.0	1500 - 10000
Very severe exposure	> 2.0	> 10000

Exposure Class	Restriction
Negligible exposure	None
Moderate exposure	ASTM Type II OPC or slag cement used with < 0.5 W/C ratio
Severe exposure	ASTM Type IV OPC with < 0.45 W/C ratio
Very severe exposure	ASTM Type V OPC plus pozzolanic admixture with < 0.45 W/C ratio

Other chemical reactions which may occur, but are not discussed in detail are attacks by acids and other aggressive salts. Soluble salts affect cement hydration by accelerating the reactions, which may be undesirable (Alexander & Mindess, 2005). Sodium chloride (NaCl) in concrete increases the reactive alkali content which may escalate the potential alkali-aggregate reactions (Alexander & Mindess, 2005). The high calcium content of the cement paste increases the potential for acid attack (Addis, 2008). The acid attack converts the compounds of the cement paste into soluble salts and acid-proof concrete is not possible when using Portland-type cements (Addis, 2008).

Aggregates/rocks used in concrete are usually comprised of several minerals. The minerals are solid, inorganic elements or elemental compounds which have a definite atomic structure and chemical composition that may vary within defined limits (Pellant, 2000). As stated the aggregates are formed into three main groups: igneous, metamorphic and sedimentary. The mineral grains are fused, cemented or bound together during the formation of different rocks (Pellant, 2000). Minerals which are found in concrete aggregates are listed in Table 3.14. The commonly found aggregate in the Western Cape, greywacke, contains abundant quartz-feldspar and rock fragments (Pellant, 2000). The rock matrix which cannot be seen with the naked eye consists of clay, chlorite, quartz and pyrite (Pellant, 2000).

Table 3.14 Minerals found in concrete aggregates (adapted from Alexander & Mindess, 2005)

Mineral	Examples
Silica	Quartz: A common hard mineral composed of silica (SiO ₂) highly resistant to weathering and some strained quartz may be alkali reactive
	Opal: A hydrous form of silica, generally without crystal structure and are usually highly alkali reactive
Feldspars	These Alumino-silicate minerals are most abundant rock forming minerals
	Potassium Feldspar: occurs typically in igneous rocks such as granite
Ferromagnesium minerals	Amphiboles: e.g. hornblendes
	Olivines: e.g. forsterite, found in dark igneous rocks without quartz
Micaceous minerals	Micas are common in all rock types
	Biotites: Dark coloured to black
	Chlorites: Dark green coloured
Clay minerals	These are layered silicate minerals such as hydrous aluminium and iron silicates with variable cations such calcium and sodium
	Rocks containing large amounts of clay minerals are unsuitable as concrete aggregate
Zeolites	A large group of hydrated alkali-aluminium silicates, soft and light coloured
Carbonate minerals	Calcite: Calcium carbonate CaCO ₃
	Dolomite: Calcium and magnesium carbonate MgCO ₃ , soluble in acid
Sulphate minerals	Gypsum: Hydrous calcium sulphate CaSO ₄ .2H ₂ O, attack concrete mortar
	Other sulphates: sodium and magnesium sulphate
Iron sulphide minerals	Pyrite, marcasite: Frequently found in natural aggregates
Iron oxides	Magnetite: Black coloured common mineral Fe ₃ O ₄
	Haematite: Red-coloured common mineral Fe ₂ O ₃
	Frequently found as accessory minerals igneous rocks and sediments.

Chemical – Mineralogical Composition

Petrology is the science of rocks, while petrography refers to the examination and analysis of rock and rock forming minerals. Alexander & Mindess (2005) note that petrography can be used to:

- Determine and describe the aggregate constituents (minerals) in their relative amounts for classification;
- Determine the performance of concrete aggregate due to inherent physical and chemical characteristics;
- Determine the possible classification and performance of materials from new or untried sources, by comparing their characteristics to those of known aggregates;
- Provide guidance for possible further testing where characteristics may be questionable.

Limbachiya et al. (2007) investigated the chemical-mineralogical characterisation of coarse RCA. C&D waste was collected from three different construction sites in the Greater London area and was processed at a commercial recycling facility. The RCA was described as coarse, porous and rough but equidimensional when compared to natural gravel (Limbachiya et al, 2007). The RCA constituent composition was determined according to BS 8500: Part 2 and the results are given in Table 3.15 (Limbachiya et al, 2007). The chemical and mineralogical composition of the RCA was compared to both fine and coarse natural gravels (Thames Valley gravel) and Portland cement (PC) of Grade 42.5N (Limbachiya et al, 2007).

Table 3.15 RCA constituent composition compared to the BS 8500-2 limits (adapted from Limbachiya et al, 2007)

Constituents	Proportions % (m/m) 16-4mm particle size			
	RCA 1	RCA 2	RCA 3	BS 8500 limits
Concrete	92.4	92.1	85.5	-
Masonry	1.9	1.6	5.3	5.0
Asphalt	4.9	1.4	3.3	5.0
Lightweight material ($\rho < 1000\text{kg/m}^3$)	0.0	0.6	0.5	0.5
Fines	0.2	3.4	4.4	-
Foreign materials	0.5	0.9	1.0	1.0

Samples for the analyses were prepared by quartering and coning large amounts (80kg RCA & 10kg PC) to smaller amounts (5kg RCA and 2kg PC) (Limbachiya et al, 2007). The samples were then milled to a fine powder to produce 10g test samples. The mineralogical composition was determined through X-ray fluorescence (XRF) spectrometry using an ARL Advant-XP spectrometer with volatiles determined as loss on ignition (LOI) at 1000°C (Limbachiya et al, 2007). To examine the possible ions leaching from cement-based products, an ICP-AES analysis was conducted. 2g of powder was added to 100ml of distilled water. The dilution was sealed in a beaker and agitated for 1 hour, after which the solution was left to rest for 24 hours (Limbachiya et al, 2007). The solution was then filtered through a medium grade paper before conducting the ICP-AES analysis (Limbachiya et al, 2007).

The results from the XRF analysis are presented in Table 3.16 as the major elements in mass percentage in each constituent. The NA is almost pure SiO_2 , while the natural sand had a richer composition in CaO (Limbachiya et al, 2007). The RCA samples displayed comparable compositions, even though each was obtained from a different source and were richer in Ca oxides (Limbachiya et al, 2007). LOI includes the total of volatiles content of the rock (including the water combined to the lattice of silicate minerals) and the gain on ignition related to the oxidation of the rock (mostly due to Fe) (Sanchez-Garrido, 2012). The LOI amounts in all the RCA samples are higher than the NA.

Table 3.16 XRF analysis results for the concrete constituents used by Limbachiya et al. (2007)

Mineral oxide	PC	NCA	RCA 1	RCA 2	RCA 3	NFA
SiO ₂ (%)	20.60	97.03	65.37	68.43	63.61	88.54
TiO ₂ (%)	0.22	0.01	0.22	0.39	0.17	0.05
Al ₂ O ₃ (%)	5.47	0.34	5.33	5.49	3.57	1.21
Fe ₂ O ₃ (%)	3.31	0.10	2.16	2.40	2.03	0.76
MnO (%)	0.06	0.00	0.05	0.05	0.06	0.02
MgO (%)	2.26	0.65	1.91	2.84	2.62	0.42
CaO (%)	62.50	0.26	13.93	11.19	16.86	5.33
Na ₂ O (%)	0.65	0.16	1.19	0.94	0.87	0.33
K ₂ O (%)	1.71	0.01	0.61	0.62	0.51	0.31
P ₂ O ₅ (%)	0.21	0.02	0.11	0.10	0.49	0.08
LOI (%)	1.64	1.41	9.12	7.56	9.19	2.95
Total	98.63	99.99	100.00	100.01	99.98	100.00

Typical limits for RCA used as aggregate in concrete production according to Australian standards are given in Table 3.17. From the table the maximum LOI percentage is the same for material with higher proportions of brick and stony material. It is also specified that RCA must neither contain reactive contaminants and/or must not react with cement or reinforcing steel (Sagoe-Crentsil, 2002).

Table 3.17 Limits applied to RCA contaminants in Australian standards (adapted from Sagoe-Crentsil, 2002)

RCA Property	Class 1A RCA limit	Class 1B RCA limit
Brick content (max)	0.50%	30%
Stony material (<1950kg/m ³)	1%	5%
Total impurity level (max)	1%	1%
LOI (max)	5%	5%
Lost substances in washing (max)	1%	1%

The results from the water soluble contents are given in Table 3.18. The pH of leachates from the ICP-AES analysis ranged between 10.4 to 11.2, indicating alkaline solutions (Limbachiya et al, 2007). The higher Ca ions in the RCA sample was accredited to the portlandite content which is associated to the attached cement paste (Limbachiya et al, 2007). The leachable solids were compared to the solids from XRF composition and showed positive correlations (Limbachiya et al, 2007). Limbachiya et al (2007) noted that the XRF and ICP-AES methods of analysis are well established to study earth materials, but have not yet been fully utilised in the characterisation of concrete constituents.

Table 3.18 Water soluble ions content (mg/l) for the concrete constituents adapted from Limbachiya et al. (2007)

Water soluble contents	PC	NCA	RCA 1	RCA 2	RCA 3	NFA
Si	1.01	44.50	16.70	16.60	9.95	9.15
Ti	0.01	0.03	0.02	0.02	0.02	0.03
Al	0.34	0.39	0.33	0.36	0.30	0.63
Fe	0.01	0.45	0.04	0.04	0.04	0.75
Mn	-	0.02	0.01	0.01	0.01	0.02
Mg	0.08	4.38	0.95	0.75	0.81	1.36
Ca	542.00	7.64	22.60	14.30	25.70	23.20
Na	15.70	0.74	2.54	1.56	2.56	2.10
S	56.80	0.45	7.08	4.81	8.90	1.24

Concrete mixtures containing 0, 30, 50 and 100% RCA were produced to examine the mineralogical and chemical compositions at different depths (0-5, 5-10, 10-15 and 15-20mm). The samples were collected from three different locations by taking dust samples using a drill (Limbachiya et al, 2007). The three main oxides percentages in the different mixtures at the defined depths are given in Figure 3.5. Limbachiya et al (2007) stated that RCA used at 30% replacement had negligible effects of the three main oxides amounts regardless of depth. The increase in RCA percentage resulted in a marginal decrease in SiO_2 together with a small increase in Al_2O_3 and CaO , which was attributed to the proportions of cement constituent in the concrete (Limbachiya et al, 2007).

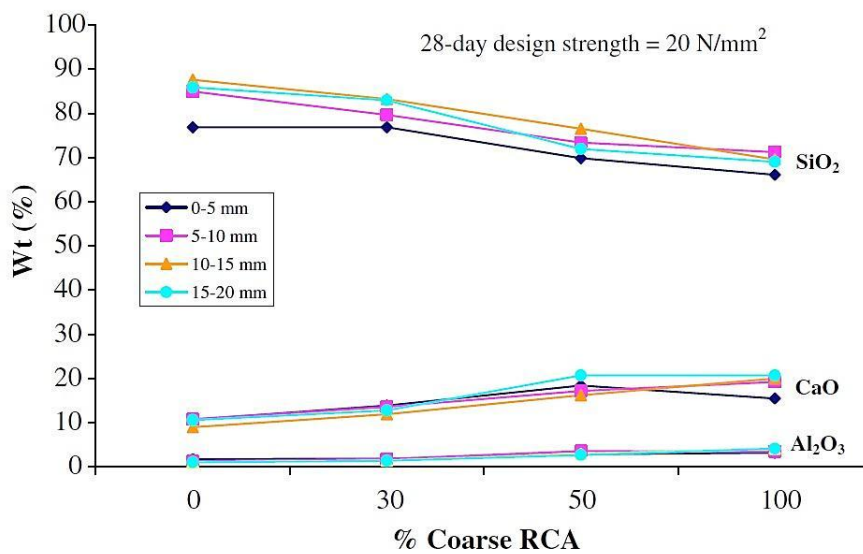


Figure 3.5 Major oxides within concrete at different depths for percentages of RCA (Limbachiya et al, 2007)

3.2 Fresh Concrete Properties

Fresh concrete properties may play the most important role in the concrete production cycle. Once the aggregates and relevant concrete constituents have been approved for inclusion in the final concrete mixture, the fresh concrete properties are examined. Examining the basic fresh concrete properties such as slump, air content and cohesiveness, in the correct manner will lead to concrete in a hardened state that is strong, durable and dimensionally stable. It is important that concrete in a fresh state has constituents that are uniformly distributed once compacted, without the loss of water through bleeding so that the constituents bind together without segregation.

3.2.1 Workability (consistency & cohesiveness)

The workability of fresh concrete is difficult to define. Researchers and industry practitioner's terminology for acceptable workability differ, for example: lean, stiff, harsh and cohesive (Domone & Illston, 2008) may be interpreted incorrectly. Two typical qualitative terms used to describe fresh concrete are; consistency and cohesiveness. The latter describes the inclination to resist segregation and bleeding, whilst the former describes the ease of flow or mobility relating to moisture condition of the fresh concrete (Crosswell & Kellerman, 2009). Workability is therefore a composite property, as defined above, and concrete with the same cohesiveness may vary in consistency. Workability is important in industry as concrete in a fresh state is transported, handled, placed, compacted and finished for a short period of time (hours) before hardening and retaining its volume for longer periods (years).

To measure the consistency of concrete, a slump/cone test is generally employed for normal concrete mixtures and is an internationally recognised method. A slump test will give an indication on whether or not a concrete mixture is consistent and/or cohesive. Figure 3.6 shows three possible outcomes for a slump test. The true slump indicates that the concrete mixture is cohesive and consistent, the shear slump shows a lack of cohesiveness and is prone to segregation or the rodding of the slump test was not done evenly. A collapsed slump is not ideal, but may still be acceptable where highly workable mixtures are required. With all the slump outcomes, segregation or cohesiveness can be checked by tapping the base plate and observing whether or not the constituents of the mixtures separate from one another.

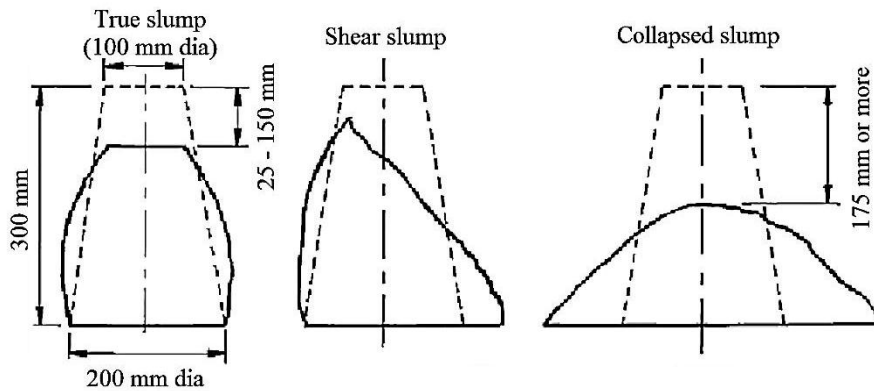


Figure 3.6 Possible outcomes from a slump test (true, shear and collapsed slump)

(adapted from Crosswell & Kellerman, 2009)

The height of the concrete slump is usually specified in order to control the degree of workability and to insure that the final concrete structure is correctly finished. SANS 5862-1:2006 *Consistence of freshly mixed concrete — Slump test* allows for a slump measurement between 5 and 175mm, containing stone no larger than 40mm and aggregate with low, normal and high density. The degree of control for the required slump limits mostly the water content and thereafter the remaining constituents. A slump is generally measured to an accuracy of 5mm with limits depending on specified slump. SANS 878:2004 *Ready-mixed concrete* defines these limits as seen in Table 3.19 for a period of 30 minutes upon arrival on site. The values defined in Table 3.19 are similar to those defined in the British/European standard BS EN 206-1:2000 where the slump and range is classified by class as shown in Table 3.20, while specific target slump tolerances are detailed in Table 3.21. For more specific structural concrete components SABS 1200 G *Concrete (Structural)* stipulates specific slump limits as defined in Table 3.22.

Table 3.19 SANS 878:2004 slump tolerances

Specified Slump (mm)	Tolerance (mm)
$0 < x \leq 50$	-15 to +25
$50 < x \leq 100$	± 25
> 100	± 40

Table 3.20 BS EN 206-1 slump values according to class

Class	Slump (mm)
S1	10 - 40
S2	50 - 90
S3	100 - 150
S4	160 - 210
S5	≥ 220

Table 3.21 BS EN 206-1 specific slump targets and tolerances

Target Value (mm)	Tolerance (mm)
≤ 40	± 10
50 - 90	± 20
≥ 100	± 30

Table 3.22 SABS 1200 G slump tolerances depending on structural component

Type of construction	Hand-placed		Vibrated	
	Max.	Min.	Max.	Min.
Paving & precast units	70	50	50	30
Heavy mass construction	70	30	50	20
Reinforcing foundation wall & footings	120	50	80	30
Slabs, beams, columns and reinforced walls	120	50	80	30
Slabs & industrial floors on ground	120	70	80	50
Plain footings, caissons & substructure walls	100	30	60	20
Heavy duty industrial floors	-	-	80	50

The workability of concrete is influenced by: mix proportions, water content, w:c ratio, binder type, fine:coarse aggregate ratio and aggregate characteristics. Alexander & Mindess (2005) emphasise the influence that aggregates have on the properties of fresh concrete. Particle shape, texture, grading and maximum aggregate size for coarse aggregates play important roles as previously mentioned in fresh concrete. The water content of a concrete mixture controls the slump and material factors control the water requirement. Addis (2008) summarises the influence that concrete constituents will have on the water requirement in Table 3.23.

Table 3.23 Factors influencing the water requirement of fresh concrete (adapted from Addis, 2008)

Material	Factors which influence water requirement	Water requirement decreases with:
Stone	Nominal particle size	Increasing size
	Packing capacity (shape & grading)	Improved packing
	Surface texture	Increasing smoothness
Sand	Particle shape	Increasing roundness
	Grading	Continuous grading
	Surface texture	Increasing smoothness
	Ultra fines (clay)	Decreasing content
Cement	Extender type	Use of extender (fly ash)
Admixture	Type	Use of plasticiser
	Dosage	Increasing dosage

A concrete mixture may initially meet the requirements of a slump test; however loss of workability can become critical with larger concrete projects, especially when utilising RCA. Loss of workability is usually attributed to mix water being absorbed by the aggregates, in the case where aggregates have not been prepared to an SSD condition, earlier hydration of binders and evaporation (Domone & Illston, 2008 and Mehta & Monteiro, 2006). Loss of workability is measured by completing a slump test over a defined period of time and noting the slump loss for that interval. Slump loss is aggravated by high ambient and concrete temperatures and is proportional to the initial slump, where the higher the original slump the greater the slump loss (Crosswell & Kellerman, 2009). Workability can be maintained if the concrete remains agitated, i.e. moving, adding additional water (retempering) and reducing the effects of the external environment.

The slump loss when using RCA has been notable in most concrete research. Most researchers reduce the loss of workability by saturating the aggregate to an SSD condition before mixing. This reduces the high water absorption associated with RCA and other factors. The inclusion of fine RCA in concrete has the greatest influence on slump loss. Kutegeza (2004) produced six concrete mixtures; XNA, XRF, XRC, XRA, CNA and CRA. The X represents a binder combination 50/50 of OPC/Corex slag. R represents recycled aggregate further defined by either F for fine recycled aggregate, C for coarse recycled aggregate or A for both recycled aggregates. The N represents the control mixture with both fine and coarse NA. The C represents a mixture with 100% OPC cement.

Figure 3.7 shows the reduced workability over time at a water:binder (w:b) ratio of 0.6 and a free water content of 180 l/m³. The aggregate in this experimental programme is in an SSD condition prior to mixing. The researcher noted that even by pre-saturating the aggregates, the workability declined faster with mixtures containing RCA. The RCA mixtures lost 50 to 65% of the initial slump (Table 3.24), while the natural aggregate mixtures lost about 25%. The mixtures XNA, XRF, XRC and XRA, which contained GGCS at 50% replacement, experienced a slower loss of slump.

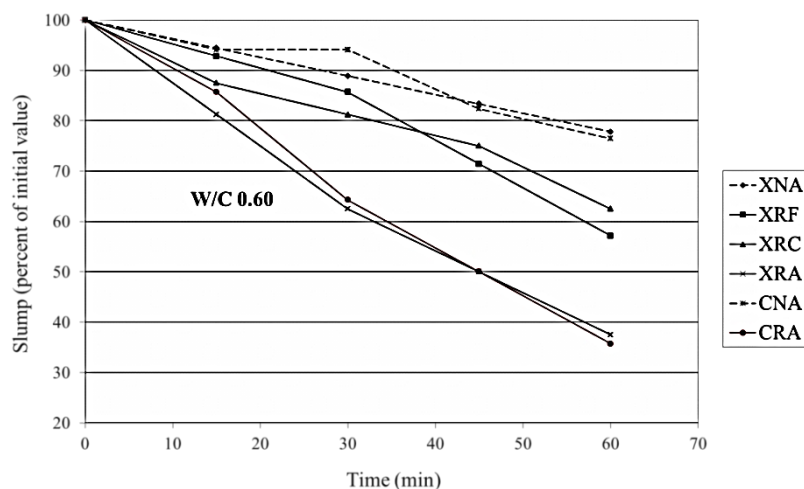


Figure 3.7 Slump loss as a percentage of initial slump value for w:b = 0.6 mixture (Kutegeza, 2004)

Table 3.24 Initial slump values for $w:b = 0.6$ mixture (Kutegeza, 2004)

Mixture	XNA	XRF	XRC	XRA	CNA	CRA
Initial slump	90	70	80	80	85	70

Poon et al. (2004) investigated the influence that the initial moisture state would have on concrete slump containing coarse RCA and NA. Four combinations of concrete mixtures were prepared: 100% natural, 80% natural & 20% recycled, 50% natural & 50% recycled and 100% recycled. Mixture proportions were based on the absolute volume method by assuming the aggregates were in an SSD condition and adjusting water content according to moisture state. Three moisture states were investigated namely oven-dry (OD), air-dry (AD) and surface-saturated dry (SSD). The initial slump and slump loss with time for the respective mixtures is illustrated in Figure 3.8.

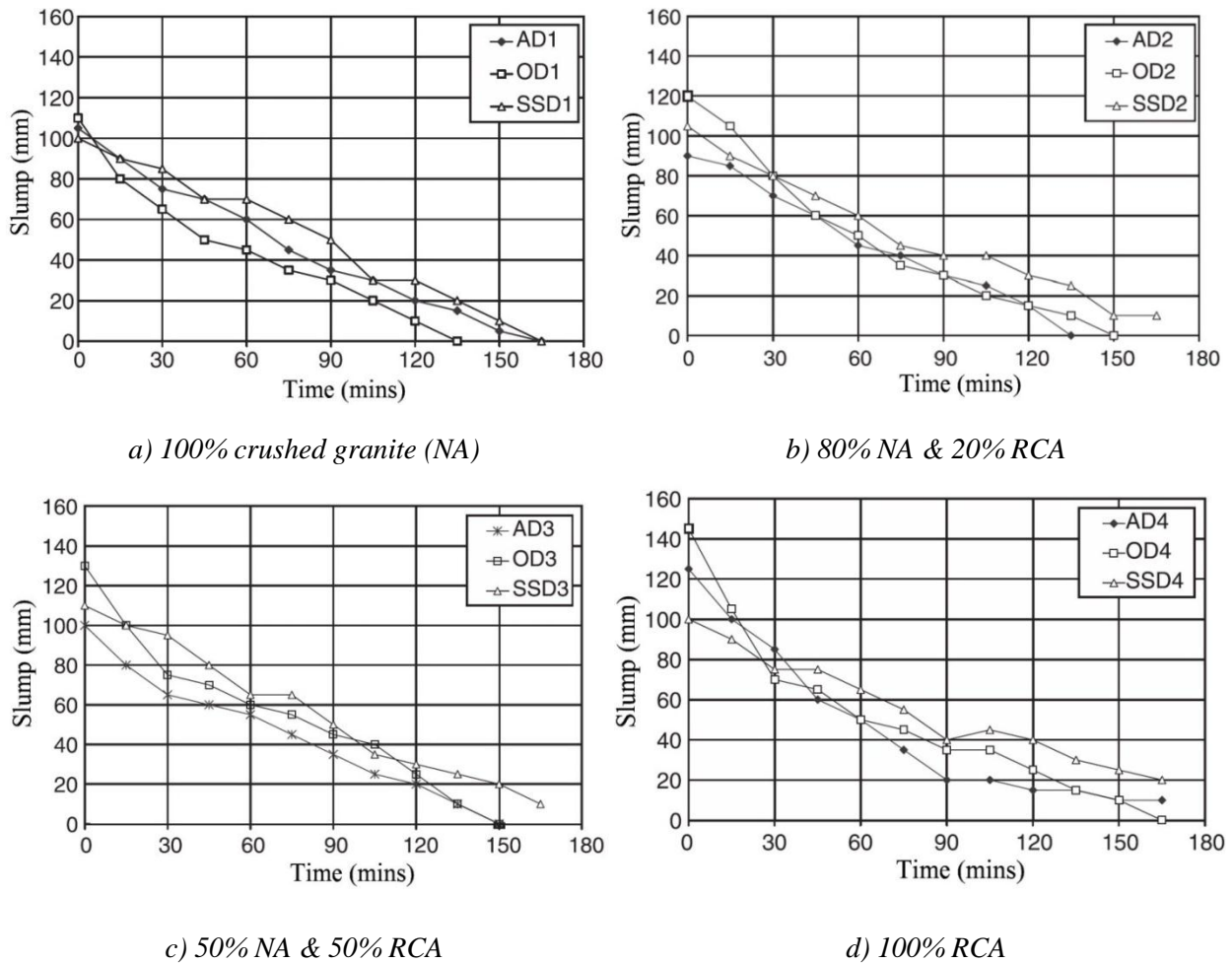


Figure 3.8 Slump loss for the four different percentage replacements (Poon et al, 2004)

Poon et al. (2004) noted that overall if recycled aggregates are used in an SSD condition, the replacement of natural aggregate by RCA at any percentage will change the initial slump only slightly. If aggregates are used in an OD or AD condition with a higher percentage replacement of RCA, the initial slump will increase due to higher amounts of free water added to assume SSD condition. The slump loss showed an increase when using natural aggregate in an OD condition, particularly within the first hour. Increasing the percentage replacement, prolonged slump loss process, where mixes in an SSD state illustrated a slower slump loss. However, using RCA between 20 to 100% replacement in an OD state demonstrated a faster slump loss than that in an SSD state.

Kearsley & Mostert (2010) prepared the coarse RCA used in the experimental programme to an SSD condition and kept the mix composition identical to that containing only natural aggregate. The initial slump was 80% lower when using 100% RCA, with the values of 50mm and 10mm for NAC and RAC, respectively. Pani et al. (2011) considered replacing natural aggregate at: 20, 50, 80 and 100% and the aggregate were mixed in an SSD condition. Figure 3.9 illustrates that with an increasing RCA percentage a greater slump loss occurs, although not significant, with the exception of 100% replacement with the least slump loss.

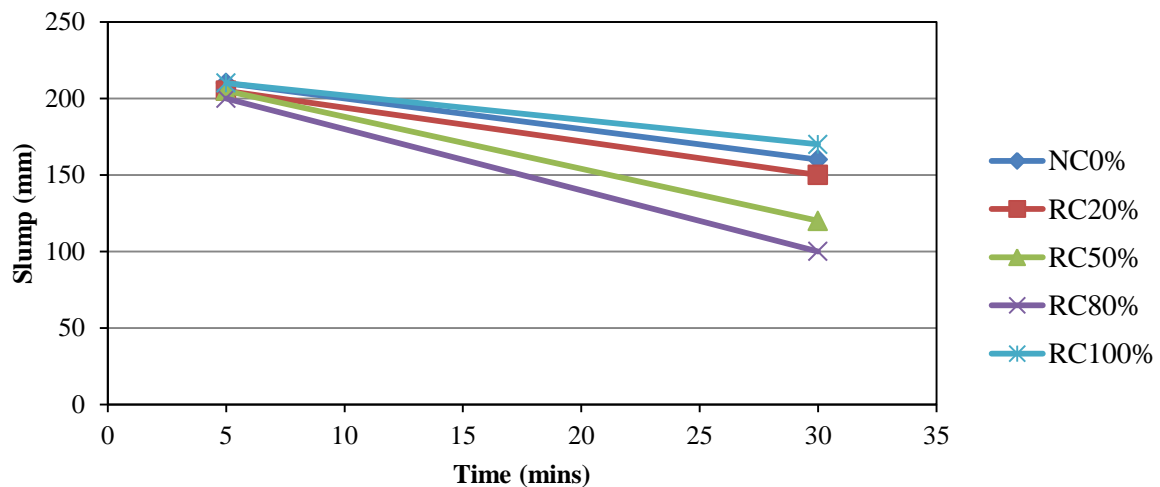


Figure 3.9 Slump loss after 30 minutes for different replacement percentages
(adapted from Pani et al, 2011)

3.2.2 Fresh density

The fresh concrete density is mostly affected by the densities of the concrete constituents, water content, air content and degree of compaction (Crosswell & Kellerman, 2009). The wet density of a concrete mixture will provide insight into whether or not the hardened concrete will be in range of the respective density required or whether the mix proportions are correct. Crosswell & Kellerman (2009)

state that with a change in water content of 10 l/m^3 , the fresh density will change by about 15 kg/m^3 and a 1% increase in air content, will result in a density reduction of 25 kg/m^3 .

Sagoe-Crenstil et al. (2001) documented a fresh density of 2466 kg/m^3 for natural basalt aggregate and 2335 kg/m^3 for RCA with the same air content of 2.4%. This indicated nearly a 5% reduction with a 100% RCA replacement when the same constituents were used. Kutegeza (2004) also observed a similar result for the wet density, with concrete comprising RCA ranging between 2129 to 2365 kg/m^3 and concrete containing NA ranging between 2414 to 2465 kg/m^3 (Figure 3.10).

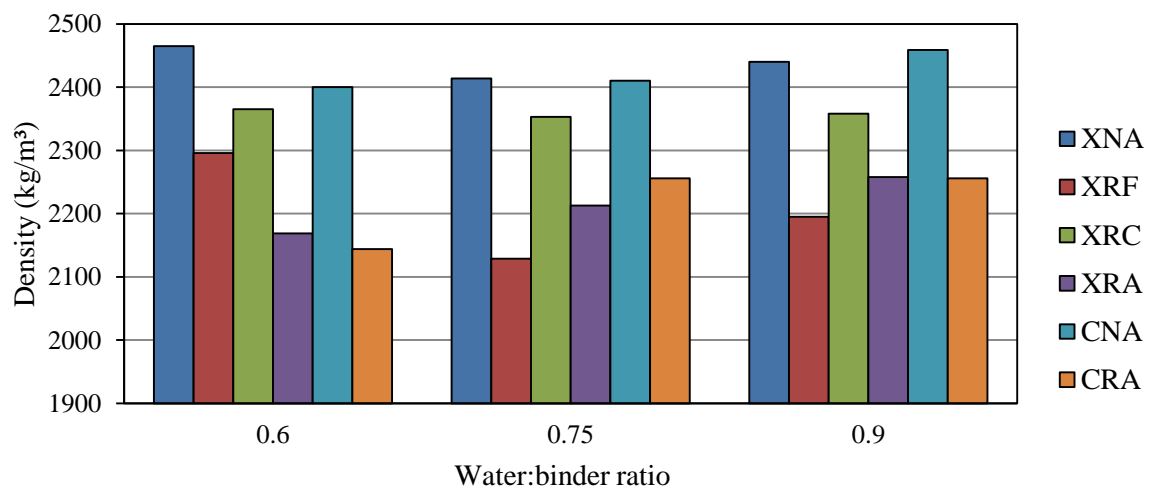


Figure 3.10 Varying fresh density results for concrete mixtures containing both fine and coarse RCA and fine and coarse NA, (adapted from Kutegeza, 2004)

3.2.3 Air content

Concrete will generally contain voids and there are three cases: capillary voids, entrapped air and entrained air. Capillary voids are defined as the space not filled by the solid constituents of hydrated cement paste (Mehta & Monteiro, 2006). As the water hydrates the cement and the original space occupied is by replaced hydration products, and therefore the remaining space not taken up form capillary voids. Capillary voids are generally irregular in shape and range in size from 10 nm in well hydrated, lower water:binder (w:b) ratio pastes to $5 \mu\text{m}$ in high w:b ratio pastes (Mehta & Monteiro, 2006).

Entrapped air, is air which after full compaction cannot be removed and typically ranges between 0.5 to 1.0% (Crosswell & Kellerman, 2009). This air is usually trapped during the mixing process of concrete production and can reach up to 3 mm in size (Mehta & Monteiro, 2006). Air can be intentionally added to fresh concrete using air entraining admixtures and in doing so, the workability

of the concrete is increased therefore the water demand (Chandra Paul, 2011). Entrained air voids range in size from 50 to 200 μ m, with the content monitored depending on the admixture dosages.

Both entrapped and entrained air voids are larger than capillary voids, and are able to adversely affect the strength of hardened concrete (Mehta & Monteiro, 2006). Addis (2008) states that for every 1% of entrapped air that is not removed, the voids will reduce the strength by 6%. Compacting the concrete in a fresh state, correctly, increases the durability, by means of decreasing the permeability of the hardened concrete. Decreased permeability reduces the potential of chemical attack by gases and soluble agents. Chandra Paul (2011) notes general recommendations for the total air content depending on the exposure class in accordance with the Portland Cement Association as defined in Table 3.25.

Table 3.25 Recommendations for air content from the Portland Cement Association (Chandra Paul, 2011)

Nominal maximum aggregate size (mm)	Air content (%)		
	Severe exposure	Moderate exposure	Mild exposure
9.5	7.5	6	4.5
12.5	7	5.5	4
19	6	5	3.5
25	5.5	4.5	3

Sagoe-Crenstil et al. (2001) found that the air content is similar when using 100% RCA replacement at 2.4%, however with the inclusion of slag cement the air content decreased to 1.8%. Chandra Paul (2011) noted similar results where the inclusion of 50% GGCS reduced the air content for all replacement percentages (Figure 3.11). Steps 2 and 3 were concrete mixtures with different RCA samples and Portland cement, while Step 4 included the RCA from Step 3 and the use of the cement extender (GGCS).

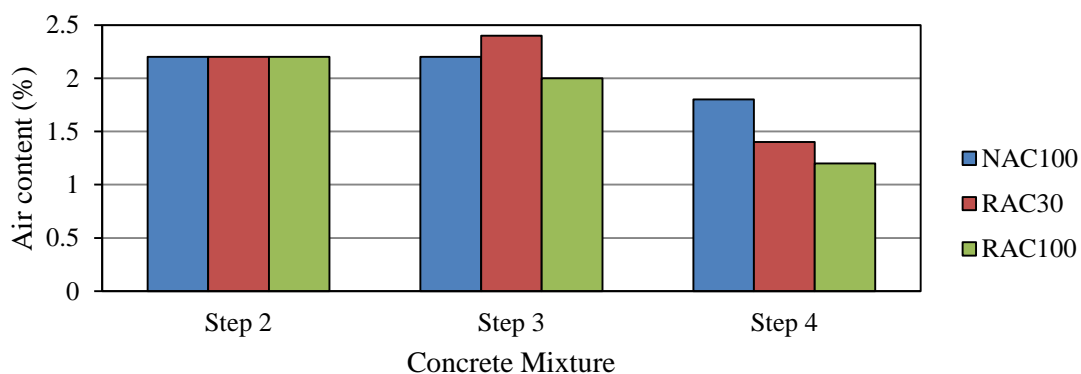


Figure 3.11 Air content for varying amounts of RCA and inclusion of slag (adapted from Chandra Paul, 2011)

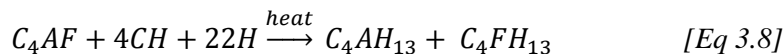
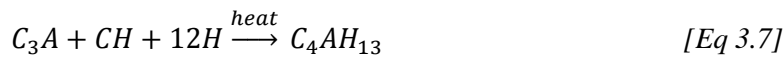
3.3 Hardened Concrete Properties

The hardened concrete properties are discussed according to the mechanical, durability and dimensional properties. The mechanical properties include the compressive and tensile splitting strength. The durability properties consist of the oxygen permeability, water sorptivity and chloride conductivity. Lastly, the dimensional properties are defined by the modulus of elasticity, shrinkage and creep of concrete.

3.3.1 Mechanical properties

The strength of hardened concrete is of the highest importance when examining the influence of RCA in concrete. Concrete in a hardened state has the ability to resist higher compressive forces compared to low tensile/flexural forces (except when reinforcing steel is included). The strength of concrete is time-dependent and generally 50 to 60% of the ultimate strength is developed at 7 days and 80 to 85% at 28 days (Domone & Illston, 2006) with possible additional strength development occurring over many years. Concrete behaviour is however also affected by environmental conditions, materials and applied stresses. The formation of hardened concrete begins in the fresh state due to the hydration of cementitious compounds.

Ordinary Portland Cement (OPC) is a combination of ground clinker and gypsum (Addis, 2008 and Domone & Illston, 2008). As discussed in Section 3.1.7, the four main compounds of clinker form the basis of cement. During hydration, these compounds react with water (H₂O or shorthand notation H) to form the cement paste, of which C₃S and C₂S are the most important compounds (Addis, 2008). In Equations 3.5 and 3.8 the hydration reactions between the compounds are given (Grieve, 2009b). All the reactions are exothermic, where the heat produced is an indication of the hydration process.



The hydration reactions are never complete (Domone & Illston, 2008), but after a few days the bulk cement paste, now hardened cement paste (hcp) is occupied by fine needles and plates of C₃S₂H₃ (C-S-H) and embedded within the C-S-H are crystals of Ca(OH)₂ (CH), where the former contribute the greatest to the hcp strength and the latter to raising the pH to approximately 12.5 (alkaline) which influences aspects of durability (Domone & Illston, 2008 and Addis, 2008). Calcium trisulfoaluminate

hydrate (ettringite) in the form of needle shape crystals are also present and form in the early stages of hydration (Mehta & Monteiro, 2006). Examining the microstructure of the cement paste with the inclusion of aggregate, the above mentioned compounds can be represented as a three phase model: a “bulk” cement paste phase, an aggregate phase and a phase linking the former and latter, known as the interfacial transition zone (ITZ) (Alexander & Mindess, 2005).

The ITZ seen in Figure 3.12 is the region between the bulk cement paste and the aggregate particle. The ITZ has a similar structure to that of the bulk cement paste however, the volumetric amounts of the various compounds differ between the two. The ITZ generally has less unhydrated cement and higher porosity, due to the presence of capillary voids by volume and amount (Alexander & Mindess, 2005). Figure 3.12 shows the presence of strength contributing C-S-H, ettringite and CH is less than the bulk cement paste. The ITZ is considered the weak link in concrete, because of the above influences and additional microcracks that may be present before concrete is stressed (Mehta & Monteiro, 2006).

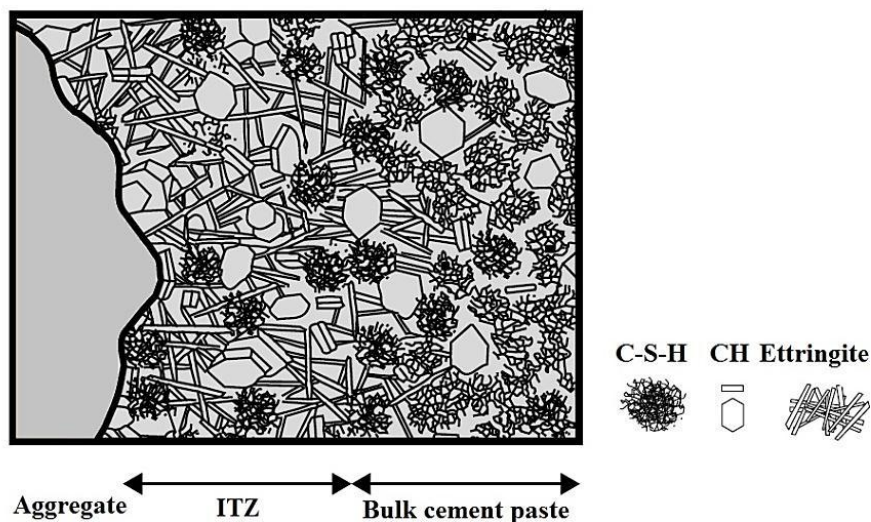


Figure 3.12 Diagrammatic representation of ITZ in concrete (Mehta & Monteiro, 2006)

As stated in Section 3.1.6 the aggregate strength is of less concern when dealing with normal strength concrete, therefore showing that the ITZ is of greater concern. The ITZ structure and concrete as a whole is continually influenced by external and internal factors, which are summarised in Table 3.26. The strength of concrete is therefore dependent on many factors. The influence that each of these factors have on the mechanical properties of concrete can be determined by testing concrete specimens either by sampling concrete from the structure directly, or in most cases replicating the concrete mixture under laboratory controlled conditions. Concrete strength is divided into two main categories: compressive strength and tensile strength and the former is the basis for structural design when concrete has to be specified.

Table 3.26 Summarised factors which influence the ITZ and strength of hardened concrete (Addis, 2008; Alexander & Mindess, 2005; Domone & Illston, 2008; Grieve, 2009b; Mehta & Monteiro, 2006 and Perrie, 2009)

Factor	Influence on concrete and ITZ
Water:binder ratio	Strength improves with decreasing w:b ratio
Age of concrete	Strength improves with increasing age, where moisture is available
Bleeding in fresh concrete	Strength increase as bleeding is reduced
Type of cementitious material	Finer particles in cement extenders have a "fine filler effect" improving strength at a later age due to slower hydration reactions
Ultra fines in aggregates	Strength is improved due to "fine filler effect" and reduced bleeding with higher amounts of very fine aggregate particles are
Surface texture of aggregates	A rougher surface texture will improve the strength of ITZ
Absorption of aggregates	Slightly absorbent aggregates will increase the strength at interface
Curing/Hydration	The presence of water will improve strength by promoting cement hydration
Temperature	Concrete cured at a higher temperature will develop a lower ultimate strength, while concrete cast at a lower temperature will have a higher ultimate strength.
Porosity	Higher porosity decreases concrete strength
Humidity	Strength is improved at high humidity
Aggregate size	Larger aggregates tend form a weaker ITZ and reduce the strength
Aggregate type	Concrete with siliceous aggregates instead of calcareous aggregates show improved strength
Segregation	Strength improves with less segregation

Xiao et al. (2005) examined the mechanical properties of RAC under uniaxial loading at the replacement percentages 0, 30, 50, 70 and 100%. The RCA used in the investigation was obtained from an airport runway in Shanghai with aggregate properties described in Table 3.27. Prior to mixing the RCA was soaked and the amount of water used to immerse the material was based on the water absorption. The w:c ratio was kept constant at 0.43 and the percentage replacement was established, where 0% indicated normal or reference concrete.

Table 3.27 Aggregate properties of NCA and RCA used in research by Xiao et al. (2005)

Coarse aggregate	Grading	Bulk density (kg/m ³)	Apparent density (kg/m ³)	Water absorption (%)	Crush index (%)
NCA	5 - 31.5	1453	2820	0.4	4.04
RCA	5 - 31.5	1290	2520	9.25	15.2

Prisms (100x100x300mm) and cubes (100x100x100mm) were cast and cured for 28 days before testing. The results for the compressive strength are summarised in Table 3.28. From the results, about a 26% decrease in strength is observed between the 0% and 100% cube results, while only a 12% decrease is found between the prism results. At 30% replacement, the difference in compressive strength between both specimens shows a minor decrease in strength when compared to the NAC.

Table 3.28 Compressive strength results for cubes and prisms at 28 days curing adapted from Xiao et al. (2005)

Specimen	Slump (mm)	Density (kg/m ³)	f_{cu} (MPa)	f_c (MPa)	f_c/f_{cu}
NAC - 0%	42	2402	35.9	26.9	0.75
RAC - 30%	33	2368	34.1	25.4	0.74
RAC - 50%	41	2345	29.6	23.6	0.8
RAC - 70%	40	2316	30.3	24.2	0.8
RAC - 100%	44	2280	26.7	23.8	0.89

f_{cu} = cube stress, f_c = prism stress

Sagoe-Crentsil et al. (2001) replaced natural aggregate with RCA at 100%. Seen in Figure 3.13 are the compressive strength results completed over 365 days. The RCA was in an SSD condition before mixing. The four mixes consist of 100% OPC & 100% NA, 100% OPC & 100% RCA, 65% OPC/35% GGBS & 100% RCA and 100% RCA with an additional 5% OPC. It was reported that there was no significant difference between concretes with OPC, based on aggregate type. The concrete containing slag achieved considerably higher later age strengths, with the 7 and 28 day strengths of 20.2 and 32.6 MPa respectively, compared to the concrete with OPC which had a 6 MPa increase between the respective days.

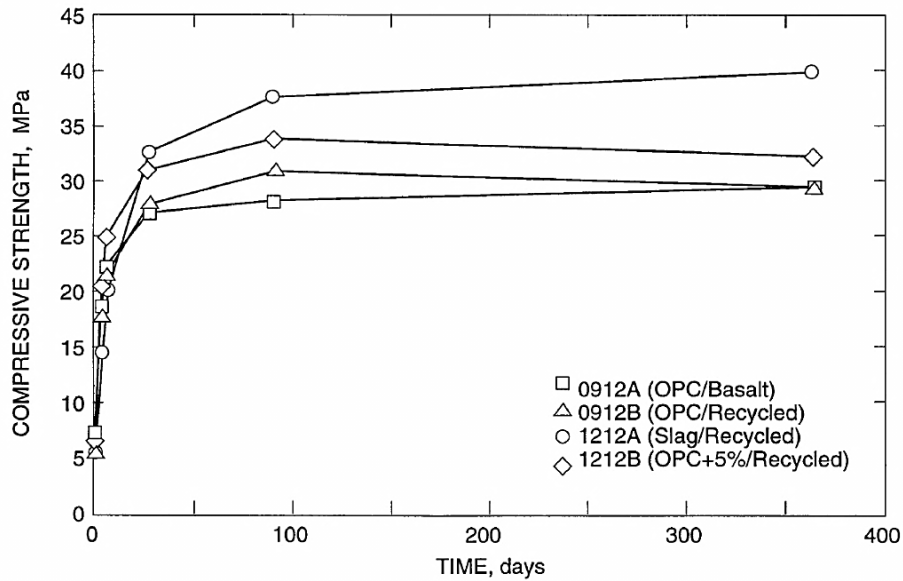


Figure 3.13 Compressive strength development over one year (Sagoe-Crentsil et al, 2001)

Figure 3.14 shows the tensile splitting strength results from the four mixtures in this research. Sagoe-Crentsil et al. (2001) noted that the tensile strength development was influenced by the type of binder used rather than aggregate. After one year, the tensile strength of the mixture containing slag cement replacement was about 25% higher than the OPC mixtures. The pattern of the indirect tension tests was similar to that of the compression tests. The addition of RCA in the concrete resulted in a insignificant difference in strength, owing to the bond characteristics of the RCA and new cement paste (Sagoe-Crentsil et al, 2001).

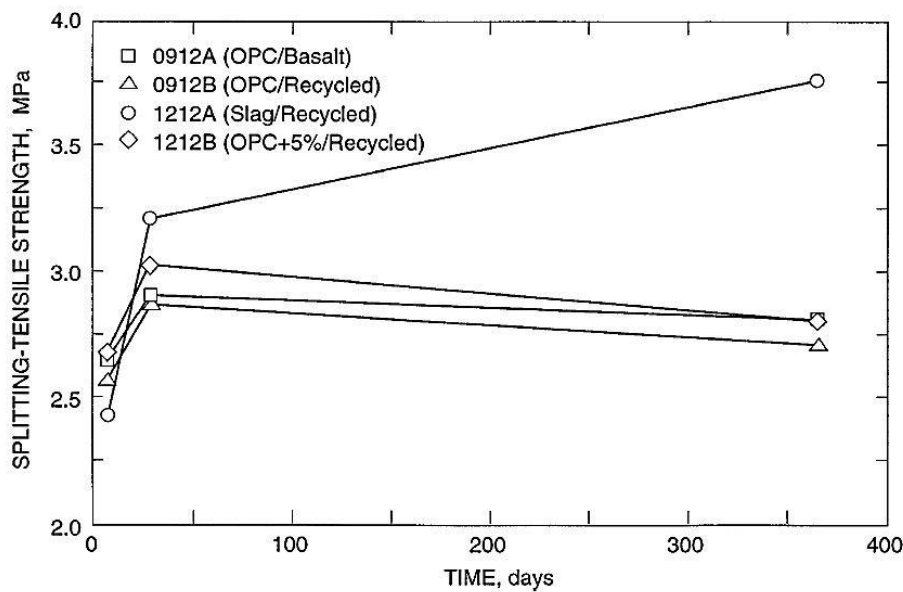


Figure 3.14 Tensile splitting strength development for one year (Sagoe-Crentsil et al, 2001)

Poon et al. (2004), as stated in Section 3.2.1, investigated the influence of aggregate moisture state on the slump and compressive strength of RCA and NA. The RCA in the investigation had water absorption of about 7% and was assumed to have an influence on the compressive strength. Figure 3.15 shows the strength development of the concrete tested at 3, 7 and 28 days. The concrete containing only natural aggregate performed similarly in an AD and SSD state, whilst the OD state had a much lower strength. The concrete containing RCA seemed to have a positive effect on strength in an OD state, compared to mixtures with aggregates in an SSD condition. The negative influence on the SSD conditions' was attributed to the presence of bleeding during the compaction of this concrete. Figure 3.16 shows the influence of RCA replacement on the compressive strength development. The figure shows that the strength of AD mixes remains almost unchanged as the RCA percentage increases, while the OD mixtures increased in compressive strength and the SSD mixtures showed a decrease. Poon et al. (2004) concluded that concrete mixtures containing RCA in an AD condition exhibited the highest compressive strength and aggregates in an SSD condition have the greatest negative effect. Poon et al. (2004) recommended that concrete containing up to 50% RCA in an AD condition would provide a normal strength concrete.

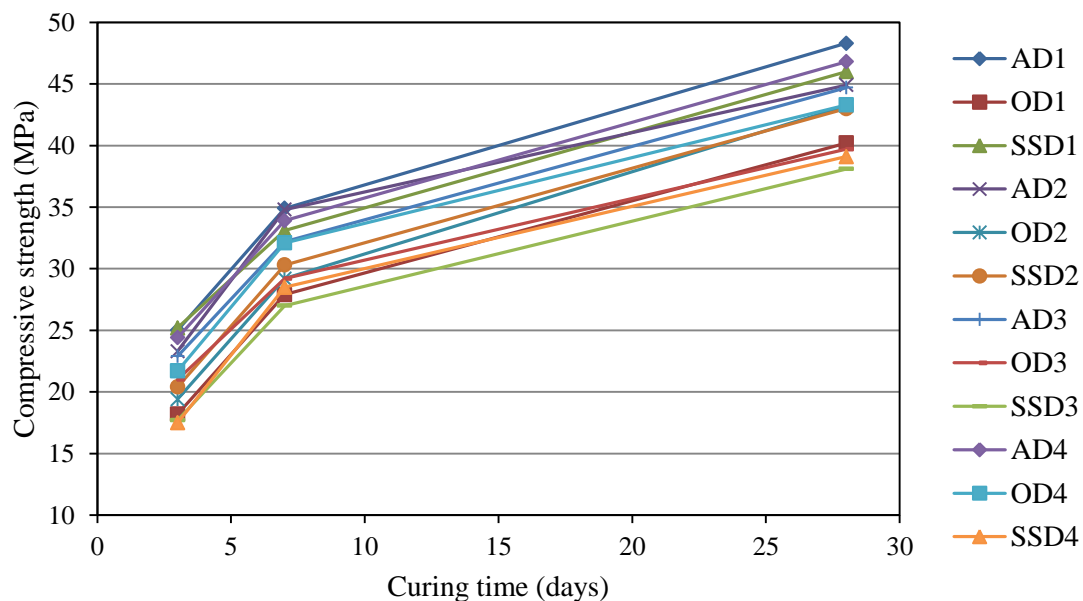


Figure 3.15 Compressive strength development for different concrete mixtures

(adapted from Poon et al, 2004)

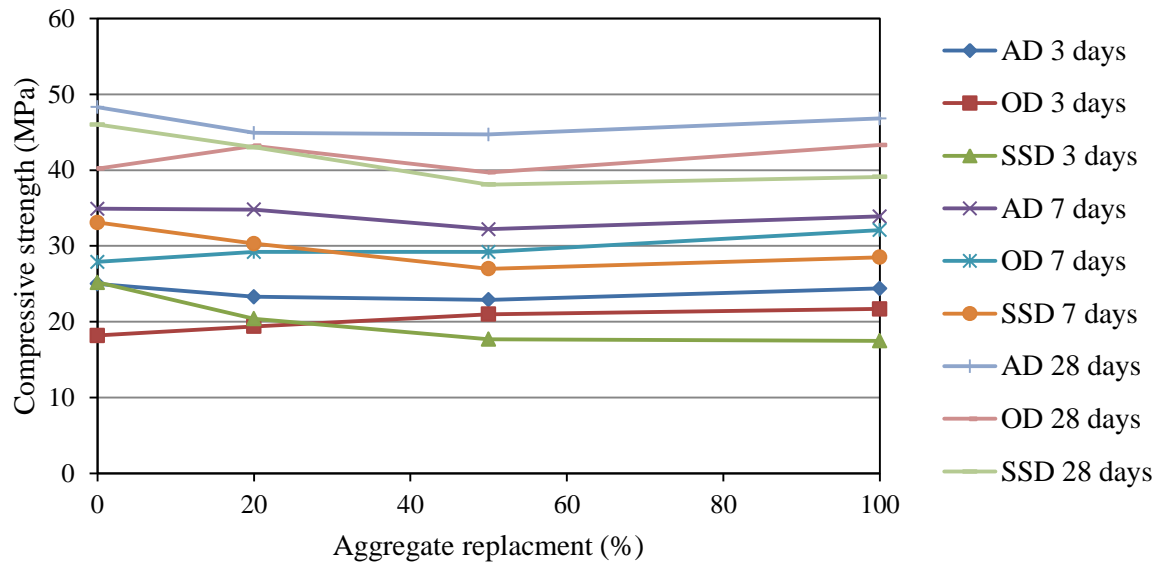


Figure 3.16 Influence of RCA replacement on the compressive strength development
(adapted from Poon et al, 2004)

Pani et al (2011) investigated the influence of percentage replacement of RCA at 0, 20, 50, 80 and 100%. The RCA had a water absorption of 3.8% and dry specific density of 2663 kg/m³ and the NA had a water absorption of 1.4% and dry specific density of 2691 kg/m³. Table 3.29 presents the data from compression tests conducted on cubes (l = 150mm) and cylindrical ($\phi = 70\text{mm}$, h = 200mm) specimens. The aggregates used in the concrete were pre-saturated to an SSD condition before mixing and a constant w:c ratio of 0.54 was used for all the mixes. The data from the tests shows that the strength of concrete decreased with about an average of 5% at each percentage replacement with cubic specimens. The cylindrical specimens displayed a similar trend until 80% and 100% replacement where the percentage decrease was significantly higher. Pani et al. (2011) determined in the conclusion, that 50% replacement with RCA could be used for concrete class C30/37 and up to 100% for class C25/30 concrete.

Table 3.29 Compressive strength (cube and cylinder) and tensile splitting (cube) strength (adapted from Pani et al, 2011)

Concrete	f_{cu} (MPa)	Δ (%)	f_c (MPa)	Δ (%)	f_{ctm} (MPa)	Δ (%)
NC0	45.36	0	47.87	0	5.47	0
RC20%	43.86	-3	45.78	-4	5.1	-7
RC50%	43.43	-4	45.32	-5	4.33	-21
RC80%	42.51	-6	40.44	-16	4.43	-19
RC100%	41.6	-8	37.88	-21	4.13	-24

The tensile splitting was included in the investigation by Pani et al. (2011). The specimens used in the tensile test consisted of 150mm cubes and the results from the tests are also given in Table 3.29. The mixtures containing 50 to 100% RCA had an average tensile splitting strength loss of about 21% compared to the mixture containing 100% NA. The researchers concluded that the concrete failed, not because of the failure between the aggregate and existing cement paste, but rather due to the failure of the aggregate itself. It was noted that the RA surface showed contact between the new cement mortar and the existing one and the original aggregate (Pani et al, 2011).

Tabsh et al. (2009) considered the effect that the original concrete strength may have on the strength of new concrete containing the RCA derived from the original concrete. The test specimens consisted of cylinders with a radius of 150mm and height of 300mm. Four coarse aggregates were used in the experimental programme: natural aggregates, RCA from an unknown source, RCA from 30 MPa and 50 MPa laboratory cast concrete. No admixtures were used in the mixtures and the mixtures containing RCA required about 10% more water due to the absorption percentage. Two concrete mixtures were designed with strengths of 30 and 50 MPa with w:c ratio of 0.58 and 0.37 respectively, with a total of eight concrete mixtures produced for testing.

Tabsh et al. (2009) states that concrete containing RCA has a high bonding strength between the aggregate and cement paste, due to the angularity of the particles and the residual cementation on the surface of the aggregate. From Figure 3.17 it is evident that concrete made with stronger original concrete produced the same strength as concrete made with 100% NA. The 30 MPa and unknown RCA concrete mixtures resulted in a strength reduction of about 30%. Figure 3.18 shows a similar trend, however the decrease in compressive strength is much less at about 10 and 15% lower strength with the 30MPa and unknown RCA mixtures. The influence of the additional 10% water may have played a significant role in reducing the strength of the concrete mixtures, and with the use of admixtures to maintain the same workability; the RAC would have performed better (Tabsh et al, 2009).

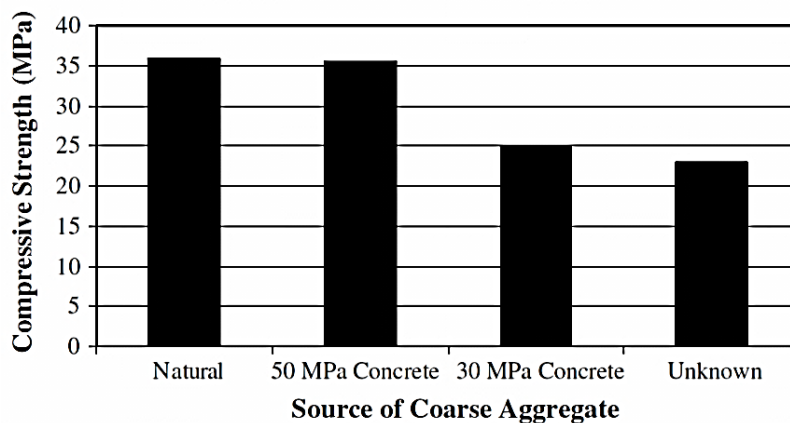


Figure 3.17 Compressive strengths of 30 MPa concrete mixtures (Tabsh et al, 2009)

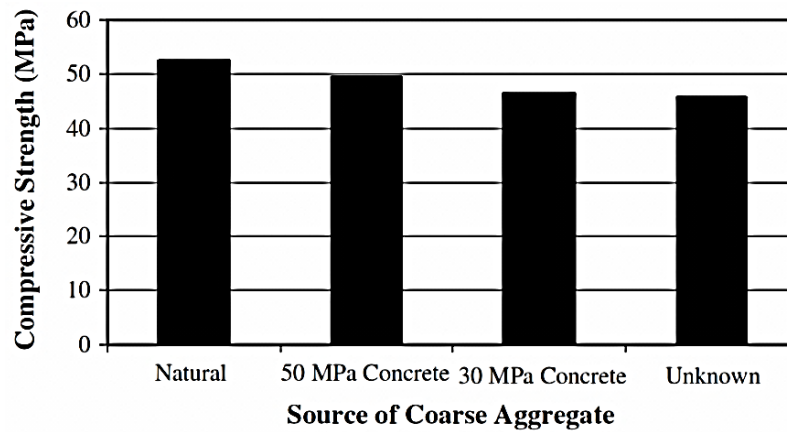


Figure 3.18 Compressive strengths of 50 MPa concrete mixtures (Tabsh et al, 2009)

The tensile splitting strength was also examined by applying a compression load to the side of $\phi 100 \times 200$ mm cylinders. The results from these tests conducted on mixtures as described above are shown in Figures 3.19 and 3.20. The RCA originally derived from the 50 MPa concrete produced strength similar to that of the concrete containing NA. There was a 25 to 30% decrease in tensile strength in the mixtures containing 30 MPa RCA and unknown strength RCA (Figure 3.19). The 50 MPa mixture in Figure 3.20 had a similar trend to that of the 30 MPa mixture, except the overall tensile strength increased. The decrease tensile strength in the 30 MPa RCA and unknown RCA mixture was less, with a loss of 10 to 15% based on the mixture containing NA. The influence of the original concrete strength is evident with the results of the compression and tension strength tests, where the use of stronger original concrete will result in improved concrete strengths in the new concrete.

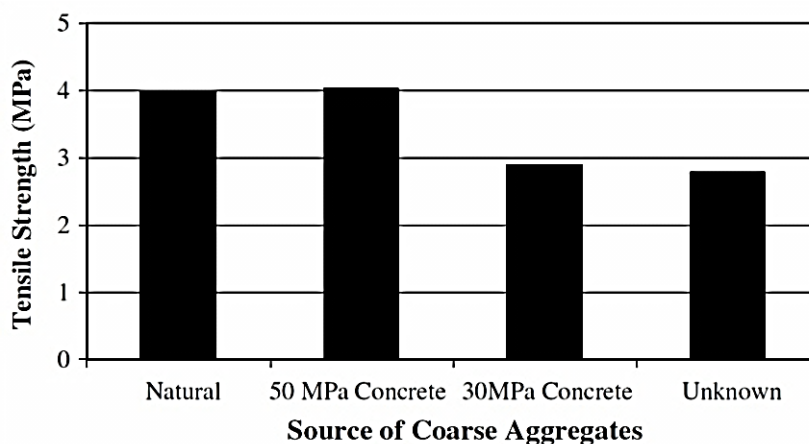


Figure 3.19 Tensile splitting strength of 30 MPa concrete mixtures (Tabsh et al, 2009)

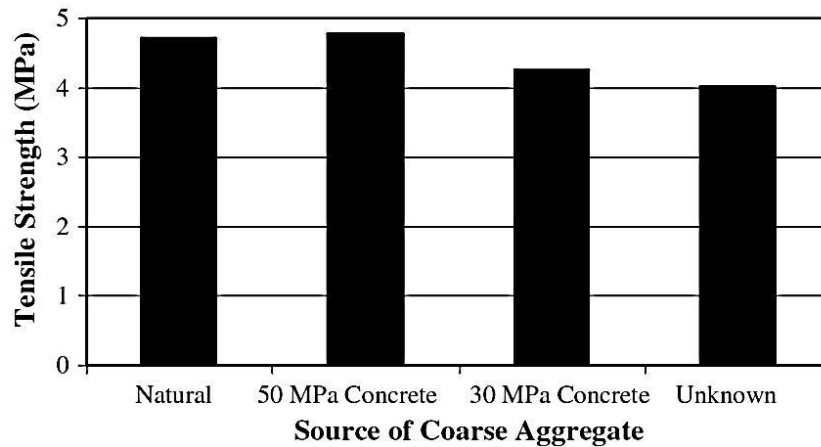


Figure 3.20 Tensile splitting strength of 50 MPa concrete mixtures (Tabsh et al, 2009)

From South African studies on RCA, Kutegeza (2004), as stated in Section 3.2.1, investigated the influence of both coarse and fine RCA on the properties of concrete. The hardened concrete density results from this study are shown in Figure 3.21. The hardened concrete densities are lower when coarse and fine RCA are included in concrete. Mixes containing both aggregates had densities 20% lower than concrete with natural aggregates, however the mixture containing only coarse RCA attained a concrete density of about 5% lower than NAC.

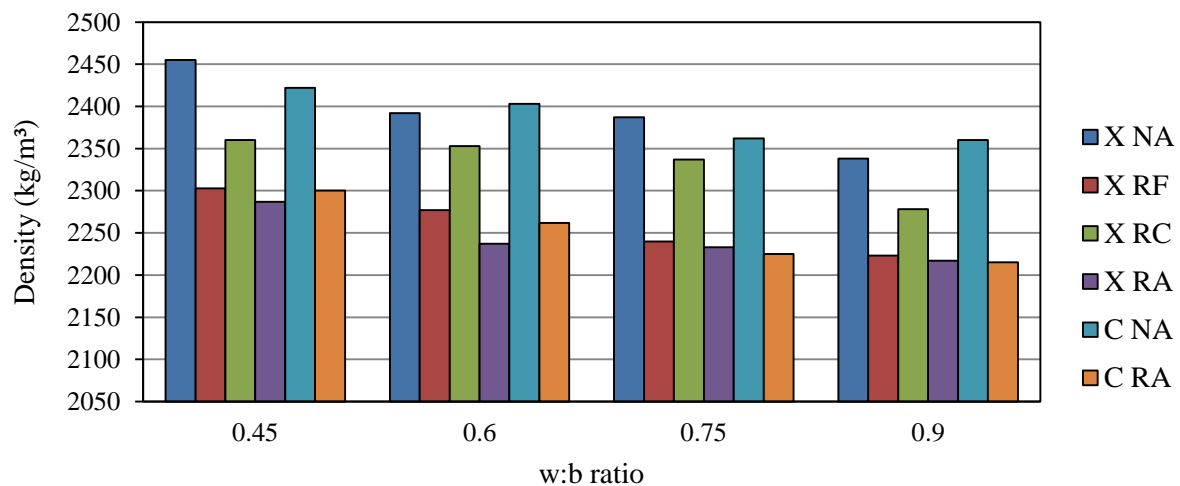


Figure 3.21 Hardened concrete density after 28 days curing for the six concrete mixtures adapted from Kutegeza (2004)

The compressive strength also decreased with the presence of RCA in the concrete as seen in Figure 3.22. The mixture containing 50% Corex® slag and both coarse and fine natural aggregates (XNA) obtained the highest strength at 120 days; however the mixture containing only OPC and natural aggregates had the highest 3 day strength. The three mixtures that obtained the lowest compressive strength at 120 days were, XRF, CRA and XRA. The XRF mixture comprised of 30% coarse RCA, 70% coarse NA and fine RCA with a 50% slag replacement. The mixtures CRA and XRA both contained 100% coarse and fine RCA with a cement replacement of 50% only present in the latter.

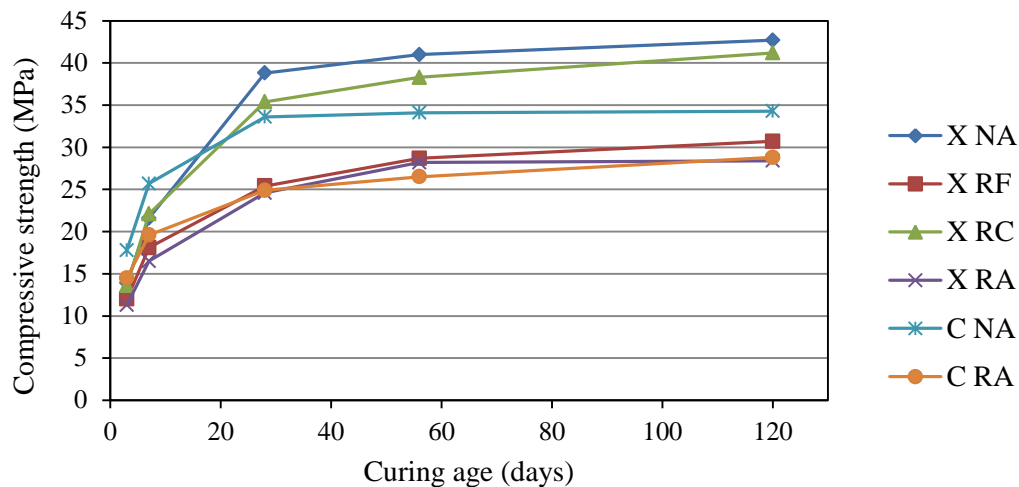


Figure 3.22 Compressive strength development for $w:b = 0.6$ for the six concrete mixtures (adapted from Kutegeza, 2004)

Figure 3.23 shows the compressive strength at 28 days for the different $w:b$ ratios. Across all the different $w:b$ ratios there is a decrease in compressive strength when comparing the mixtures to the strongest mixture (XNA). The compressive strength loss at 28 days ranged from 2% at the lowest and about 40% at the highest. The increase of the $w:b$ ratio decreases the strength of the concrete, because of the reduction of cementitious content and therefore decreasing the products of hydration. The mixture containing 100% RCA and 50% slag replacement (XRF) performed similarly to the XNA mixture across the different $w:b$ ratios, with the lowest strength lost of 4% for $w:b = 0.45$ and the highest of 12% for $w:b = 0.9$.

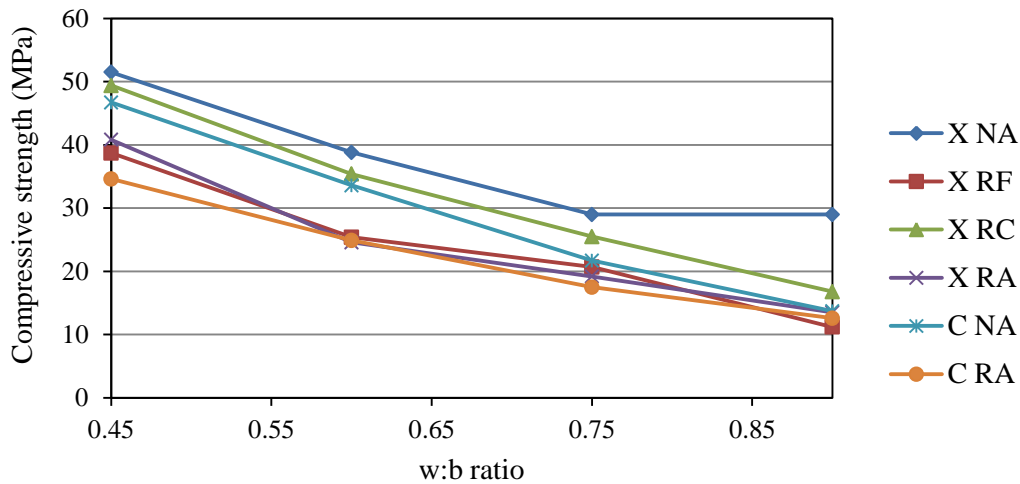


Figure 3.23 Compressive strengths at different w:b ratios for the six mixtures
(adapted from Kutegeza, 2004)

Chandra Paul (2011) examined the influence of percentage replacement of RCA at 0, 30 and 100%. From Figure 3.24 the concrete indicated by the number “-2” contains RCA which was obtained from a crushing plant and “-3 & -4” was collected from the demolition of the Athlone towers as discussed in Chapter 2. The “-2 & -3” concrete mixtures consisted of only OPC, while “-4” included a 50% Corex® slag replacement. RCA30-2 and RCA100-2 displayed a strength reduction of about 16% and 28%, respectively when compared to NCA100-2 at 56 days. The RCA30-3 had a similar strength to NCA100-2, while RCA100-3 had about a 20% decrease in strength.

The mixtures containing slag showed a relatively low strength at an early age, but developed the highest strengths at 56 days across all the mixtures. The RCA30-4 and NCA100-4 had similar compressive strengths, with the former marginally higher. The RCA100-4 produced about a 14% lower strength when compared to NCA100-4, but only approximately 5% strength loss when compared to NCA100-2. The influence of a cement extender is evident from this result and 100% RCA replacement.

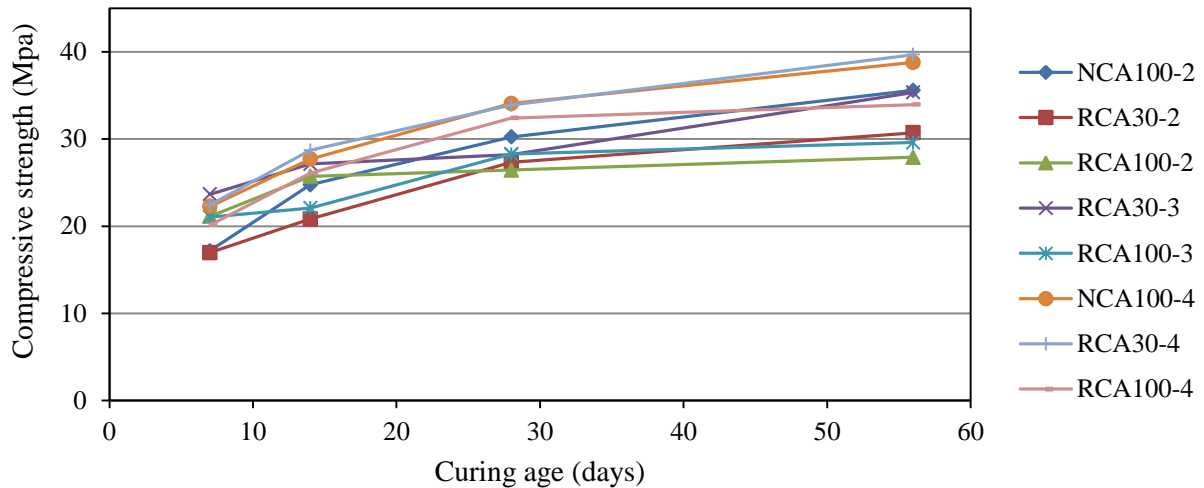


Figure 3.24 Compressive strength development for different batches of RCA
(adapted from Chandra Paul, 2011)

The tensile splitting strength was also determined for the concrete mixtures in this research programme with the addition of “-1” concrete mixture, which included RCA that was derived from the Stellenbosch landfill site in the Western Cape. The concrete mixture only contained CEM II 32.5 and replacements of NA with RCA at 30% and 100%. Table 3.30 shows the tensile strength results for the four mixtures. Chandra Paul (2011) notes that the EN 1992-1 suggests that the direct tensile strength is about 90% of the indirect tensile strength. The splitting tensile strength is therefore greater than the direct tensile strength, but lower than the flexural strength (modulus of rupture) which is another indirect measure of tensile strength. As seen from the table as the percentage replacement increases, the tensile strength decreases. Upon examination of the split specimens Chandra Paul (2011) confirms the failure mode that Pani et al. (2011) recorded. The mixtures containing RCA had failure planes which passed through the aggregate and not along the ITZ.

Table 3.30 Tensile splitting strength results adapted from Chandra Paul (2011)

Step	Case No	f_{st}	COV (%)
1	NCA100	3.17	3.91
	RCA30	3.15	5.73
	RCA100	3.17	9.19
2	NCA100	3.8	5.11
	RCA30	3.64	6.44
	RCA100	3.15	4.81
3	RCA30	3.43	5.76
	RCA100	3.36	2.15

Table 3.30 continued...

Step	Case No	f_{st}	COV (%)
4	NCA100	4.04	9.18
	RCA30	3.73	10.48
	RCA100	3.93	15.72

Alexander & Heiyantuduwa (2002) compared the compressive strengths of RAC mixtures with aggregates in an AD and SSD condition. The aggregates used in the mixture had a water absorption of 4.16% as noted in Section 3.1.5 The concrete mixtures consisted of 50% OPC and 50% GGCS as binders with fine natural aggregate. The mixture with RCA in an AD condition had additional mixing water provided, while the mixture with RCA in an SSD condition had less mixing water due to the water content of the aggregate. Table 3.31 provides the results for the difference between two RAC mixtures. The difference in overall strength and strength development displayed no significant difference between the two mixtures (Figure 3.25). The outcomes from this data shows that the concrete strength can be controlled by either adding additional mixing water to AD aggregates or decreasing the mixing water amount in the case of SSD aggregates.

Table 3.31 Compressive strengths of concrete mixtures containing AD and SSD aggregates adapted from Alexander & Heiyantuduwa (2002)

Concrete	SSD RAC		AD RAC	
Age	f_{cu}	COV	f_{cu}	COV
3	16.5	1.31	17.1	4.89
7	23.5	0.69	24.0	3.25
28	31.4	2.10	30.7	1.73
56	34.0	1.10	32.5	1.40

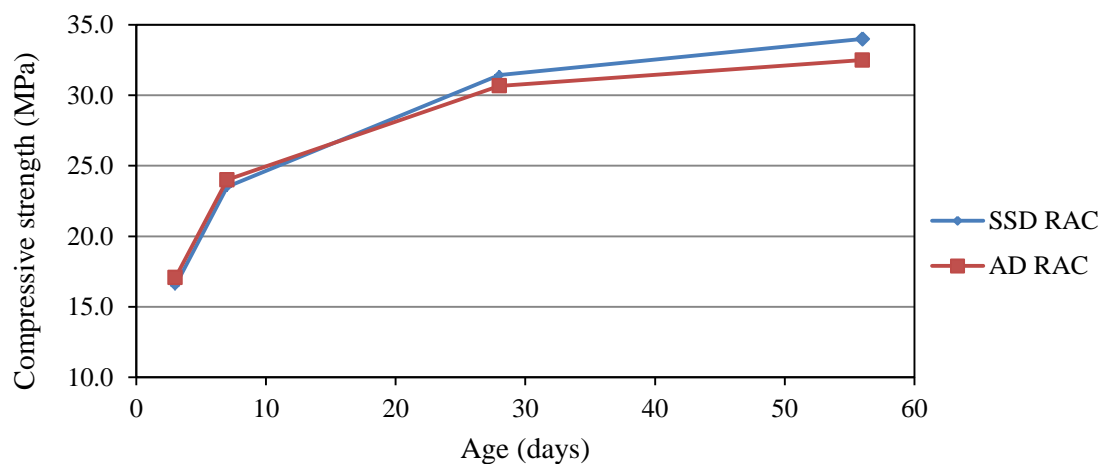


Figure 3.25 Compressive strength development of RAC with aggregates in an AD and SSD condition adapted from Alexander & Heiyantuduwa (2002)

3.3.2 Durability properties

The durability of a material is its resistance to degradation and the ability to remain serviceable for the designed period for which that material will be in use (Alexander & Mindess, 2005 and Domone & Illston, 2008). Concrete's durability properties have generally been the least concern for structural engineers when designing for its use (Alexander et al, 2009). However, in some cases where concrete is to be used in harsh environments or specialised circumstances, the durability of the material needs to be considered. By improving the durability of structures, less maintenance and premature demolition actions would be necessary, where it is estimated by Metha & Monteiro (2006) that in industrially developed countries, nearly 40% of the total resources of the construction resources are applied in repair and maintenance of existing structures.

Mechanisms of concrete deterioration have been investigated to understand how the inherent durability properties may be compromised and the factors which cause these mechanisms to occur. The rate of concrete degradation is controlled by the rate of moisture, air or other aggressive agents' ingress into the material (Domone & Illston, 2008). These degradation agents are transported through the concrete by either of the following processes as defined by Domone & Illston (2008):

1. Permeation – the movement of a fluid by a pressure differential; and/or
2. Diffusion – the movement of ions, atom or molecules by a concentration gradient; and/or
3. Sorption – the movement of fluid into an empty or partially empty pore space through a capillary action.

Alexander & Mindess (2005) include the process of conduction along with diffusion, as conduction or migration arises from an electrical potential difference. The above mentioned processes are influenced by the concrete's permeability and porosity. A concrete structure may be highly porous, but it may be less permeable and therefore the movement of agents to the porous regions is controlled at the surface. On the other hand, a concrete structure may be more permeable through cracks, but less porous resulting in degradation at a surface level. The instance where concrete durability is highly vulnerable is when the material is both highly porous and permeable, allowing for deleterious actions to take place both at the surface and within the concrete. These instances are graphically illustrated in Figure 3.26, where the pores (porosity) are seen as the open areas within the concrete and the cracks (permeability) are indicated by the openings at the surface leading through the concrete.

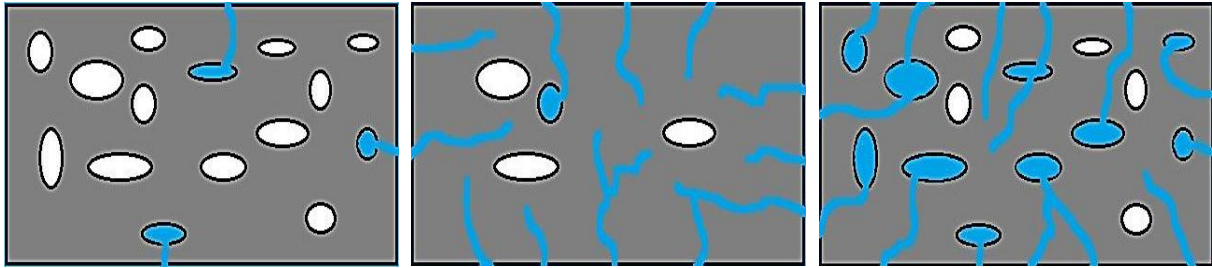


Figure 3.26 Diagram to show difference between permeability and porosity
(adapted from Domone & Illston, 2008)

Water is considered the primary mode of transport in the degradation of concrete, where it may cause either physical or chemical processes of degradation (Mehta & Monteiro, 2006). The physical and/or chemical processes that may occur in concrete are summarised by Alexander et al. (2009) in Table 3.32. The processes of degradation can be separated into two different components. These processes however generally interact with one another causing an overall deleterious action. For example, concrete may crack prematurely under early age loading allowing for the ingress of water transporting chemically aggressive agents.

Table 3.32 Manners by which concrete degradation can occur (Alexander et al, 2009)

Physical	Chemical
Abrasion/Erosion	Nature and concentration of aggressive agents
Erosion	Internal chemical instability (incompatibility between mix constituents)
Cavitation	Coupling with effects of temperature and relative humidity
Freeze-thaw	
Salt crystallisation	
Effects of cracking due to loading or thermal effects	

The transport mechanisms of water are influenced by the permeability and/or porosity of concrete are controlled by the state of hardened concrete through its constituents. The hardened cement paste, aggregates and ITZ are indentified as areas of focus in the “penetrability” of concrete (Alexander & Mindess, 2008 and Alexander et al, 2009). The hardened cement paste usually has a low permeability comparable to that of dense aggregates due to the ongoing hydration of cementitious material which is continually changing (Alexander & Mindess, 2005 and Mehta & Monteiro, 2006). The volume of pores in natural aggregates compared to that of the cement paste is usually under 3% and rarely exceeds 10%, whereas the latter has a 30 to 40% capillary porosity (Mehta & Monteiro, 2006). Alexander & Mindess (2005) and Mehta & Monteiro (2006) agree that the reason for the higher

permeability of bulk paste than the permeability of the cement paste is due to the ITZ between the aggregate and cement paste.

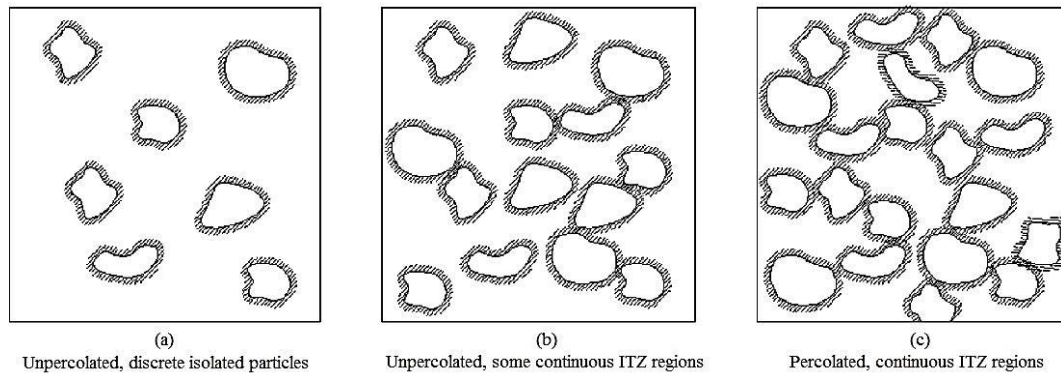


Figure 3.27 Concept of percolation between ITZ regions of aggregate (Alexander & Mindess, 2005)

Figure 3.27 illustrates Alexander & Mindess (2005) description of the concept of percolation through the ITZ, where the ITZ regions around aggregate particles may be linked to a lesser or greater degree increasing the penetrable path for water. Mehta and Monteiro (2006) note that the strength of concrete is greatly influenced by the ITZ and the capillary porosity and therefore the factors controlling the strength/ITZ are in some cases applicable in controlling the permeability of concrete as well. Several authors (Alexander & Mindess, 2005; Mehta & Monteiro, 2006; Addis, 2008; Domone & Illston, 2008 and Alexander et al, 2009) mention the influence that certain concrete factors may have on the ITZ and these factors may be caused by internal and external variables as follows:

Internal Variables:

- Water/binder ratio
- Binder type and content
- Other concrete constituents
- Aggregates and admixtures
- Design mix proportioning
- Aggregate size and type
- Degree of saturation

External Variables:

- Production and/or construction processes such as mixing, placing and consolidation
- Curing (temperature and moisture/humidity of environment)
- Early age temperature history
- Environmental circumstances
- Loading conditions

The internal and external variables may collaborate with another, increasing the potential for loss of durability within a structural concrete element. Alexander et al. (2009) note that the factors dominating the durability concerns of concrete are the binder type and water:binder ratio, the curing and early age temperature. Domone & Illston (2008) state that using a high cement content and low water:cement ratio will result in a higher quality concrete that is less permeable. The use of a low water:cement ratio along with an increasing degree of hydration will also reduce the reactive nature of the calcium hydroxide (CH) and atmospheric CO₂ (Addis, 2008). Mehta & Monteiro (2006) state that larger aggregates increase the permeability of concrete by propagation of microcracks within the ITZ becoming interconnected with other nearby ITZs as shown in Figure 3.27. The chemical actions occurring between the aggregates, concrete and water are discussed in Section 3.1.7.

The concern of concrete durability in most case related to the durability of steel reinforcing contained within the concrete. The concrete acts as a protective layer for the steel and once the concrete has degraded to a point where the steel reinforcing is exposed to the elements, eventual loss of structural integrity may occur (Domone & Illston, 2008). The processes relating to the degradation of steel are less complex than the mechanisms of the concrete degradation, they are however more difficult to avoid and control.

The corrosion of steel occurs through the presence of water near the surface of the steel or iron, where the water acts as the electrolyte of the corrosion cell (Domone & Illston, 2008). The agents and actions which cause the deterioration of the electro-chemically passive, gamma-ferric oxide layer on the surface of steel are not aggressive to the concrete itself (Alexander et al, 2009). The corrosion cells present on the surface of steel are inactive when embedded in concrete due to:

- the alkaline (pH = ±13) conditions in concrete due to Ca(OH)₂ (Domone & Illston, 2008); and
- the absence of aggressive electrolytes (Alexander et al, 2009); and
- the insufficient availability of oxygen to sustain corrosion reaction (Alexander et al, 2009).

The loss of protection/passivation and consequent corrosion of steel may be caused by either or both carbonation-induced corrosion or chloride-induced corrosion (Domone & Illston, 2008). Carbonation occurs when atmospheric CO₂ dissolved in water reacts with the Ca(OH)₂ forming calcium carbonate (CaCO₃) and in doing so reducing the pH to about 8 (Domone & Illston, 2008). Chloride-induced corrosion occurs through the ingress of ionic solutions disrupting the passivating layer of reinforcing steel (Alexander et al, 2009).

Chlorides can occur in concrete through the following sources: calcium chloride (effective accelerator), contamination in aggregates, sea water in coastal regions and road de-icing salts, particularly on bridge decks (Domone & Illston, 2008). The importance of concrete cover or the surface layer above the steel reinforcing is of the greatest concern in preventing the corrosion of steel design codes such as SANS 10100 and EN 206-1, define exposure classes prescribing the necessary measures needed to prevent either carbonation or chloride attack.

Many factors are at play in respect of the durability of concrete and methods of reproducing these factors and the effects thereof in laboratory conditions due to the long term nature of the degradation (Mehta & Monteiro, 2006). Testing procedures to correctly assess the durability of concrete materials have also been investigated as destructive and non-destructive testing methods are available, each with both advantages and disadvantages. South Africa has developed performance based testing methods for the durability of concrete structures (Alexander et al, 2009) through the use of Durability Index (DI) test methods. The test methods consist of the Oxygen Permeability Index (OPI), water sorptivity and chloride conductivity. The DI test methods examine the concrete durability on surface/cover level where the initial layer steel reinforcing is generally located. The testing of concrete utilised in *in-situ* applications may be cast through reproduction of the mix proportions through non-destructive testing or core samples which can be taken from the actual structure, resulting in destructive testing.

The University of Cape Town (UCT) in partnership with the University of the Witwatersrand (Wits) have investigated the durability of concrete for close to 20 years (Alexander, 2010) to develop an understanding of the interaction of systems such as concrete hydration, microstructure and aggressive agents. The need for more practical durability tests instead of lengthy, sophisticated and complex monitoring systems for accurate modelling of these mechanisms was the main reason for the development of the DI approach (Alexander et al, 1999). Alexander et al. (1999) explains the term “indexing” using the compression test of concrete as an analogy. The tests illustrate little resemblance to the conditions that exist within a real structure; however correlation between experience and structural performance have allowed for structures to be designed for different levels of stress. The transport mechanisms such as gaseous and ionic diffusion and water absorption are therefore linked to concrete through the particular index test reflecting that mechanism.

The outcomes from the controlled laboratory and in situ studies have resulted in performance based specifications, where an acceptable or non-acceptable range is defined for different durability classes. Alexander et al. (1999) stated that the criteria need to be continually redefined to benefit all stakeholders involved. Table 3.33 provides the suggested ranges for the three DI tests for four different durability classes. The different DI tests are then discussed with particular reference to RCA use in concrete.

Table 3.33 Performance indexes for different durability index tests (Alexander et al, 1999)

Durability class	OPI (log scale)	Sorptivity (mm/ \sqrt{h})	Conductivity (mS/cm)
Excellent	> 10	< 6	< 0.75
Good	9.5 - 10	6 – 10	0.75 - 1.5
Poor	9.0 - 9.5	10 – 15	1.5 - 2.5
Very Poor	< 9.0	> 15	> 2.5

Oxygen Permeability

The permeability of the concrete cover layer is assessed by the Oxygen Permeability Index (OPI) test. The term “permeation” is used to describe the transport of substances through saturated pores or cracks in concrete under a pressure gradient (Alexander & Mindess, 2005). The permeability of concrete is dependent on the microstructure, the moisture conditions of the material and the characteristics of the permeating fluid (Alexander et al, 1999). The test will therefore reflect the degree of compaction, presence of bleed voids, percolation between ITZs (Alexander et al, 2009) and nature of concrete constituents.

Different methods have been developed for measuring the permeability concrete such as throughflow, inflow and falling-head type tests. Alexander & Mindess (2005) state that the simplest expression defining the permeability of a material is defined by D’Arcy in Equation 3.9:

$$\frac{\delta m}{\delta t} = \frac{k}{g} \cdot \frac{\delta P}{\delta z} \quad [Eq. 3.9]$$

where $\delta m/\delta t$ is rate of mass flow per unit cross-sectional area

$\delta P/\delta z$ is the pressure gradient in the direction of flow

k is the coefficient of permeability

g is the acceleration due to gravity.

The coefficient of permeability is the key parameter in defining the performance of concrete permeability. To determine the coefficient of permeability the OPI test measures the pressure decay of oxygen passing through a circular disc specimen placed in a falling head permeameter as seen in Figure 7.2 (Alexander et al, 2009). The coefficient of permeability is determined by plotting the logarithm of the ratio of pressure heads versus time (Alexander et al, 1999) and the OPI is calculated as negative log of the coefficient of permeability, expressed by Equations 7.2 and 7.5 respectively.

Alexander & Heiyantuduwa (2002) included the OPI test in the investigation for the potential use in semi-structural concrete containing RCA. The concrete mixtures containing RCA were tested under three different curing periods, namely 1, 3 and 28 days. The specimens cured at 1 and 3 days had similar OPI results of 8.5 and 8.4, respectively, while the 28 day cured specimens had an average OPI value of 9.5. The test showed that longer curing periods increase the performance of concrete, even though in this case, the concrete performance is in the poor range. The authors concluded that the porous nature and pre-existing cracks and fissures in RCA may have attributed to the poor performance of the concrete.

The effect of using coarse RCA at varying percentages on the durability in a normal concrete mixture was examined by Olorunsogo & Padayachee (2002) through the DI tests described by Alexander et al. (1999). The properties of the aggregates are given in Table 3.34 to provide a basis for reference and the constituents of the RCA were described in Section 3.1.4. The percentage replacements of 0, 50 and 100% used concrete mixtures with the same w:c ratio of 0.50 and only OPC cement was used as a binder. The results from the 28 day cured concrete specimens are presented in Figure 3.28a at the varying percentages of RCA, while in Figure 3.28b the effect of curing on the OPI results are provided.

Table 3.34 Properties of aggregates used in investigation by Olorunsogo & Padayachee (2002)

Aggregate	Relative density	Moisture content (%)	Fineness modulus	CBD (kg/m ³)
NFA	2.6	4.53	2.9	1441
NCA	2.61	5.13	-	1458
RCA	2.6	5.32	-	1397

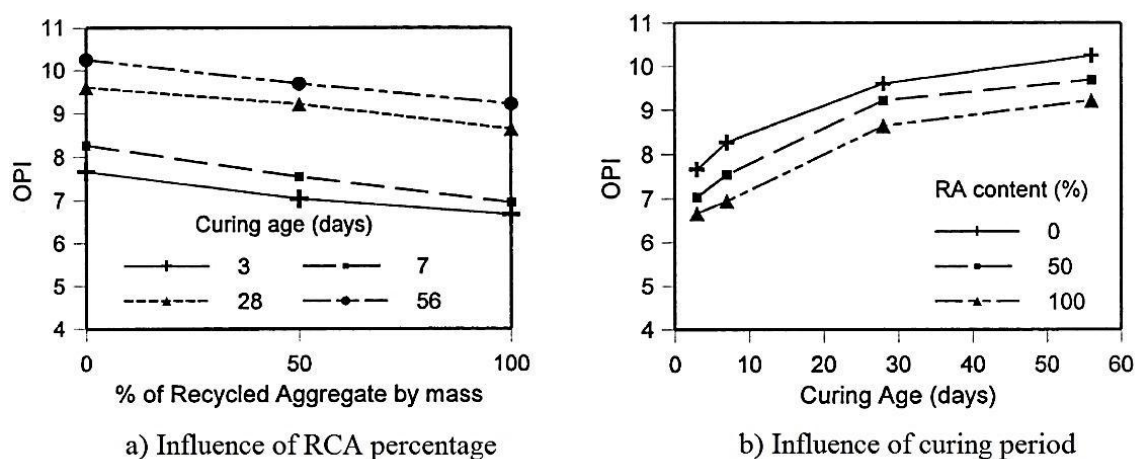


Figure 3.28 Influence of RCA percentage and curing period on OPI test

(adapted from Olorunsogo & Padayachee, 2002)

The properties of the RCA used in this investigation are comparable to that of the natural aggregate (crushed granite), where 85% of the RCA consisted of a stone/mortar combination and 6% brick. The increase in RCA percentage in the concrete resulted in a decrease in OPI value and although the OPI value improved with longer curing, the mixtures containing RCA performed poorly when compared to mixtures of natural aggregates only obtaining a “good” durability classification. The OPI value increased by 33.6%, 37.6% and 38.2% between 3 and 56 days curing for the percentages 0, 50 and 100%, respectively. Olorunsogo & Padayachee (2002) established that the conglomerates of mortar and stone inherent to RCA, likely have crack and fissures in the weaker mortar. The cracks would then create pathways for the permeation of fluids in the concrete.

Kutegeza (2004) noted that four variables can be distinguished by their influence of the OPI results, namely: aggregate type, w:b ratio, curing period and binder type (Figure 3.29). A general trend developed, where the OPI value increased with a lower water:binder and an increasing wet curing period. The aggregate type affected the concrete permeability by lowering the OPI value in the case of recycled aggregates. XNA containing 50/50 Corex® slag/OPC and both fine and coarse NA had higher OPI values than the mixture comprising of 50/50 slag/OPC and both fine and coarse RCA. The CNA and CRA mixtures are similar to the mixtures previously mentioned, except for the fact that only OPC is used as a binder. Kutegeza (2004) also stated that the decrease in OPI value with mixtures containing RCA could be attributed to the porous and more permeable nature of RCA.

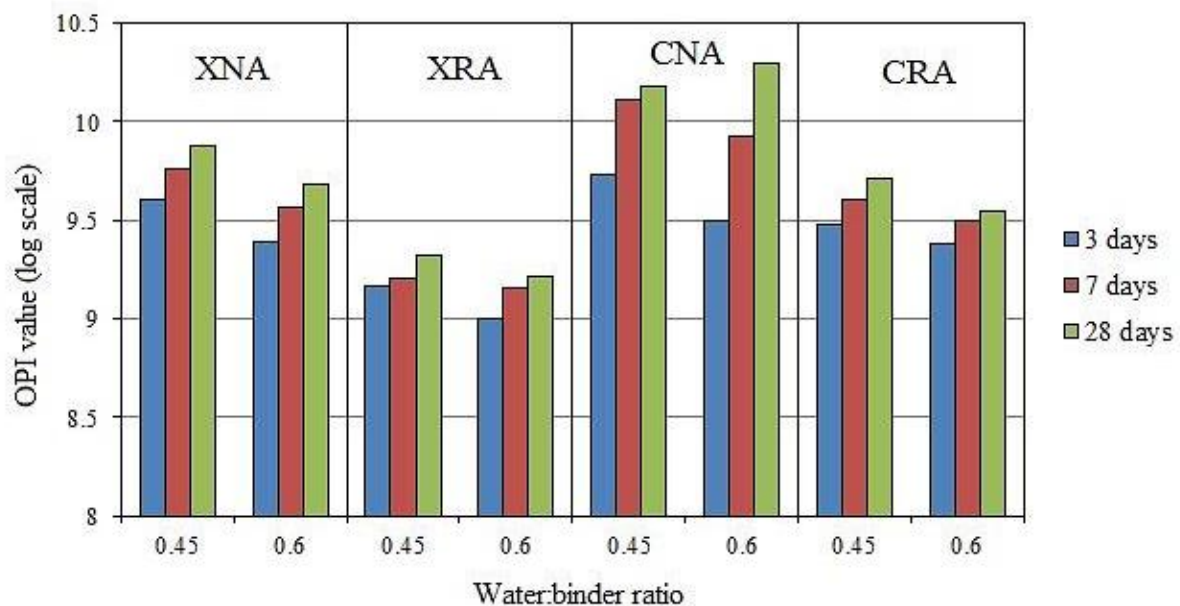


Figure 3.29 Influence of binder type, w:b ratio, aggregate type and curing period on the OPI result (adapted from Kutegeza, 2004)

The increase in OPI value, due to a low w:b ratio, can be attributed to the increase in cementitious content allowing for more products of hydration to form thus making the concrete less permeable. The effect of improved hydration is also evident with the increase in wet curing time. The binder type, in this case Corex slag, reduced the OPI value. Kutegeza (2004) noted that the inclusion of slag cement extender should improve the OPI value and the author's data contradicted the assumption. Heiyantuduwa & Alexander (2009) reported that including a particular cement extender at certain replacement amounts would result in higher OPI values as seen in Figure 3.30 and accompanying Table 3.35. Kutegeza (2004) therefore related the decrease in OPI to the possible prolonged bleeding in the fresh concrete, creating interconnected capillaries.

Table 3.35 Description of concrete mixtures used in the Heiyantuduwa & Alexander (2009) investigation

Label	Description
OPC	100% CEM I
BS	50% CEM I / 50% GGBS
CS	50% CEM I / 50% GGCS
FA	70% CEM I / 30% FA
SP	85% CEM I / 15% Superpozz (FA)
SF	93% CEM I / 7% CSF

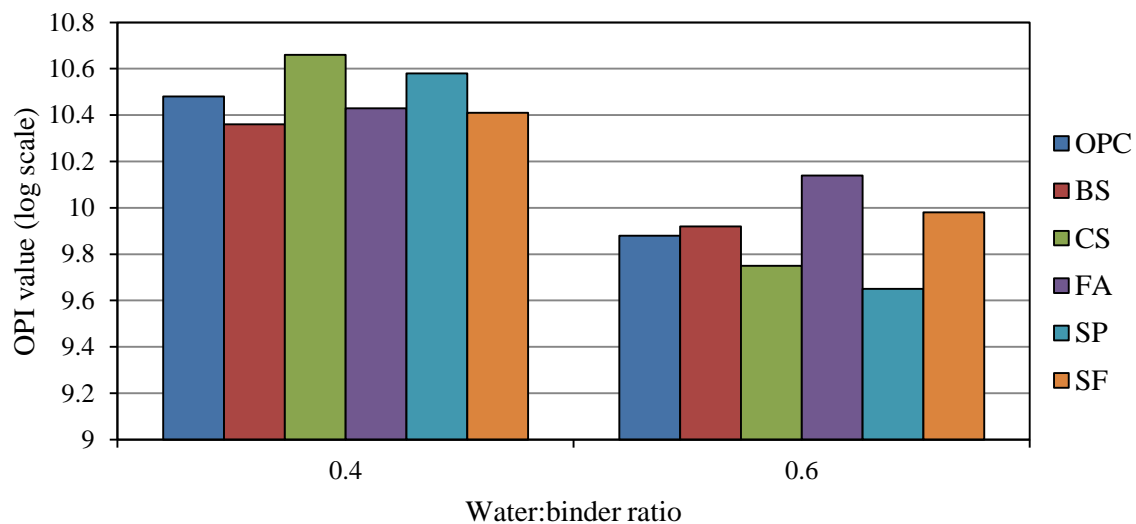


Figure 3.30 Influence of water:binder ratio and binder type on the OPI results at 28 days curing (adapted from Heiyantuduwa & Alexander, 2009)

Water Sorptivity

The absorption refers to the process by which fluid is drawn into a porous, unsaturated material through capillary suction (Alexander et al, 2009). The degree of absorption is dependent on pore size, pore distribution, saturation level on the material and to a lesser degree the absorption capability of the aggregate (except with porous aggregates) (Alexander & Mindess, 2005). Several absorption tests have been developed to measure the penetration of fluid into concrete such as the Initial Surface Absorption Test (ISAT) where water enters the top of a concrete sample (Alexander et al, 2009). Concrete samples have been saturated in water to determine the water absorption, but really only measure the porosity of the concrete and not the rate of water absorption (Alexander et al, 1999).

Alexander et al. (1999) used a modified version of Kelham's sorptivity test to determine the uni-directional rate of water absorption using specimens identical to those used in the OPI test. Circular discs (± 30 mm thick, ± 70 mm diameter) are sealed along the outer edge and placed in a few millimetres of solution, the mass of the sample is determined at regular intervals as seen in Figure 7.3. The test focuses on the rate of water absorption through the surface layer of concrete by stopping the test before complete saturation of the sample. A linear relationship between the mass of water absorbed and square root of time is observed and the sorptivity, S is determined using the slope of this relationship using Equation 7.7 (Alexander et al, 1999). The porosity is also determined by vacuum saturating the sample after testing.

Alexander & Heiyantuduwa (2002) found that the water sorptivity improved and overall durability with increased curing. Sorptivity values of 12.2, 10.7 and 8.5 were achieved for the curing periods 1, 3 and 28 days, respectively for Grade 25 concrete containing 100% coarse RCA. The effects of curing conditions was investigated by Alexander et al (1999) and determined that wet cured concrete produced sorptivity values significantly different to that of dry cured concrete. The wet cured concrete had sorptivity values lower (± 9.5 to ± 14) than that of moist and dry cured concrete (± 10.5 to ± 19.5) depending on the w:c ratio. The results showed that the hydration of concrete is important in reducing the capillary pores within the cement paste and ITZ around the aggregates. Included in the investigation was the effect of different w:c ratios on the water sorptivity on the concrete. The decrease in the w:c ratio resulted in a decrease in sorptivity of concrete confirming that a high cement content will improve durability.

The outcomes from the water sorptivity tests conducted by Olorunsogo & Padayachee (2002) are seen in Figure 3.31. Figure 3.31a shows that an increase in RCA percentage will result in an increase in the sorptivity value. The concrete mixtures cured at 3 days displayed the greatest increase in sorptivity of 47.3% from 0% RCA to 100% RCA concrete. The improved sorptivity due to longer periods of curing is also confirmed from the investigation as seen in Figure 3.31b. None of the concrete mixtures

examined in this investigation obtained “good” sorptivity standards according to Table 3.33 (Olorunsogo & Padayachee, 2002) which may be due to the fact that the natural and recycled aggregates had similar high moisture contents. The high moisture content indicates that the aggregates themselves are very porous in nature and will therefore increase the water absorption rates in concrete.

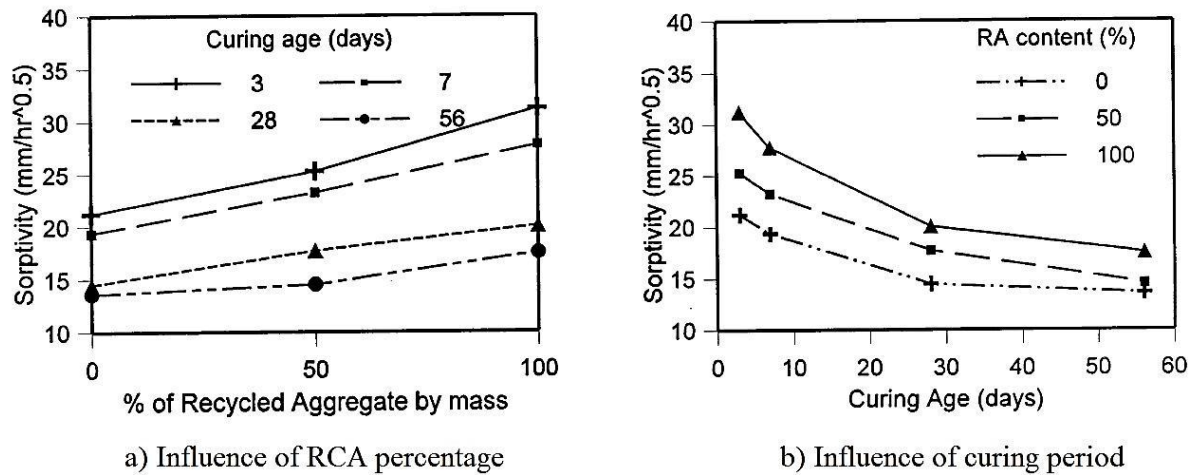


Figure 3.31 Influence of RCA percentage and curing period on water sorptivity test
(adapted from Olorunsogo & Padayachee, 2002)

Kutegeza (2004) further confirmed the influence of longer curing and lower w:b ratios as seen from the results presented in Figure 3.32. The inclusion of both fine and recycled RCA in the concrete mixtures had a detrimental effect on the durability (Kutegeza, 2004). The mixtures containing RCA had water sorptivity values about 20% to 35% higher than that of mixtures containing only NA at w:b ratios 0.45 and 0.6, respectively (Kutegeza, 2004). The porosity of the concrete mixture is given in Figure 3.33 and from this it can be seen that the RCA mixtures had approximately double the porosity compared to the NA mixtures, which was attributed to the porous nature of the RCA and constituents (Kutegeza, 2004).

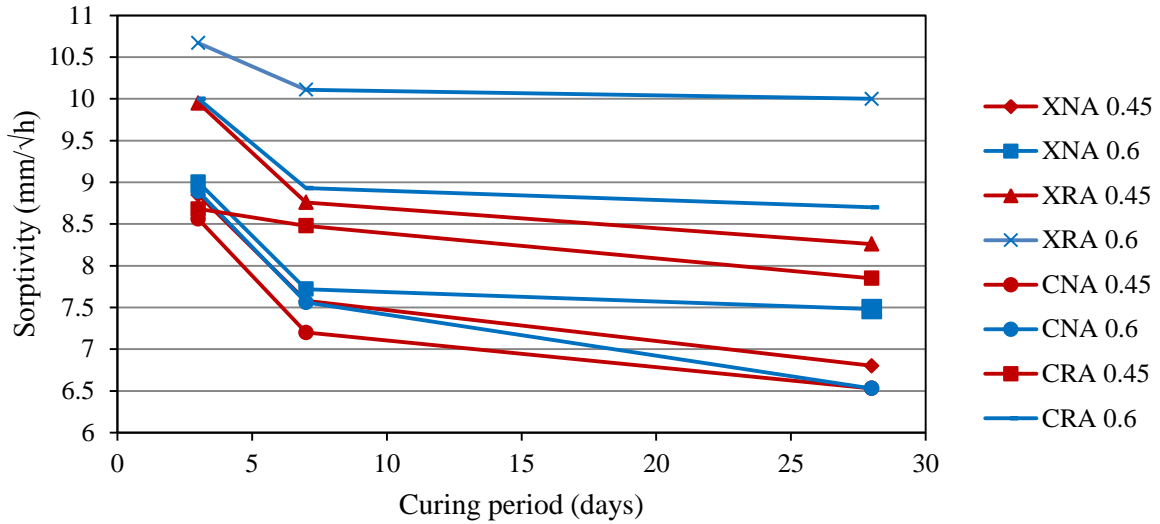


Figure 3.32 Influence of binder type, water:binder ratio, aggregate type and curing period on the water sorptivity result (adapted from Kutegeza, 2004)

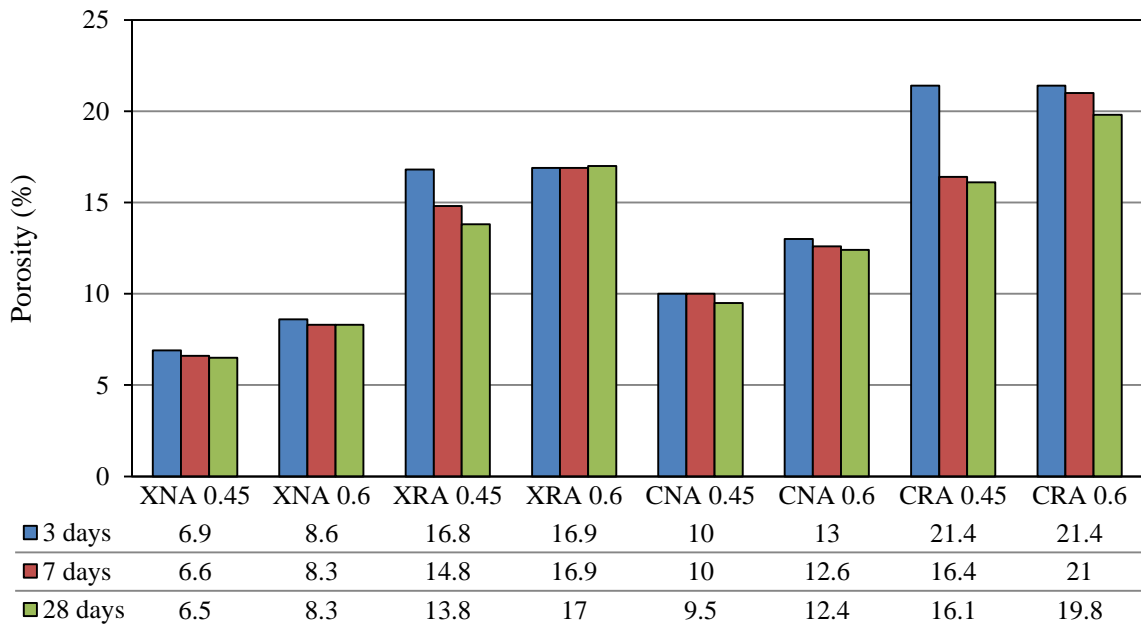


Figure 3.33 Influence of binder type, w:b ratio, aggregate type and curing period on the porosity (adapted from Kutegeza, 2004)

The mixtures containing Corex® slag had higher sorptivity values than mixtures containing only CEM I 42.5 cement, even though the latter had a higher porosity in both the NA and RCA mixtures. Kutegeza (2004) determined that the effects of bleeding influenced the outcome which contradicted the research of some authors. The inclusion of cement extenders improved the water sorptivity in the concrete mixtures investigated by Heiyantuduwa & Alexander (2009). Figure 3.34 displays the results from the investigation and from this it is evident that the addition of a cement extender will improve the water sorptivity aspect of durability in concrete. Alexander et al (2003) stated that concrete containing slag requires good curing conditions or a poor surface layer will be produced that allows for easy penetration of water and harmful agents.

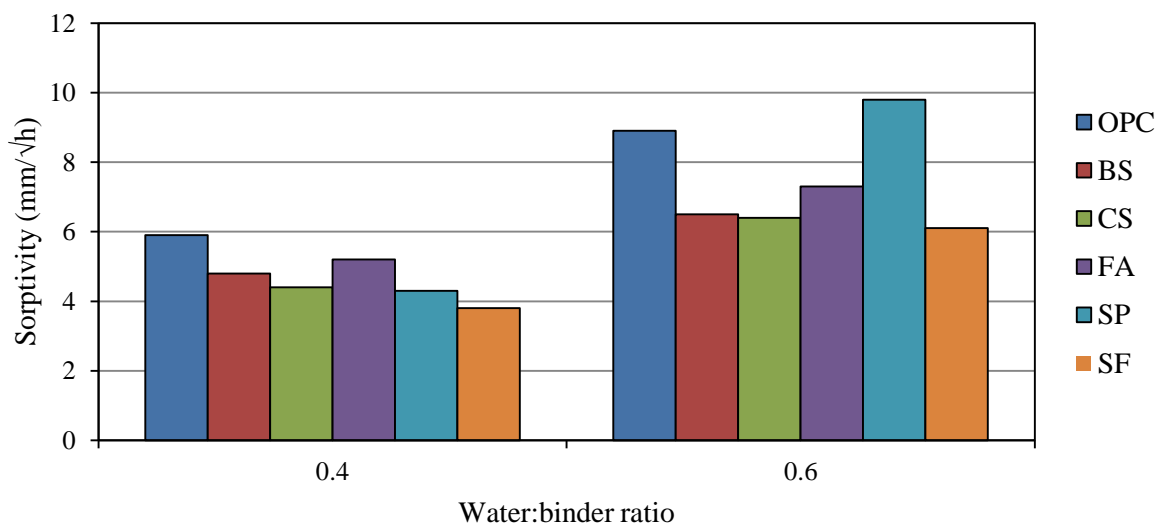


Figure 3.34 Influence of w:b ratio and binder type on the water sorptivity results at 28 days curing (adapted from Heiyantuduwa & Alexander, 2009)

Chloride Conductivity

Diffusion or conduction is the process by which liquids, gases or ions move through the pore structures within concrete under the action of a concentration gradient (Alexander et al, 1999). In the case of conduction the movement of ions is caused by an electrical potential differential (Alexander & Mindess, 2005). The Nernst-Planck equation is the governing expression for the conduction of ions across a material, is given by Equation 3.10 (Alexander & Mindess, 2005).

$$J = \frac{ZF}{RT} \cdot DC \cdot \frac{dE}{dx} \quad [Eq. 3.10]$$

where D is the diffusion coefficient (m^2/s)

C is the concentration (g/m^3)

Z is the electrical charge

F is the Faraday constant ($\text{J}/\text{V}\cdot\text{mol}$)

R is the gas constant ($\text{J}/\text{mol}\cdot\text{K}$)

T is the absolute temperature (K)

dE/dx is the gradient of the electrical field (V/m)

The moisture state of the concrete is an important factor, as conduction of ions is transported through the partially or fully saturated porous material by fluids. The binder type, binder content and hydration of cement have the greatest influence on the conduction potential in concrete due to the binder chemistry (Alexander & Mindess, 2005). The aggregates and other constituents are less significant in terms of conduction ability, unless the concentrations of ions such as chlorides are high and the pore structure (ITZ) surrounding the aggregate is increased (Alexander & Mindess, 2005).

The rapid chloride conductivity test was developed by Steicher (1995) at UCT, where a current (ionic flux) arises by conduction due to a 10V potential difference across a concrete specimen identical to that used in the OPI and water sorptivity tests (Alexander et al, 1999). The concrete specimens are pre-saturated in sodium chloride (5M NaCl) solution and the apparatus used to apply voltage and measure the current across the specimen is seen in Figure 7.4. The chloride conductivity decreases with the addition of cement extenders, longer curing periods, lower w:b ratio and higher binder content (Alexander et al, 1999).

Olorunsogo & Padayachee (2002) found that the chloride conductivity increased with increasing RCA percentage replacement and decreased with longer curing periods (Figure 3.35). At a curing age of 28 days, the concrete mix that contained 100% RCA showed a 73.2% increase in chloride conductivity compared to the mixture containing 0% RCA (Olorunsogo & Padayachee, 2002). The concrete mixture of 100% RCA had a 59.2% decrease in chloride conductivity between 3 and 56 days curing, while the 100% NA mixture showed a 69.0% decrease in chloride conductivity over the same period (Olorunsogo & Padayachee, 2002). The 100% NA mixture obtained a “good” classification according to Table 3.33 with a value of 1.48 mS/cm, while the mixture of 50% and 100% RCA obtained “poor” to “very poor” results.

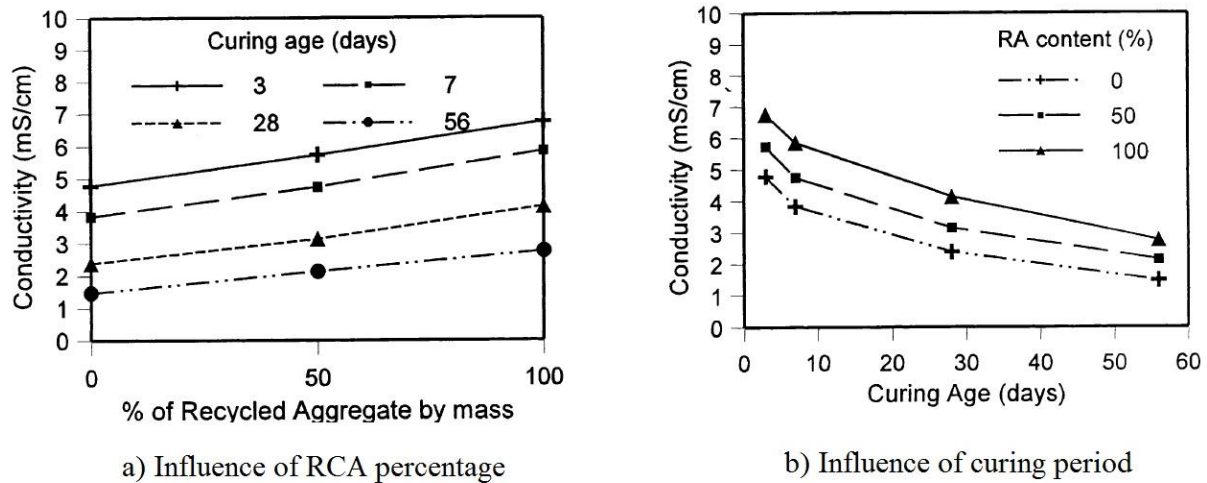


Figure 3.35 Influence of RCA percentage and curing period on chloride conductivity test
 (adapted from Olorunsogo & Padayachee, 2002)

Kutegeza (2004) found similar results for the chloride conductivity test, where the RCA mixtures had higher conductivity than the mixtures containing NA. The inclusion of Corex® slag had a significant effect on the chloride conductivity when used at a certain w:b ratio (Figure 3.36). The RCA mixtures had a chloride conductivity of about 50% and 100% higher than NA mixtures made with CEM I and slag respectively (Kutegeza, 2004). Alexander et al. (2003) noted that the chloride resistance would improve with the inclusion of cement extender such as Corex® slag because of the increased chloride binding by aluminate phases contained in materials such as fly ash and slag. The slag cement extenders should be included at 50% or more for effective chloride resistance to be achieved (Alexander et al, 2003).

Alexander et al. (2009) stated that chloride conductivity test is capable of identifying the difference in w:b ratio, binder type and curing conditions on a statistically significant level and the results correlate well with other test methods for chloride resistance. The increase in the binder content and lower w:b ratio would decrease the volume of pore structures in concrete due to the continued formation of hydration products (Kutegeza, 2004). The lower volume of pores would therefore reduce the available space for saturation of pores and movement of ions.

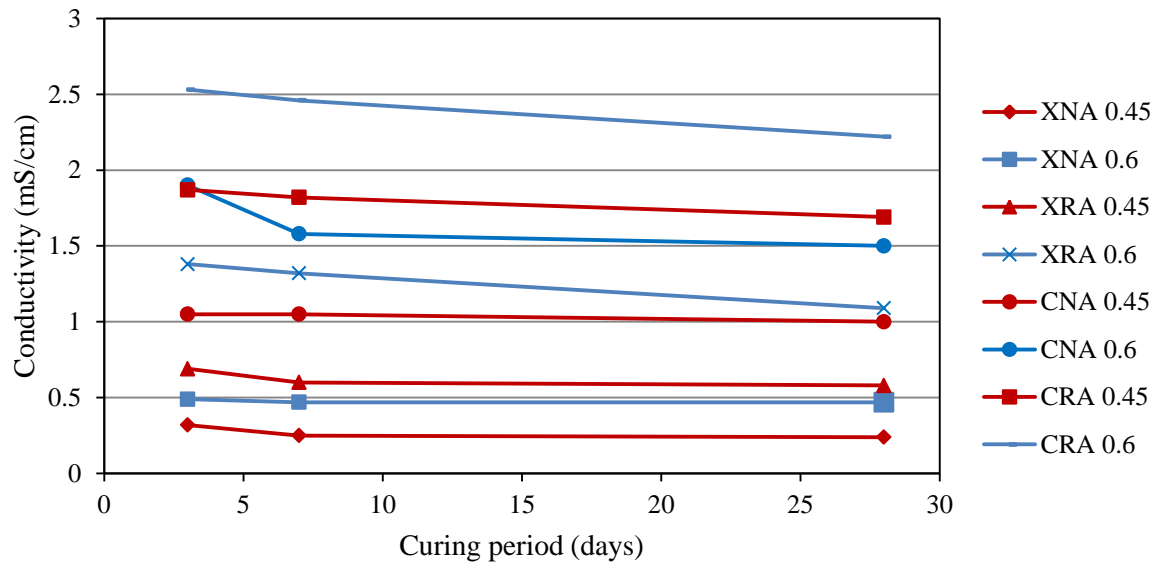


Figure 3.36 Influence of binder type, w:b ratio, aggregate type and curing period on the chloride conductivity result (adapted from Kutegeza, 2004)

3.3.3 Dimensional stability properties

The dimensional or deformation properties of hardened concrete can be defined by short-term (elastic) and long-term (shrinkage and creep) deformations (Alexander & Mindess, 2005). The dimensions of concrete elements within a structure do not remain constant, however small these changes, the effects thereof are critical in the overall structure (Addis, 2008). The serviceability of the structure is affected due to the deflections and cracking caused by dimensional changes (Alexander & Beushausen, 2009). The deformation of concrete may occur due to two external factors, namely applied loading or stress and environment conditions. The short-term deformations are generally as a result of the loading conditions, while the long-term deformations are influenced by both factors. The shrinkage of concrete is for the most part only affected by environmental conditions, whereas creep is a result of both environmental conditions and applied loading. The deformation changes may be almost completely reversible in the case of elastic deformation, but partially reversible for the cases of shrinkage and creep. In examining the deformations of concrete, the three phases of the material: bulk cement paste, aggregate and ITZ are discussed for their influences. Each of these phases is affected by the constituents of the concrete, curing period and age of concrete and the dimensions of concrete. Each of the deformations cases are discussed separately with reference to investigations including RCA.

Modulus of elasticity

Concrete is considered a nonlinear material and the modulus of elasticity (E) or stiffness of concrete is measured in the elastic region between the applied stress and instantaneous strain (Mehta & Monteiro, 2006). Alexander & Beushausen (2009) explain that the non-linear stress strain behaviour within concrete is due to reactions between the cement paste and ITZ and micro-cracking. The relationship between the stress and strain is not perfectly elastic or linear, but for simplification a linear estimation is sufficient and is given by Equation 3.11 also known as the Young's modulus. The stress-strain relationship is the basis for most computations in determining design stress, moments and deflections when utilising concrete in structural elements (Mehta & Monteiro, 2006).

$$E = \frac{\sigma}{\varepsilon} \quad [Eq. 3.11]$$

where E = Young's modulus or modulus of elasticity

σ = stress defined by the applied force over cross sectional area of loading (P/A)

ε = strain defined by the change in length over the original length ($\Delta L/L$)

The factors which influence the elastic modulus include the moisture condition of the concrete, the aggregate, concrete age, curing conditions, loading rate and strength of the concrete. Domone & Illston (2008) explain that the elastic modulus increases with the age and strength of the concrete (lower w:b ratio) and water saturated cement paste has a slightly higher modulus of elasticity than dry cement paste. Addis (2008) and Alexander et al. (2009) note that the relative volumes of cement paste and aggregates play significant roles in the stiffness. The aggregate is much stiffer than the cement paste and combined with the concrete has a stiffness greater than the cement paste but less than the aggregate (Figure 3.37). The higher the aggregate stiffness and aggregate content, the higher concrete stiffness (Addis, 2008 & Alexander & Mindess, 2005).

As with the strength of hardened concrete, the ITZ interface has a pronounced influence on the concrete stiffness. The ITZ is influenced by both the aggregate and cement paste phases. The aggregate within the concrete influences the ITZ through its properties such as, size, shape, surface texture, grading and mineral composition (Mehta & Monteiro, 2006). The thinner, denser and stronger the ITZ, the greater the concrete stiffness due to the reduced capillary voids and microcracks (Mehta & Monteiro, 2006 and Addis, 2008). Controlling the variables (Table 3.26) which influence the strength of hardened concrete will therefore result in an improved concrete stiffness.

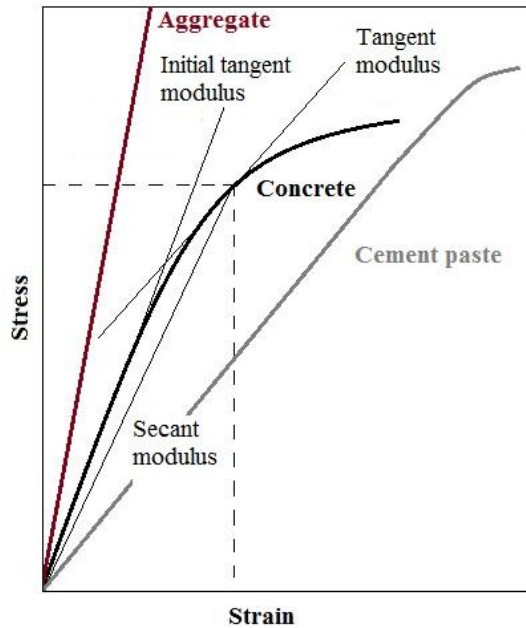


Figure 3.37 Stress-strain diagrams for aggregate, concrete and cement paste and three forms of elastic modulus (adapted from Alexander & Beushausen (2009) and Addis (2008))

Three types of elastic moduli can be determined from the stress-strain relationship of concrete: secant modulus, chord modulus, tangent modulus and a additional initial tangent modulus (Figure 3.37) (Metha & Monteiro, 2006). Typically 30 to 40% of the ultimate (failure) load is used in determining the different elastic moduli. The secant modulus is calculated as the slope of the line passing through the origin to the 30-40% load. The tangent modulus is given by the slope of a line tangent to any point along the stress-strain curve. The initial tangent modulus is determined as the slope from a very small instantaneous strain and the line drawn from the origin. The chord modulus is the slope of a line drawn through the point of the 30 to 40% load and a point corresponding to a 50 microstrain (Mehta & Monteiro, 2006). According to Metha & Monteiro (2006) the chord modulus corrects the slight initial concavity at the start of the stress-strain curve.

Xiao et al. (2005) calculated the elastic modulus using the chord modulus method for the concrete mixtures from Section 3.3.1. The elastic modulus decreased with increasing RCA replacement percentage indicated by Figure 3.38. The concrete mixture containing 100% RCA had a 45% lower elastic modulus than the 100% NA concrete mixture and noted that aggregate stiffness was the influencing factor. Xiao et al. (2005) concluded by noting that the commonly used relationships between compressive strength and modulus of elasticity for normal concrete was not applicable when using RCA. Pani et al. (2011) similarly found a decrease of elastic modulus in concrete containing increasing amounts of RCA. The elastic modulus in this investigation only decreased by 11% at 100% RCA replacement. At 20% and 50% replacement the elastic modulus was similar to that of the control mixture.

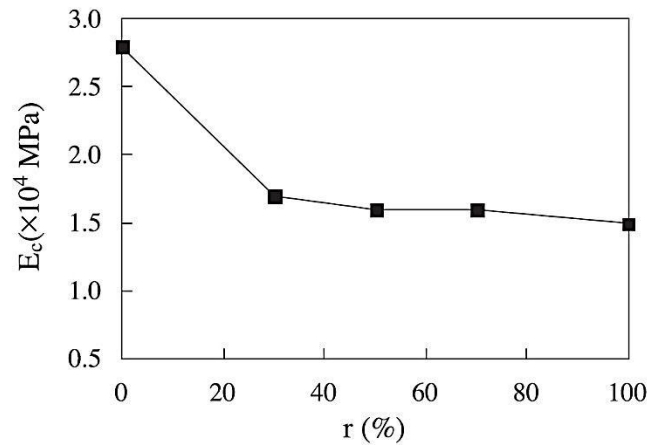


Figure 3.38 Modulus of elasticity results at different RCA percentages in concrete (Xiao et al, 2005)

The elastic moduli from concrete prisms for the mixtures, investigated by Kutegeza (2004), are shown in Figure 3.39. The elastic modulus improved only slightly with a longer curing period and the decrease in water:binder ratio resulted in lower elastic moduli for all the mixtures. Kutegeza (2004) reported that the mixtures containing RCA had about a 20 to 25% decrease in elastic modulus when compared to the mixtures containing NA. The mixtures containing Corex® slag had higher elastic moduli than the mixtures containing CEM I 42.5 in all the NA concrete mixtures, however rather insignificantly. Alexander et al. (2003) noted that the aggregate plays a greater role than the binder type even when a cement extender such as slag is used.

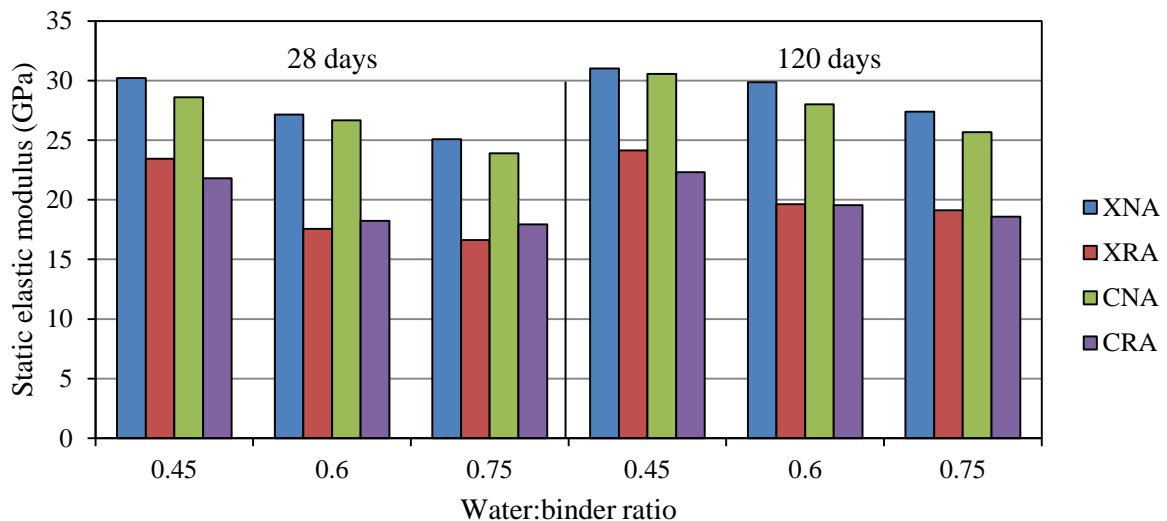


Figure 3.39 Modulus of elasticity results for concrete mixture with different w:b ratios and ages (adapted from Kutegeza (2004))

Chandra Paul (2011) investigated the influence of RCA replacement at 30 and 100% and found that the modulus of elasticity decreased at 100% replacement. Table 3.36 shows the results from the concrete mixtures examined in the investigation. The mixtures containing 30% RCA had a marginally higher elastic modulus than the mixtures containing 100% NA. The inclusion of slag (Step 4) resulted in a higher compressive strength, but a lower elastic modulus compared to mixtures containing only OPC (Chandra Paul, 2011). The modulus of elasticity increased with longer curing and the 30% RCA and 100% mixtures showed no significant difference at the different curing periods, while the 100% RCA had a lower elastic modulus at each curing period.

Table 3.36 Elastic modulus results for the different RCA samples and concrete mixtures (adapted from Chandra Paul (2011))

Step 1			Step 2		
Mixture	$f_{k,cy}$ (MPa)	E_k (GPa)	Mixture	$f_{k,cy}$ (MPa)	E_k (GPa)
NCA100	27.2	35.0	NCA100	30.2	31.7
RCA30	26.4	34.0	RCA30	27.3	32.2
RCA100	26.7	29.9	RCA100	26.5	23.4

Step 3			Step 4		
Mixture	$f_{k,cy}$ (MPa)	E_k (GPa)	Mixture	$f_{k,cy}$ (MPa)	E_k (GPa)
NCA100	30.2	31.7	NCA100	34.1	28.6
RCA30	28.2	34.6	RCA30	33.9	32.0
RCA100	28.3	28.1	RCA100	32.4	25.8

Oliveira et al. (2004) considered the effects of percentage replacement on the water absorption, compressive strength and modulus of elasticity. Aggregate and concrete blends of the RCA percentages: 0, 10, 20, 30, 40 and 100% were examined for the properties stated above. Both the aggregate and concrete had increasing water absorption with increasing RCA replacement with the former having 0.9 to 10.2% water absorption and the latter 5.5 to 14.2% water absorption. The concrete mixtures were designed so that the strength of the concrete would be equal for all the mixtures by adjusting the w:c ratio and cement content. The concrete mixtures' compression strengths were all 27 MPa as a result of the mix design. The elastic moduli for the 0%, 10% and 20% concrete mixtures were 40 GPa, the 30% and 40% mixtures had an elastic modulus of 38 GPa and the 100% RCA mixture had an elastic modulus of 33 GPa. Oliveira et al. (2004) concluded that the higher water absorption and lower specific gravity of the aggregate were related to the lower elastic modulus and compressive strength.

Gómez-Soberón (2002) investigated the shrinkage of concrete with RCA percentage replacement. Included in the study were the concrete properties of compressive strength and Young's modulus. Table 3.37 shows the results from the concrete mixtures at 7, 28, 90 and 180 days and the original concrete (OC) properties were also examined at these ages. The strength of the concrete improved significantly with increasing age, while the elastic modulus only increased marginally. The effects of water absorption were accounted for by adding additional mixing water for each concrete mixture. The compression strength at 28 days was 11.5% lower in the 100% RCA mixture than the control mixture (0% RCA) and the modulus of elasticity was 9.1% lower for this case. The margin of difference between the 0% and 100% RCA mixtures increased with age for compression strength of modulus of elasticity, owing to the possible improved ITZ in the control mixture.

Table 3.37 The compressive strength and elastic modulus results at different concrete ages adapted from Gómez-Soberón (2002)

Mixture	Compressive Strength				Young's modulus			
	Age	7	28	90	180	7	28	90
0%	33.3	39	42.1	47	27.6	29.7	32.4	32.9
15%	33.9	38.1	41.6	46.6	27.2	29.1	30.1	30.8
30%	34.8	37	39.5	44.1	26.5	27.8	29.4	29.9
60%	30.6	35.8	38.3	44.1	25.5	26.6	27.6	27
100%	30.7	34.5	37.5	43	26.9	26.7	26.4	26.5
OC	35.2	38.4		45.1*	33	33.7	-	35.2*

* 173 days

Shrinkage

The shrinkage of concrete occurs both in the fresh and hardened states for the most part through the loss of moisture due to environmental conditions. This shrinkage is usually defined as drying shrinkage and is a long-term dependent deformation (Alexander & Mindess, 2005). There are other types of shrinkage which contribute along with the drying shrinkage to the total shrinkage. These include autogenous shrinkage and carbonation shrinkage.

Autogenous shrinkage (basic shrinkage) occurs due to the continued hydration of cementitious material in the presence of moisture (Domone & Illston, 2008). The concrete will swell initially because of the production of hydration products and shrink once water is removed from surrounding capillary pores to continue the hydration process (Domone & Illston, 2008). Autogenous shrinkage is determined by preventing the loss of moisture to the external environment. In normal concrete the changes are small compared to the other shrinkage mechanisms (Alexander & Beushausen, 2009).

Carbonation shrinkage is a chemical reaction between CO_2 and constituents (especially $\text{Ca}(\text{OH})_2$) of the hardened cement paste and does not occur from a loss of water (Domone & Illston, 2008). The rate of carbonation shrinkage is dependent on the relative humidity, where carbonation is reduced at either higher or lower humidities (Alexander & Beushausen, 2009). High carbonation shrinkage occurs at 50% relative humidity as the pores are slightly saturated allowing for the reaction to take place and CO_2 to move into the open pores (Domone & Illston, 2008).

With normal strength concrete ($w:c > 0.4$) the total measured shrinkage is generally as a result of drying shrinkage (Alexander & Beushausen, 2009). The shrinkage of concrete contributes to the total deformation of a structural element and the consequences may affect the dimensional stability, structural integrity and durability of that element. Most structural members are restrained in some form (friction & connections) and shrinkage of these members may result in cracking due to tension forces, widening of joints between members, differential movement between other materials (e.g. tiles or facades) and deflections in flexural members to different levels of reinforcement (Addis, 2008).

The source of shrinkage in concrete is largely influenced by the hardened cement paste content (Addis, 2008 and Alexander & Beushausen, 2009). The inclusion of more aggregate in concrete results in a lower shrinkage (Figure 3.40) as the aggregates are more dimensionally stable and the cement paste volume is reduced (Alexander & Mindess, 2005). Normal density aggregates are stiffer than lightweight aggregates and therefore provide more dimensional restraint (Domone and Illston, 2008). Aggregate water requirements together with the $w:b$ ratio determine the amount of mixing water needed and this will control aggregate and paste content (Alexander and Mindess, 2005). The shrinkage in concrete will therefore be lower with aggregates which require less water i.e. lower water absorption.

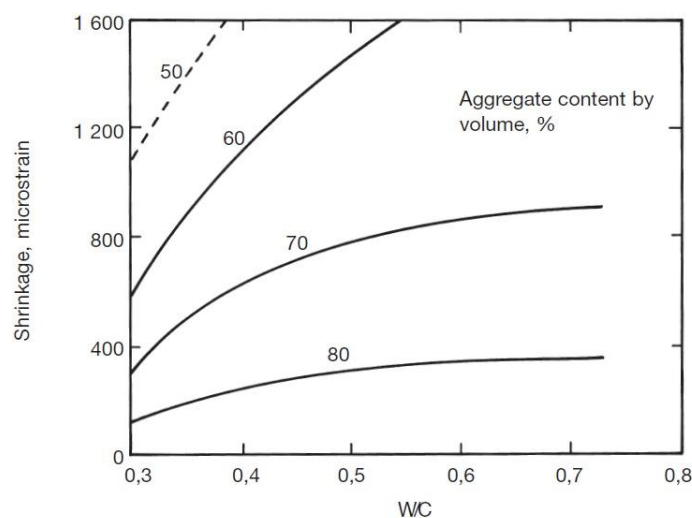


Figure 3.40 The relationship between aggregate volume, w/c ratio and shrinkage strain (Alexander & Beushausen, 2009)

The size of the concrete member plays a significant role in the shrinkage mechanism, where slender members (high surface-area-to-volume ratios) shrink more so than bulky members because of increased moisture loss (Addis, 2008). The environment and time influences the degree of shrinkage due to differential conditions between the concrete and external environmental conditions. Low relative humidity and high temperature will result in a higher degree of shrinkage than in conditions with higher humidity and lower temperature. The shrinkage of concrete due to environmental conditions is time-dependent, where the rate of shrinkage decreases with time (Alexander & Beushausen, 2009). The effect of a longer curing period in normal concrete has a minor effect on the shrinkage and is not an important factor to consider (Alexander & Beushausen, 2009).

The tests measuring the shrinkage of a concrete specimen are usually examined at temperatures of 20 to 23°C and 50% relative humidity (RH) for mild conditions (ASTM C 157-06 & RILEM: CPC 9 (1975)). These tests are conducted by measuring the linear (one-dimensional) contraction of a prismatic specimen with time (Alexander & Beushausen, 2009). Alexander & Beushausen (2009) describe the measurement direction of the specimen as relatively long and perpendicular to the moisture movement, and the potential free shrinkage of the cross section is not comprehended because of the continuity of the section. Alexander & Beushausen (2009) further explain that the plane sections remain plane and the strain measured is actually a composite consisting of elastic, shrinkage and creep strains.

The inclusion of RCA has been reported to increase the shrinkage of concrete when compared to concrete made with natural aggregates. Alexander & Heiyantuduwa (2002) reported the RCA at 100% replacement resulted in a shrinkage of 420 microstrain and 800 microstrain examined at a temperature of 22°C and 65 ±5% humidity and 50°C and 20 ±5% humidity, respectively. The shrinkage was considered substantially higher than concrete made with natural greywacke aggregate (Alexander & Heiyantuduwa, 2002). The higher shrinkage was assumed to be attributed to the lower aggregate stiffness and higher porosity. Sagoe-Crentsil et al. (2001) reported a 35% higher shrinkage with concrete containing RCA and slag cement replacement, and a 15% increase in shrinkage strain with concrete comprising of RCA and OPC.

Domingo et al. (2010) also found that the shrinkage strain was 70% higher in concrete containing 100% RCA and 20% higher at 50% aggregate replacement (Figure 3.41). Interestingly Figure 3.41 shows that the increase in relative humidity caused the shrinkage to reduce. The adhered mortar resulted in an increase in overall cement paste and in the presence of a humidity gradient and high porosity, the loss of water increased similarly (Domingo et al, 2010).

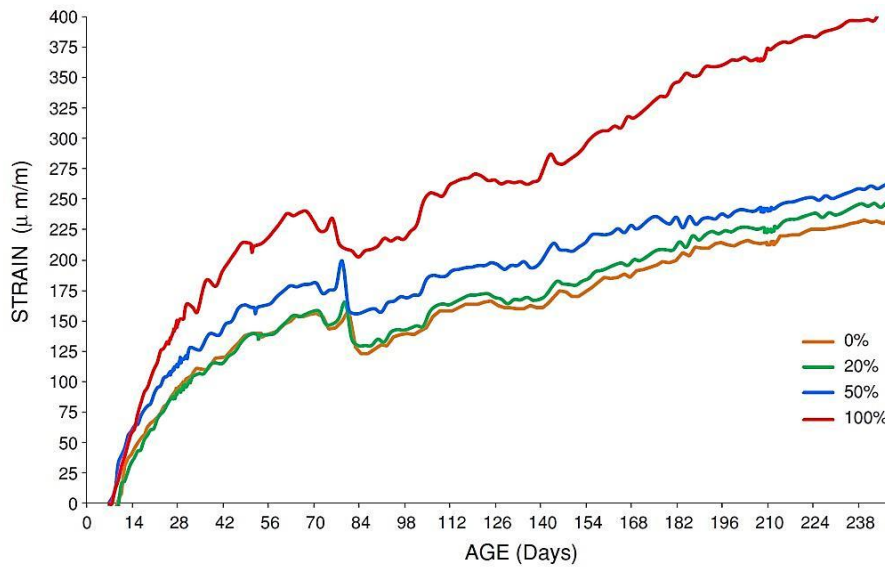


Figure 3.41 The shrinkage strains for concrete mixtures containing varied percentages of RCA (Domingo et al, 2010)

The concrete mixtures containing both fine and coarse RCA in the investigation by Kutegeza (2004) had higher drying shrinkage and lower autogenous shrinkage than the mixtures containing natural aggregates. The RCA mixture consisting of only OPC (CRA) had the highest drying shrinkage while the mixtures containing slag were marginally higher than the control mixtures (Figure 3.42b). Kutegeza (2004) stated that the slag mixtures may have had a lower shrinkage because of decreased porosity and capillary pores. The autogenous shrinkage was lower than the drying shrinkage and the retained moisture in the RCA could have contributed to the resulting shrinkage values (Kutegeza, 2004). Figure 3.42a shows that slag control mixture (XNA) had the highest shrinkage and slag 30% coarse RCA mixture (XRF) had the lowest autogenous shrinkage.

Chandra Paul (2011) reported that replacing 30% of the natural aggregate with coarse RCA would result in no significant difference in shrinkage rates. The 100% NAC had a final shrinkage strain of 822 $\mu\text{m/m}$ after 90 days and the 30% RAC had a drying shrinkage strain of 839 $\mu\text{m/m}$. The measured shrinkage values had a high coefficient of variation at an early age, but measurements had less variation with increasing age. Chandra Paul (2011) noted that almost 30% of the total 90 day shrinkage was recorded within the first six hours of testing. The RCA used in this investigation had much higher water absorption percentages than the natural aggregate. The aggregate was conditioned to an SSD state before mixing and the retained water may have improved the shrinkage rates.

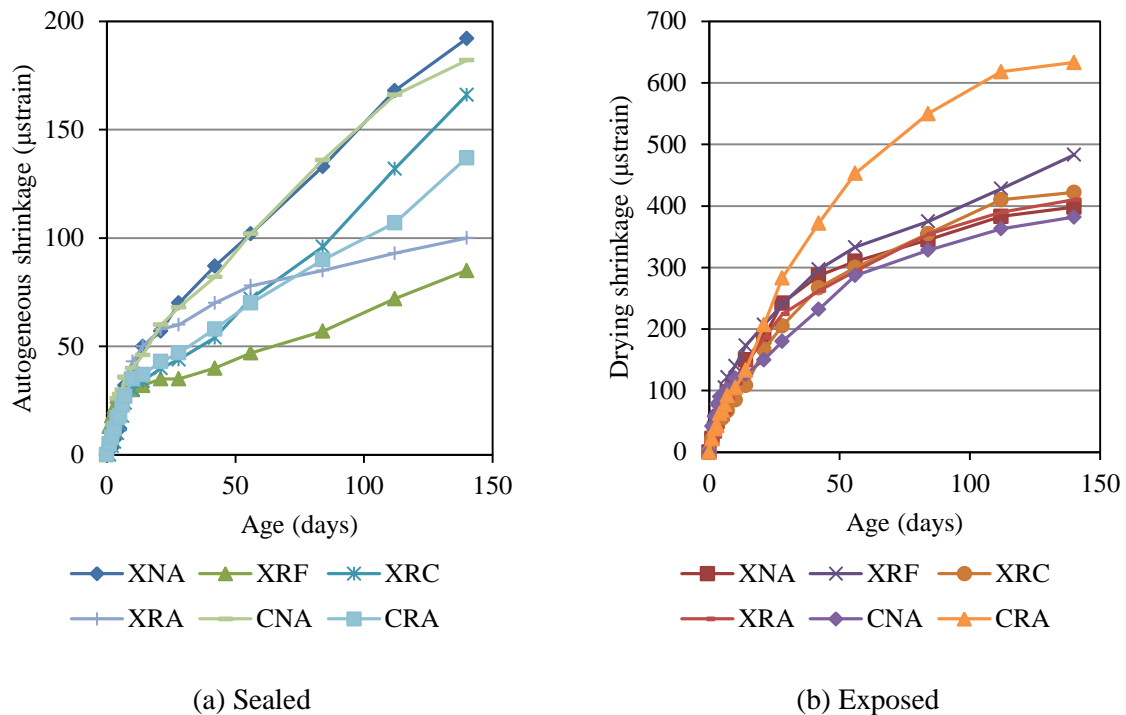


Figure 3.42 Autogeneous and drying shrinkage strains for concrete mixtures with $w:b = 0.6$
(adapted from Kutegeza, 2004)

The shrinkage of concrete with replacement of aggregate with RCA was investigated by Gómez-Soberón (2002). The test was conducted with concrete cylinders ($\phi 150\text{mm} \times 450\text{mm}$), cured for 28 days and placed in a climate chamber at 20°C and 50% relative humidity. Specimens were completely sealed to measure autogeneous (basic) shrinkage while the specimens were left exposed and were used to measure the total shrinkage. Table 3.38 contains the calculated values for the three different types of shrinkage investigated. The basic shrinkage for the mixtures of 30% and less resulted in negative (expansive) shrinkage, while the mixtures with higher than 30% replacement had positive basic shrinkage. The drying shrinkage was higher in the 60 and 100% RCA mixtures, while drying shrinkage of mixtures below and including 30% had similar shrinkage strains at 270 days.

The concrete mixtures containing the RCA from the original concrete (OC) had considerably higher total shrinkage rates due to high porosity and permeability of the RCA (Gómez-Soberón, 2002). The rate of shrinkage decreased with increasing age as seen in Figure 3.43. Gómez-Soberón (2002) concludes by stating that including less than 30% of RCA in concrete mixtures will result in reliable concrete.

Table 3.38 Various shrinkage strains measured at different ages (adapted from Gómez-Soberón, 2002)

Strain (mm/m)	$\epsilon_{sh \text{ basic}}$	$\epsilon_{sh \text{ total}}$	$\epsilon_{sh \text{ drying}}$	$\epsilon_{sh \text{ basic}}$	$\epsilon_{sh \text{ total}}$	$\epsilon_{sh \text{ drying}}$
Mixture\Age	28 days			270 days		
100%	0.01	0.2411	0.2401	0.04	0.528	0.488
60%	-0.0283	0.2231	0.2514	0.056	0.537	0.481
30%	-0.0017	0.2307	0.2324	-0.003	0.422	0.425
15%	-0.012	0.2367	0.2487	-0.002	0.441	0.443
0%	-0.019	0.206	0.225	-0.016	0.429	0.445
OC (2*)	-0.017	0.0771	0.0941	-0.043	0.2041	0.2471

(2*) 193 and 435 days

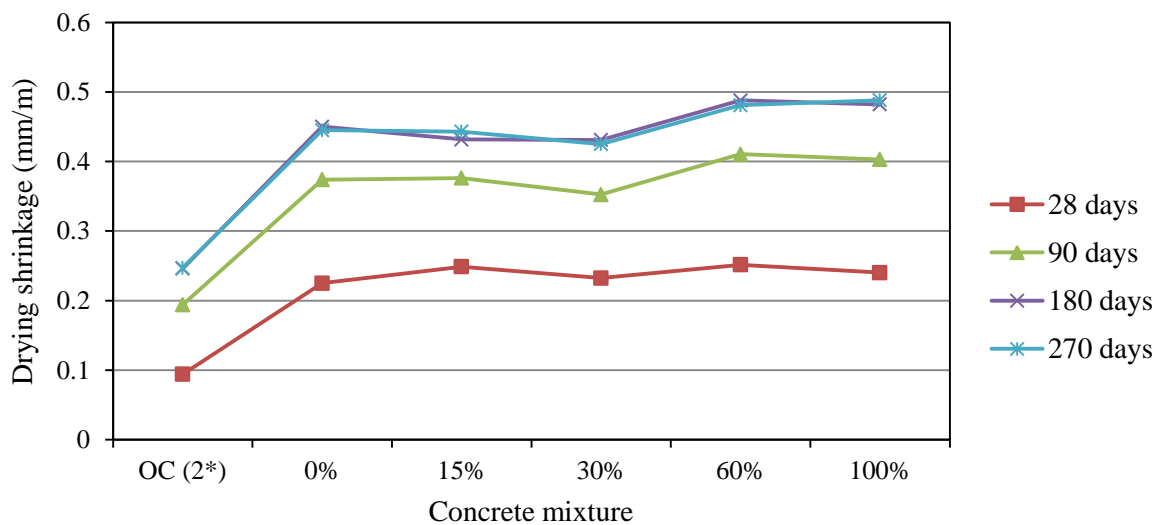


Figure 3.43 The drying shrinkage strains at different ages for various percentages of RCA (adapted from Gómez-Soberón, 2002)

Creep

Creep of concrete is defined as the time-dependent increase in strain due to a constant or controlled stress (Alexander and Beushausen, 2009). The magnitude of creep strains can be several times higher than the initial (elastic) strain on loading (Domone & Illston, 2008). Creep and shrinkage are interdependent and originate from the same source, the bulk cement paste. The total strain of concrete under loading consists of elastic strain (ϵ_{st}), drying shrinkage strain (ϵ_{sh}), basic creep strain (ϵ_{bc}) and drying creep strain (ϵ_{dc}) (Figure 3.44) (Domone & Illston, 2008). The creep strain (ϵ_{cr}) is a combination of basic creep and drying creep strain. Creep strain occurs at all stress levels and upon removal of the applied stress the strain may become permanent or reversible (Addis, 2008).

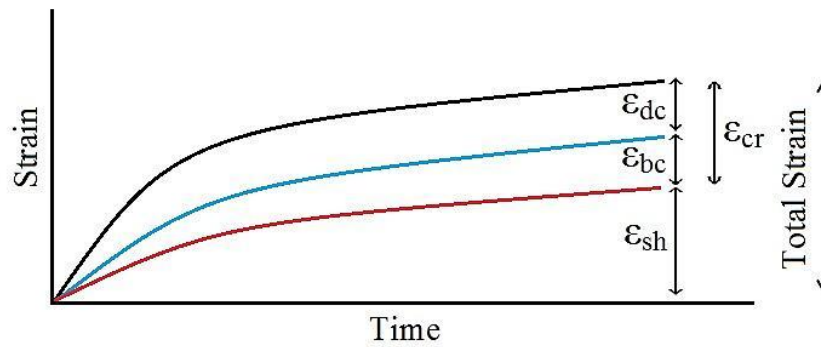


Figure 3.44 Different components of the total strain (excluding elastic strain) measured in concrete (adapted from Domone & Illston, 2008)

The factors which influence the drying shrinkage of concrete, usually influence creep in the same manner (Mehta & Monteiro, 2006). The creep of concrete is reduced if the moisture content is reduced before loading and the creep for concrete with w:c ratios 0.4 to 0.6, increases linearly with the applied stress increase (Domone & Illston, 2008). This may be defined as the specific creep with the units of creep strain per unit stress ($\mu\text{m}/\text{MPa}$). Creep decreases with increasing concrete strength and with the reduction of bulk cement paste through the inclusion of increasing aggregate volume (Addis, 2008). External factors influence the creep of concrete in the same manner as the drying shrinkage, with an additional factor due to loading. The creep strain of concrete is influenced by the applied stress to strength of concrete ratio, curing, age at loading, duration of loading and type loading (Alexander & Beushausen, 2009). At higher applied stresses creep increases due to change in internal stresses resulting in the movement of moisture from smaller to larger pores (Alexander & Beushausen, 2009 and Domone & Illston, 2008). Strength increases with an increase in curing period and age of the concrete and therefore decreases the creep (Alexander & Beushausen, 2009). The mechanism of creep will continue over a long period, possibly indefinitely, and it is difficult to determine the amount of creep deformation within a period of time (Addis, 2008). The applied stress may be in the form of compression, tension, flexure and dynamic loading and minimal work has been done to investigate the effects under different loading conditions (Alexander & Beushausen, 2009).

No test standard for creep exists in South Africa however numerous types of creep testing apparatus have been designed, based on the principles of mechanical or hydraulic loading. For the most part tests are conducted by applying a load of 30 to 40% of the ultimate strength to either prisms or cylinders of concrete (ASTM C512-02) and 20% of the ultimate load according to RILEM CPC-12.

Domingo et al. (2010) also investigated the influence of RCA percentage replacement on the creep deformation. Creep deformations were calculated by subtracting the deformation due to shrinkage and elastic deformations from the total deformation. The creep deformation increased with increasing replacement percentage (Figure 3.45). The creep deformation was 35%, 42% and 51% higher in RCA mixtures, 20%, 50% and 100% replacement, respectively when compared to the control mixture (Domingo et al, 2010). The creep coefficient was determined in the investigation, but did not allow for reflective comparison between the mixtures. Different loads were applied to the different specimens according to strength to maintain the 35% applied load and therefore the specific creep was used as a better comparison (Domingo et al, 2010). Seen in Figure 3.46 are the specific creep rates for the different mixtures. The specific creep in the 20%, 50% and 100% RCA mixtures was 25%, 29% and 32% higher than the control mixture (0% RCA) (Domingo et al, 2010).

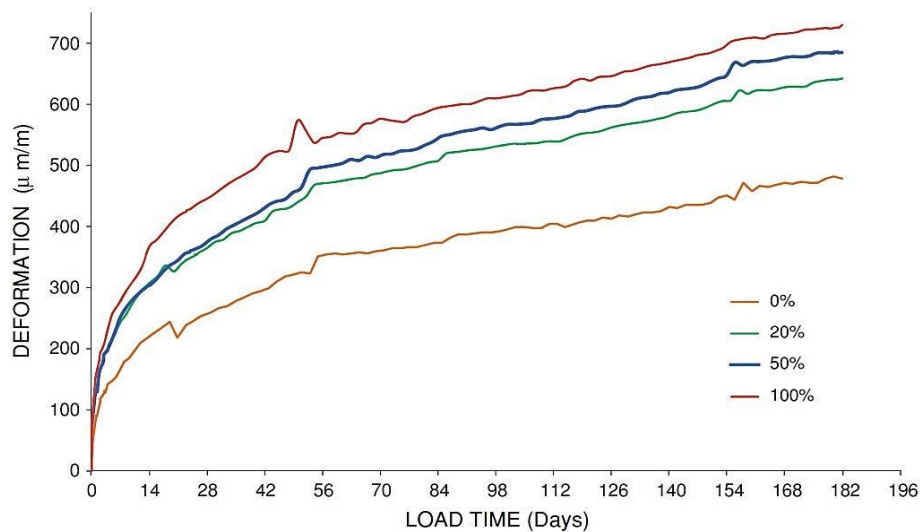


Figure 3.45 Actual measured deformation creep strains in the investigation by Domingo et al (2010)

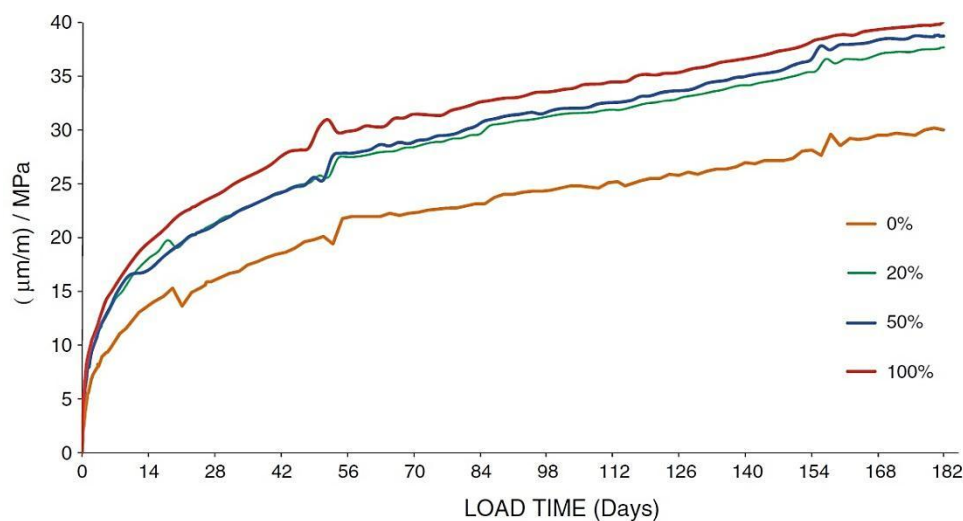


Figure 3.46 Specific creep rates calculated from the measured strain in the investigation by Domingo et al (2010)

The creep of mixtures containing both fine and coarse RCA and combination of OPC and Corex® slag was investigated by Kutegeza (2004). The specimens were sealed and unsealed to measure the basic creep and drying creep respectively. The specimens were loaded at different stresses according to concrete strength and therefore the specific creep was determined to compare the mixtures. The difference between the strains in the sealed specimens was minimal, with the RCA mixtures exhibiting 5 to 15% higher strain than the mixtures containing only NA (Figure 3.47a). The retained moisture was concluded as a possible influence for the lower strain, as under loading, the pores do not compress with the presence of water (Kutegeza, 2004). The mixtures containing slag had lower specific creep rates than the OPC mixtures.

The exposed specimens displayed significantly different results when compared to the sealed specimens (Figure 3.47b). The specific creep was 50% and 100% higher in the mixtures containing RCA with binders OPC/slag and OPC respectively (Kutegeza, 2004). The higher creep strain of the RCA mixtures was attributed to the presence of a higher moisture content in the aggregates (Kutegeza, 2004). The greater the moisture content at loading, the greater the creep under drying conditions because voids and pores lost the compressive resisting water due to evaporation. The mixtures containing slag once again had lower specific creep rates than the OPC mixtures with the NA and RCA. The greater strength and lower porosity of these mixtures could be contributed to the lower creep strain.

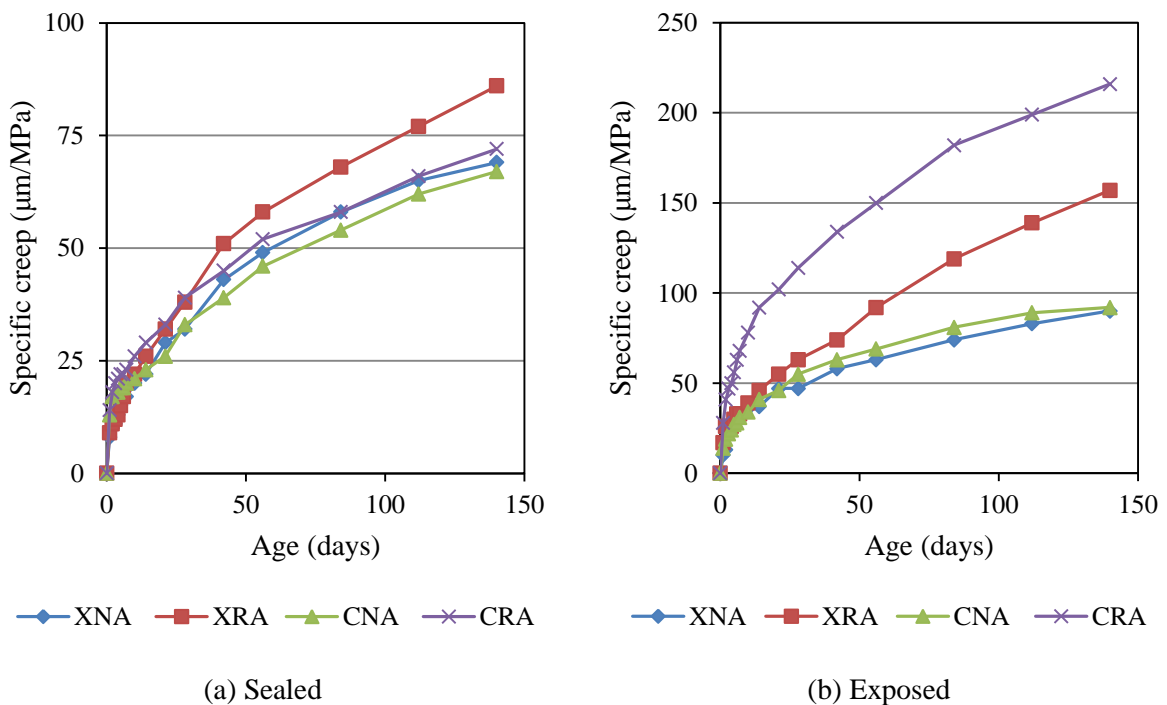


Figure 3.47 The specific creep values for sealed and exposed concrete specimens
(adapted from Kutegeza, 2004)

Chandra Paul (2011) reported that the total deformation of concrete containing 30% RCA was 21% higher than 100% NA concrete mixture. The total measured deformation strains were 2140 $\mu\text{m/m}$ and 1771 $\mu\text{m/m}$ for the RAC 30% and NAC 100% mixtures respectively as seen in Figure 3.48. The creep strain was calculated by deducting the free drying shrinkage strain and elastic strain from the total strain (Chandra Paul, 2011). The creep strain difference was higher than the total strain difference. The calculated creep strain was 571 $\mu\text{m/m}$ and 954 $\mu\text{m/m}$ for the NAC 100% and RAC 30% concrete mixtures, which resulted in 67% difference between the mixtures (Chandra Paul, 2011). The difference between the drying shrinkage of the two mixtures in this investigation was minimal and therefore the difference between the strains must be associated with the elastic strain or the load applied to the specimens. The specific creep was calculated using the applied load (12 MPa) and the specific creep was 67% higher in the RAC 30% mixture (Chandra Paul, 2011) and therefore the difference can be isolated to the applied load and strength of concrete mixtures.

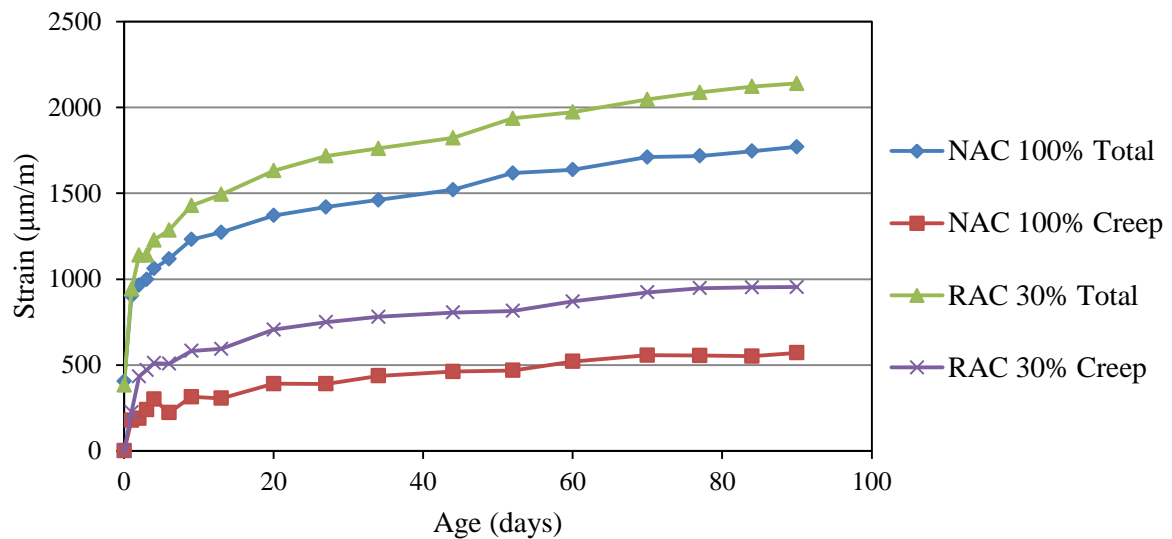


Figure 3.48 The total creep deformation strain and the calculated creep strain
(adapted from Chandra Paul, 2011)

3.4 Specifications and Standards

Countries such as Germany, Switzerland, Netherlands, Denmark, Great Britain, Japan, USA and Russia all have established standards or specifications for the use of RCA in concrete (Dehn, 2007). The South African standard for aggregates does not include specific guidelines for the use of RCA, but does make note of “aggregates derived from sources that yield material of unknown or suspect mineralogical and performance characteristics need to be subjected to further testing” (SANS 1083:2006, p. 4). The need to include specifications for RCA in a South African standard, whether in high-grade or low-grade applications, will provide assurance to engineers and relevant stakeholders that the material has been properly specified. Discussed in this section are international standards and specifications relating to the use of RCA specifically in concrete, as well as the current South Africa standard for aggregates. In doing so, a possible draft guideline can be proposed for the inclusion of RCA specifications in a South African framework in relation to RCA investigated in this study.

3.4.1 SANS 1083:2006 *Aggregates from natural sources - Aggregates for concrete*

The SANS 1083 specifies the requirements of fine and coarse aggregate derived from natural sources to be used in concrete of any grade. Coarse aggregates are defined as aggregates not passing the 4750 μ m sieve and fine aggregates as the material passing this sieve. The aggregate assessed in the standard are “known not to contain deleterious contaminants other than those for which limits have been laid down in this standard and that can be complied with by normal processing, including washing with water” (SANS 1083:2006, p. 4). The focus of this study is aimed at the coarse aggregate properties and therefore will be the only portion of the standard discussed in detail.

Table 2 in Appendix A is extracted from the SANS 1083:2006 and defines the limits for the properties considered for coarse aggregate. These properties can be identified as the basic properties which aggregates should meet and are not highly complicated to assess. The 10% FACT value test is the preferred test method in assessing the strength of aggregate, the ACV test can be used when aggregates are assumed to have sufficient strength to meet the requirements, because it is rapid and repeatable (SANS 5841:2008).

The aggregates should be visually inspected to ensure that material does not contain any foreign matter and that the description of aggregates meets the documentation pertaining to the aggregate quality which should contain:

1. the class/method of production defined as either:
 - a) aggregate formed by the natural disintegration of rock;
 - b) aggregate produced by the mechanical crushing or milling of rock; and
 - c) aggregate derived from a mixture (blend) of (a) and (b) above;
2. and in the case of coarse aggregate the nominal size, the coefficient of uniformity (when relevant), the proportional blend of nominal sizes (when relevant), and whether the coarse aggregate is suitable for use in concrete subject to surface abrasion.

Annex C of the SANS 1083:2006, aggregates which may require additional testing for the suitability in concrete or special applications are defined. It states that publications and experts should be consulted when assessing the outcomes from the additional tests prescribed. A petrographic analysis should be completed and assessed by specialist geologist on aggregates from a particular source when nothing is known about the mineralogical and performance characteristics. Through this assessment the additional tests necessary to classify the aggregate's suitability can be specified. The additional properties/tests which may be necessary for assessing coarse aggregates are listed below:

- Presence of sulfates or sulfides (or both);
- Water absorption;
- Shrinkage;
- Soundness and durability;
- Shape, surface texture and water requirement;
- Presence of material of low density;
- Friability;
- Abrasion resistance;
- Solubility in acid;
- Alkali-silica reactivity;
- Polished-stone value.

The SANS 1083 states if the use of aggregates which do not meet the requirements in the standard is unavoidable, attention must be made to the assessment of all the aggregate properties to ensure that the concrete quality and in particular, the long term durability is not compromised. Assessing RCA according to this standard mostly takes into account the geometrical properties of aggregates, which according to other specifications are not sufficient. The additional tests specified are taken into consideration in the international standards along with defined requirement limits.

3.4.2 RILEM TC 121 – DRG 1994 *Specifications for concrete with recycled aggregates*

The RILEM recommendation defines the specifications for recycled coarse aggregate ($\geq 4\text{mm}$) for concrete. The fine aggregate ($< 4\text{mm}$) specifications should meet the traditional specifications by assumption. Recycled fine aggregate is not included in the standard due to the following reasons:

- High amounts of contaminants;
- The impacts on concrete durability and strength has not been examined sufficiently;
- Test methods to determine the strength of fine recycled aggregate were not available;
- Test methods to determine the residual alkali reactivity were not available;
- Using fine recycled aggregates lead to problems in controlling the free water content for concrete mixture.

The recycled coarse aggregates are categorized into three types and appropriate applications for concrete containing these aggregates are specified. The applications are dependent on environmental exposure and strength classes which are defined in Eurocode 2. The three types of recycled coarse aggregate according to RILEM TC 121 – DRG are:

1. Type I: aggregates which are implicitly understood to originate primarily from masonry rubble.
2. Type II: aggregates which are implicitly understood to originate primarily from concrete rubble.
3. Type III: aggregates which are implicitly understood to consist of a blend of recycled aggregates and natural aggregates. The minimum content of NA is at least 80% (m/m). The maximum content of Type I aggregates is 10% (m/m).

The mandatory requirements for each type of recycled aggregate are specified in Table 3.39. The aggregate may also have to comply with properties listed below found in national or European Committee for Standardisation (CEN) standards:

- Grading;
- Static strength;
- Form index;
- Abrasion value;
- Chloride content;
- Iron and vanadium content for clean concrete applications;
- Pop-out potential (Ca, Fe content);
- Content of swelling clay;
- Frost resistance.

The national requirements for environmental and health related aspects should also be met are:

- The contamination of aggregates by heavy metals, polyaromatic carbons (PAC); and
- leaching characteristics; and
- radiation.

The specification includes a note relating to the setting time of concrete containing recycled aggregate. The RCA material should be free of foreign items or substances which should not retard the setting time by more than 15% when compared to an identical mixture consisting of normal aggregates.

Table 3.39 Classification of recycled coarse aggregate for concrete (RCAC) (RILEM TC 121 – DRG)

Mandatory requirements	RCAC Type I	RCAC Type II	RCAC Type III	Test Method
Min. dry particle density (kg/m ³)	1500	2000	2400	ISO 6783 & 7033
Max. water absorption (% m/m)	20	10	3	ISO 6783 & 7034
Max. content of material with SSD < 2200 kg/m ³ (% m/m)	-	10	10	ASTM C123
Max. content of material with SSD < 1800 kg/m ³ (% m/m) ^a	10	1	1	ASTM C123
Max. content of material with SSD < 1000 kg/m ³ (% m/m & % v/v)	1	0.5	0.5	ASTM C123
Max. content of foreign materials (metals, glass, soft material, bitumen) (% m/m)	5	1	1	Visual
Max. content of metals (% m/m)	1	1	5	Visual
Max. content of organic materials (% m/m)	1	0.5	0.5	NEN 5933
Max. content of filler (<0.063 mm) (% m/m)	3	2	2	prEN 933 -1
Max content of sand (<4 mm) (% m/m) ^b	5	5	5	prEN 933 -1
Max. content of sulphate (% m/m) ^c	1	1	1	BS 812, part 118

^a Water saturated surface dry condition

^b If the maximal allowable content of sand is exceeded, this part of the aggregates shall be considered together with the total sand fraction

^c Water soluble sulphate content calculated as SO₃

From Table 3.40 it is clear that the quality of the aggregate defines the provisions for the strength and exposure classes. Type I aggregates are basically used in environments where durability is not of concern, typical of low-grade concrete elements. Type III aggregates may be used in higher grade applications which require durable concrete. The exposure classes are concerned with the rate of carbonation and chloride ingress which may be higher when recycled aggregates are utilised.

Table 3.40 Provisions for the use of recycled aggregate (RILEM TC 121 – DRG)

Recycle aggregates	RCAC Type I	RCAC Type II	RCAC Type III
Max. allowable strength class	C16/20 ^a	C50/60	No limit
Additional testing required when used in exposure class 1 ^b		None	
Additional testing required when used in exposure classes 2a, 4a	ASR expansion test ^c + Use in class 4a not allowed		ASR expansion test
Additional testing required when used in exposure classes 2b, 4b	Use in classes 2b, 4b not allowed		ASR expansion test + Bulk freeze-thaw test
Additional testing required when used in exposure class 3	Use in class 3 not allowed		ASR expansion test + Bulk freeze-thaw test + Deicing salt test

^a However the strength class may be increased to C30/37 subject to the condition that the surface saturated dry (SSD) density of the recycled aggregate exceeds 2000kg/m³

^b Conforming with ENV 206-1

^c Expansion test to evaluate alkali silica reactivity

The designated exposure classes to which the RCAC provisions are made are listed below according to EN 206-1:2000:

- Class 1: No risk of corrosion or attack;
- Class 2: Corrosion induced by carbonation;
- Class 3: Corrosion induced by chlorides other than from sea water;
- Class 4: Corrosion induced by chlorides from sea water;
- Class 5: Freeze/thaw attack with or without de-icing agents;
- Class 6: Chemical attack.

The RILEM standard takes into account the possible influence that the density of RA may have on the strength and deformation characteristics. The design values used to determine the strength and deformation of concrete containing RA are adjusted according to the factors in Table 3.41. Experimental analyses should be carried out when accurate data is needed. When no experimental data is available the design value may be multiplied by the factors in Table 3.41 to estimate the necessary material characteristics. The higher creep is accounted for because of the decrease in modulus of elasticity, to which it is proportional (RILEM TC 121 DRG).

Table 3.41 Factors for the evaluation of the material properties of recycled concrete (RILEM TC 121 – DRG)

Design values	RCAC Type I	RCAC Type II	RCAC Type III
Tensile strength (f_{ctm})	1	1	1
Modulus of elasticity (E_{cm})	0.65	0.8	1
Creep coefficient ($\phi(\infty, t_0)$)	1	1	1
Shrinkage (ϵ_{cs0})	2	1.5	1

3.4.3 ACI 555R – 01 *Removal and Reuse of Hardened Concrete* & ACI E1 – 07 *Aggregates for Concrete*

The ACI 555R-2001 is a guideline used in the removal and reuse of hardened concrete. The document is divided into four main chapters which discusses various research and investigations pertaining to concrete as a secondary material. The chapters are listed below with a brief description of the content covered in each section:

- Chapter 2. Kinds of concrete and degree of removal:
Includes details for the complete and partial removal of concrete from different types of structures. The issues of safety, stability, constructability, cost and environmental impact of such removals are considered.
- Chapter 3. Removal methods:
The various options available for the removal and demolition of concrete from different structures. The various options are discussed for the systematic removal of concrete from a structure.
- Chapter 4: Surface removal
The surface removal of concrete for the purposes of repair, correction and preparation are discussed. The description of available systems, their probable application and the advantages and disadvantages of various types of removal are provided.
- Chapter 5: Production of concrete from recycled concrete
The recycling processes for the production of recycled aggregates, such as plant design and operations are proposed through examples. The aggregate quality relating to properties such as: aggregate size, density, water absorption and contaminants are described. The effects which recycled aggregates may have on concrete properties are also covered along with considerations for concrete mixture proportions when using recycled aggregates.

The ACI 555R – 01 should only be used as a guideline, as the information and data provided is collected from various sources which may have resulted from individual case studies. Investigations should be completed on material relevant to the specific projects and compared to the information provided in this publication with competent recommendations.

The ACI E1-07 (2007) Aggregates for Concrete is “intended for the use of individuals who are competent to evaluate the significance and limitations of its content and recommendations and who will accept responsibility for the application of the material it contains” (ACI E1-07). The document covers the properties and test methods used to classify aggregates which is to be used in concrete such as: grading, relative density, absorption, particle shape, chemical stability and harmful substances. The document makes reference to the ASTM C33 *Standard Specification for Concrete Aggregates* which is a more formally accepted standard and can be used as is. The publication also covers specific topics relating to aggregates which include sampling methods, blast-furnace slag aggregates, lightweight aggregates and recycled aggregates.

Recycled aggregates according to ACI E1-07 are defined as breaking old concrete (typically pavement), removing the reinforcement, and crushing the resulting material to specific sizes and gradation. Testing may be required on certain recycled aggregates which may be prone to D-cracking or derived from concrete with ASR potential. The document notes that both fine and coarse recycled aggregates may be used in concrete, with up to 100% of coarse recycled aggregate and only 10 to 20% of fine aggregate. The reason for the limit on fine recycled aggregates is because of the high water absorption. The properties discussed in the ACI E1-07 specifically related to recycled aggregates are discussed below:

- **Gradation and surface condition:**
Most stone gradings are possible through the crushing of the material and the process may leave some residual dust on the particle surface which can be removed through washing.
- **Specific gravity:**
The relative density will be lower than normal aggregates, approximately between 2.2 and 2.5 in an SSD condition. The relative density decreases as the particle size decreases.
- **Absorption:**
The absorption will be higher than normal aggregates due to the attached mortar. The water absorption for coarse RA is typically between 2 to 6% and higher in fine RA. The higher absorption could make fresh concrete less workable and to correct this additional water in can be included.
- **Durability:**
Abrasion loss, sulphate soundness and residual chlorides are not of concern in both fine and coarse recycled aggregates, except when the original concrete has been exposed to sea water. Of particular concern is the ASR potential of coarse recycled aggregates. Both the original

and new concrete alkali levels can contribute to the expansion caused by this reaction. Assessing the potential ASR should be done by examining: the original alkali levels of the old concrete, the expansion of the old concrete, the remaining potential for expansion and the alkali content of the new concrete.

Recycled aggregates should meet the specifications intended for normal aggregates as well as the guidelines described above.

3.4.4 JIS A 5021 Class H Recycled aggregate for concrete-class H

According to Tam (2009) three Japanese Industrial Standards for recycled aggregate use in concrete exist. The recycled aggregate should meet the specifications within each standard for suggested applications seen in Table 3.42. The JIS A 5021 Class H aggregates can be considered as high-grade aggregates and the details of this standard are further discussed.

Table 3.42 Japanese standards of recycled aggregates according to recycling process and classification (adapted from Tam, 2009)

Class of RA	Requirements of RA	Suggested concrete applications
JIS A 5021 Class H	Recycled aggregate which has been processed by advanced methods and has been classified from the original structure	The RA can be used in concrete located in the main structure and can be compared to natural river gravel and sand
JIS A 5023 Class L	Recycled aggregate which has been processed by basic methods and not derived from a wastewater treatment plant	The RA can be used in concrete without applying energy and costs. Three types are recommended: a stock item, a salt regulation article and a technical specification article
JIS A 5022 Class M	Recycled aggregate which has been processed by basic methods and has been classified from the original structure	The RCA can be used in elements much are not easily influenced by drying shrinkage and freezing & thawing such as: steel tubing in filled concrete

The recycled aggregate specified by this standard must be designated according to class, grading division and alkali silica potential. The class may be either fine or coarse aggregate. The grading division defines the particle size range. The alkali silica potential is either “harmless” or not. Figure 3.49 provides an example of the recycled aggregate designation.

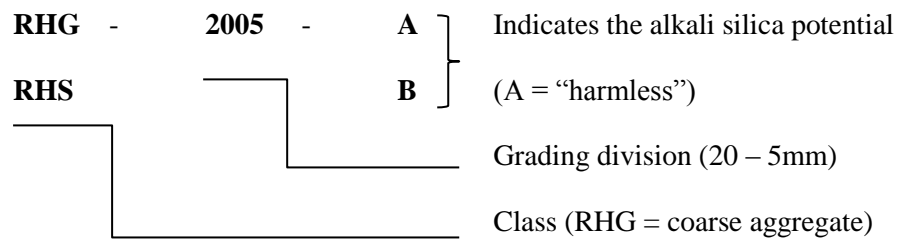


Figure 3.49 How the recycled aggregates are designated according to class, grading and ASR potential (JIS A 5021 Class H)

The quality of the aggregate is assessed through representative sampling and the properties listed below. The quality of the aggregate is defined by the limits in Tables 3.43 and 3.44.

- Amount of impurities;
- Density in oven-dry condition;
- Water absorption percentage;
- Abrasion loss;
- Content of materials finer than 75 μ m sieve;
- Alkali-silica reactivity;
- Grading;
- Solid content percentage for shape determination;
- Chloride content.

Table 3.43 Upper limit of the amount of impurities (JIS A 5021 Class H)

Classification	Contents of impurities	Upper Limit (%) ¹
A	Tile, brick, pottery and asphalt	2.0
B	Glass pieces	0.5
C	Gypsum and gypsum board pieces	0.1
D	Other inorganic boards	0.5
E	Plastics pieces	0.5
F	Wooden pieces, paper scraps, asphalt lumps	0.1
Sum of amount of impurities (total amount)		3.0

¹The upper limit is shown in mass ratio and indicate the value compared with the sum of the contents of the impurities in each class

Table 3.44 Limits on the physical properties of recycled aggregate (JIS A 5021 H)

Test item	RHG	RHS
Density in oven-dry condition (g/cm ³) ¹	≥ 2.5	≥ 2.5
Water absorption (%)	≤ 3.0	≤ 3.5
Abrasion loss (%) ²	≤ 35	-
Content of material (< 75 μm sieve) (%)	≤ 1.0	≤ 7.0

¹ ±0.1 g/cm³ tolerance

² Applicable to the case of using for pavement

The alkali-silica reactivity is assumed to be “harmless” if the material complies with all of the following: the original concrete has been identified and the alkali-silica test defined in the Japanese standard has been approved. The recycled fine/coarse aggregate H has also been determined as “harmless”.

The grading should comply with the limits defined in the standard, and in conjunction with the RHS (fine), the percentage passing should not exceed 45% on any sieve. The solid content for determining the grain shape for RHG material should be at least 55 ±1.5% and for RHS material should be 53 ± 1.5%. The standard makes note that the fineness modulus and solid content limits may be relaxed when mixed with natural gravels or crushed stones.

The chloride (NaCl) content of both fine and coarse recycled aggregates should be equal to or less than 0.04%, but may be equal to or less than 0.1% when approved by the purchaser. The standard also provides specifications concerning the manufacture of recycled aggregates, method of inspection, marking and reporting the specifications.

The JIS A 5021 provides two standard documents for classifying the fine and coarse recycled aggregates according to the above mentioned properties and related limits. The documents are clearly defined and ensure no confusion can be made with the assessment of the incoming material. The Japanese standard highlights the importance of assessing the original concrete as it will help improve the scope of the recycled aggregates application in concrete.

3.4.5 BS EN 12620:2008 Aggregates for concrete

The European/British standards for concrete structures are highly integrated which allows for specifications for a range of related topics. Figure 3.50 is a summarised version of the European/British standards and the relevant constituent parts related to structures utilizing concrete. The EN 206-1 and Eurocode 2 are used interchangeably, while the standards specifically related to concrete as a material succeed the EN 206-1. The EN 206-1 applies to the following areas related to concrete:

- Structures cast in situ, precast structures, and structural precast products for buildings and civil engineering structures;
- Concrete compacted to retain no appreciable amount of entrapped air other than entrained air;
- Normal-weight (2000 to 2600 kg/m³), heavy-weight (>2600 kg/m³) and light-weight (800 to 2000 kg/m³) concrete.

The aggregates may be either normal-, heavy- or light-weight and are defined as granular mineral materials suitable for use in concrete. Aggregates may be natural, artificial or recycled from material previously used in construction. Normal aggregates should conform to BS EN 206-1, where provisions for recycled aggregates have not yet been included, but should meet the same requirements as for normal aggregates. Materials should not contain any harmful components in such quantities that may compromise the durability of the concrete or cause corrosion of the reinforcement

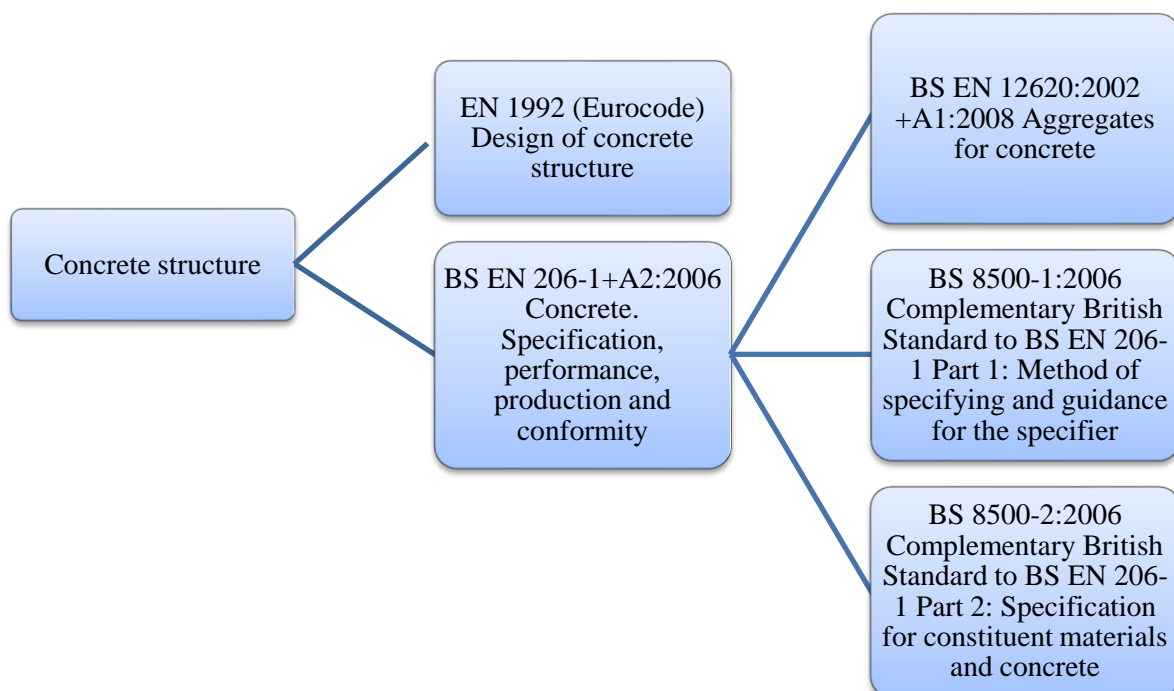


Figure 3.50 A summarized list of European/British standards related to concrete structures

The BS EN 12620 is discussed with relevance to recycled aggregates and some important aggregate properties. The BS EN 12620 is a complex document with specifications for the properties defined by categories rather than a range. A supporting document, PD 6682-1:2009 *Aggregates-Part 1: Aggregates for concrete – Guidance on the use of BS EN 12620*, is provided to correctly interpret the standard.

The BS EN 12620 was amended in 2008 to include specific specifications for recycled aggregates. Recycled aggregates definitions are not yet provided for in the current form of the standard, but the terms listed below are included in the BS 8500 series:

- RA: recycled aggregate principally comprising crushed masonry (brickwork and blockwork) (PD 6682-1:2009). Aggregate resulting from the reprocessing of inorganic material previously used in construction (BS 8500-1:2006).
- RCA: recycled aggregate principally comprising crushed concrete (PD 6682-1:2009 & BS 8500-1:2006).

The amended BS EN 12620 covers coarse RA with densities between 1500 kg/m³ and 2000 kg/m³ with appropriate restrictions as well as fine RA (4mm) with appropriate restrictions. The recycled aggregates are required to meet the standard specifications for traditional aggregates and discussed below, are the restricted specifications for recycled aggregates.

1. *Physical requirements:*

- Durability

The magnesium sulphate test is not suitable for recycled aggregates with cement bound fractions. RA should not be assessed to the categories defined for the percentage loss for magnesium soundness. RA may contain expansive material such as un-slaked lime. The requirements for volume stability (drying shrinkage) are not provided because no test methods are available. General recycled aggregates are regarded as potentially alkali-silica reactive, unless it has been specifically established to be non-reactive. Recycled concrete aggregates are assessed differently. The original concrete should be assessed for reactive/reacting aggregate. If the alkali content of new concrete is limited, the RCA alkali content has to be determined and taken into account.

- Classification of the constituents of coarse recycled aggregates

The proportions of constituent materials in coarse recycled aggregate should be classified according to Table 3.45. The definitions for the respective constituents are given in Section 5.1.6.

Table 3.45 Categories for the constituents of coarse RCA (adapted from BS EN 12620)

Constituent	Content Percentage by mass	Category
Rc	≥ 90	Rc ₉₀
	≥ 80	Rc ₈₀
	≥ 70	Rc ₇₀
	≥ 50	Rc ₅₀
	< 50	Rc _{Declared}
	No requirement	Rc _{NR}
Rc + Ru	≥ 95	Rcu ₉₅
	≥ 90	Rcu ₉₀
	≥ 70	Rcu ₇₀
	≥ 50	Rcu ₅₀
	< 50	Rcu _{Declared}
	No requirement	Rcu _{NR}
Rb	≤ 10	Rb ₁₀₋
	≤ 30	Rb ₃₀₋
	≤ 50	Rb ₅₀₋
	> 50	Rb _{Declared}
	No requirement	Rb _{NR}
Ra	≤ 1	Ra ₁₋
	≤ 5	Ra ₅₋
	≤ 10	Ra ₁₀₋
X + Rg	≤ 0.5	XRg _{0.5-}
	≤ 1	XRg ₁₋
	≤ 2	XRg ₂₋
Constituent	Content cm ³ /kg	Category
FL	≤ 0.2 ^a	FL _{0.2-}
	≤ 2	FL ₂₋
	≤ 5	FL ₅₋

^aThe ≤ 0.2 category is intended only for special applications requiring high quality surface finish

2. Chemical requirements:

- Chlorides

The chlorides may be combined with the calcium aluminate and other phases in recycled aggregate, mainly those that contain hardened concrete mortar. The chlorides are unlikely to be insoluble in water even if the sample is ground to a fine powder. The chloride ion content is expected to be low and therefore the acid-soluble chloride content of recycled aggregates should on request be declared by the producer. The acid-soluble chloride content is stated to probably be an overestimation and will provide a margin of safety.

- Sulphur containing compounds

Recycled aggregates may contain sulphates which are expansive. The water soluble sulphate content of recycled aggregates should be declared in accordance with Table 3.46, and are essentially potentially reactive sulphates such as gypsum plaster.

Table 3.46 Categories for maximum values of water soluble sulphate content of RCA (adapted from BS EN 12620)

Water soluble sulphate content Percentage by mass	Category (SS)
≤ 0.2	SS _{0.2}
No requirement	SS _{NR}

- Other constituents

The constituents of recycled aggregates may adversely affect the rate of setting and hardening of concrete. The constituents may include inorganic substances which are not detected by the specified standard. Sugars, organic and other substances should not:

- Increase the stiffening time of the mortar test specimens by more than 120 minutes
- Decrease the compressive strength of mortar test specimens by more than 20% at 28 days.

The influence of water-soluble materials in recycled aggregates on the initial setting time of concrete should be determined when required and assessed according to Table 3.47.

Table 3.47 Categories for the influence of RCA on the initial setting time of concrete (adapted from BS EN 12620)

Change in initial setting time, t_e (min)	Category (A)
≤ 10	A ₁₀
≤ 40	A ₄₀
> 40	A _{Declared}
No requirement	A _{NR}

In the case of recycled aggregates, the knowledge of the raw material is of importance. The BS EN 12620 states that for input control the following should be specified: nature of raw material, source and place of origin and supplier and transporting agent. The standard also provides a frequency of minimum tests to be carried out on aggregates from a particular source. For example the minimum frequency for assessing the constituents of coarse RCA is one sample per month.

The BS 8500 series contains additional United Kingdom provisions to be used in conjunction with BS EN 206-1. The BS 8500-2:2006 specifies the constituent materials and concrete. Specifications for fine RCA/RA are not provided in this standard because of the wide range of composition and lack of detailed information such as appropriate test methods, are not available. Fine RCA/RA may be used if due to the source of material, significant quantities of deleterious materials are not present and its use has been specified. The specifications for RA are limited and for suitable use in concrete, the following may need to be specified for a particular project:

- maximum acid-soluble sulphate;
- method for determination of the chloride content;
- classification with respect to alkali–aggregate reactivity;
- method for determination of the alkali content;
- any limitations on use in concrete.

Combinations of coarse RCA or coarse RA and natural aggregates should meet the requirements of BS EN 12620 and requirements of Table 3.48.

Table 3.48 Limits for the amount of foreign materials that may be derived for RCA (BS 8500-2:2006)

Type of aggregate	Requirement ^{A)} given as mass fraction (%)					
	Max masonry content	Max fines	Max lightweight material ^{B)}	Max asphalt	Max other foreign material e.g. glass, plastics, metals	Max acid soluble sulphate (SO ₃)
RCA ^{A), C)}	5.0	5.0	0.5	5.0	1.0	1.0
RA	100.0	3.0	1.0	10.0	1.0	^{D)}

^{A)} When the material to be used is obtained by crushing hardened concrete of known composition that has not been in use, e.g. surplus precast units or returned fresh concrete, and not contaminated during storage and processing, the only requirements are those for grading and max. fines

^{B)} Material with a density less than 1000kg/m³

^{C)} The provisions for coarse RCA may be applied to mixtures of natural coarse aggregates blended with the listed constituents

^{D)} Specified when necessary

The chloride content of the specified concrete should be checked and if the limits have not been exceeded, the chloride content of coarse RCA and coarse RA should be determined. The alkali content of RCA should be determined in accordance with BRE Digest 330. Coarse RCA may only be used in the concrete and exposure classes as defined in Table 3.49, except where permitted by the footnotes.

Table 3.49 Limits on the class of concrete and exposure classes (BS 8500-2:2006)

Type of aggregate	Limitations on use	
	Maximum strength class ^{A)}	Exposure classes ^{B)}
RCA	C40/50	X0, XC1, XC2, XC3, XC4, XF1, DC-1

^{A)} Material obtained by crushing hardened concrete of known composition that has not been in use, e.g. surplus precast units or returned fresh concrete, and not contaminated during storage and processing may be used in any strength class

^{B)} These aggregates may be used in other exposure classes provided that it has been demonstrated that the resulting concrete is suitable for the intended environment e.g. freeze/thaw resisting, sulphate resisting

For concrete classes C20/25 – C40/50, coarse RA and RCA should not be more than 20% of the mass fraction, except where specifications permit higher percentages. In classes C6/8 – C12/20 any percentage of coarse RCA and RA is permitted. The maximum aggregate size should not exceed 20mm, unless specified otherwise.

The international specifications and standards review in this section are more complex and better detailed when considering the use of recycled aggregates in concrete. The general concern of these publications is limiting the amount of foreign materials and examining the alkali-silica reactivity potential of recycled aggregates. The foreign material may be limited according to specific materials and substances or as a combination of the two. It is clear from these documents, that the normal specifications for the properties of aggregates are not sufficient in correctly assessing the potential use of RCA in concrete. The South African Bureau of Standards is currently revising the standards and test methods related to aggregates in concrete to coincide with the European standards (Perrie, 2011). It is not clear whether specifications for recycled aggregates will be included, but it is clear that in the future this topic will need to be considered.

3.5 Concluding Summary

The influence which RCA has on the aggregate, fresh concrete and hardened concrete properties has been reviewed. The inclusion of RCA mostly has a negative influence on the properties discussed, but the degree to which this secondary material may impact concrete depends largely on the source of C&D waste and the method of recycling.

The aggregate properties can be assessed according to the designations ascribed in the BE EN 12620 which are the: geometrical, physical and chemical properties. The geometrical properties include: particle shape and surface texture, grading, fineness modulus and dust content. The physical properties include: constituents of RCA, bulk densities, relative density, water absorption and aggregate strength. The chemical properties include: deleterious substances and chemical-mineralogy. To assess whether these aggregate properties permit the use of RCA in concrete, the relevant standards and specifications were discussed and reviewed.

The fresh concrete properties discussed included the: workability, fresh density and air content. The hardened concrete properties were reviewed according to the mechanical, durability and dimensional stability properties of concrete. The mechanical properties included the compressive strength and tensile strength. The durability properties included the: oxygen permeability, water sorptivity and chloride conductivity. The dimensional stability properties included the: modulus of elasticity, shrinkage and creep. The mechanical strength, specifically the compressive strength may not be affected when utilising RCA. However, the durability concerns may be of more importance, especially with a material which is of lesser quality.

The experimental programme is described in Chapter 4. The tests necessary to assess the aggregate, fresh and hardened concrete properties are discussed based on the review in this chapter. The outcomes from the relevant tests in Chapters 5, 6 and 7 are compared to the research which was found in this chapter. Assessing all the aggregate properties may not be necessary to determine whether or not a RCA sample is permitted for further use in concrete. From the results in the chapters described above, particular aggregate properties may be highlighted to readily determine to criteria for approval of an RCA batch.

Chapter 4

Experimental Programme

The purpose of this research is to determine what replacement ratio or percentage replacement of coarse recycled concrete aggregate (RCA) can be included in structural concrete. The research, knowledge and information of replacing natural aggregate (NA) with RCA in South Africa is developing, and in doing this research, scientific knowledge and recommendations will be improved relating to RCA. The RCA examined in this study was obtained from a commercial recycling facility, Cape Brick. Cape Brick in partnership with Ross Demolition collect and recycle construction and demolition (C&D) waste from projects within the greater Cape Town area. The recycled material passes through a production process similar to that described in Chapter 2. No fine recycled aggregate was examined or included in this study.

This chapter defines the experimental procedure and relevant information relating to materials, tests and standards used in the investigation. Note that test methodologies are fully explained in the following chapters: aggregate properties, fresh concrete properties and hardened concrete properties. The chapters pertaining to aggregate and hardened concrete properties are sub-divided as follows:

Aggregate Properties

- Geometrical
- Physical
- Chemical

Hardened Concrete Properties:

- Mechanical
- Durability
- Dimensional

The concrete mix design, mixing procedure and concrete production are then explained. After which a summary of all tests carried out and respective test method/standard is provided. The materials and experimental programme layout are defined in the same manner similar to the investigations described in Chapter 3, specifically to the South African studies to use as relative comparisons. The natural aggregate was substituted by RCA by the following percentages: 0, 15, 30, 50 and 100% to determine at which percentage replacement the required outcomes of the study are met.

4.1 Materials

4.1.1 Natural coarse aggregate

Common South African natural aggregates that are used in the production of concrete are listed below by decreasing order of consumption (Grieve, 2009a):

1. Quartzite and sandstone;
2. Basic igneous rocks (basalts and dolerite);
3. Granite;
4. Greywacke;
5. Tillite;
6. Miscellaneous (dolomite and felsite).

Of these aggregates Greywacke is commonly found in the Western Cape region of South Africa and is also known as Malmesbury Shale. The argillaceous rock of the Malmesbury Group is thermally metamorphosed by the intrusion of the plutons of the Cape Granite (Grieve, 2009a). Grieve (2009a) describes the rock as “glassy” and fine-grained defined by the presence of quartz, feldspar, mica and iron oxides, also alumina-sulphates (cordierite). Physical particle shape is generally elongated, by reason of crushing qualities, where typical coarse aggregate would rather be cubical in shape. The aggregate is also well known for demonstrating alkali-silica reactivity, which was first discovered in the Cape Peninsula (Western Cape) in the 1970’s (Ekolu, 2009). The aggregate used in this experimental programme was a 19mm greywacke stone from a local quarry in the greater Cape Town area seen in Figure 4.1. For consistency the same coarse natural aggregate from a single batch was utilised throughout the experimental programme.



Figure 4.1 Natural coarse aggregate (19mm Greywacke)

4.1.2 Coarse recycled concrete aggregate

The coarse RCA was obtained from manufacturers of concrete masonry, Cape Brick which is located in Cape Town's industrial area. The C&D waste is primary crushed by a mobile crusher either by a demolition contractor or Cape Brick. This material is pre-screened to remove large contaminant items such as steel, bricks and other foreign materials. The material below 100mm in size is then directed to the recycling plant for further crushing. Prior to secondary crushing the material passes over a 40mm sieve which re-directs finer material past secondary crushing. Furthermore topsoil and clay is removed and stockpiled, while light weight material is removed by air-sifting by means of a large fan. Magnets are placed over the majority of the conveyor belts to remove any ferrous metals that may not have been removed at earlier stages of the process.

The first of two crushers in the secondary crushing process is a jaw crusher which reduces the material to less than 30mm in size. The second crusher is a gyro-crusher which crushes the material to about 15mm in size. The recycled material then moves to a vertical impact crusher for final crushing where the material is then below 9mm in size. Potable water is sprayed throughout the factory to control dust and is localized over certain conveyor belts where the material becomes finer. The recycled materials are divided into two stockpiles of coarse and fine recycle concrete aggregate, with size $\pm 9\text{mm}$ and $\pm 2\text{mm}$ respectively.

The coarse RCA aggregate would need to be in the same size category as the natural aggregate used in the investigation. Consequently the recycled material was collected from a point in the production process before the vertical impact crusher. According to Alexander & Mindess (2005) appropriate sampling techniques are important as they achieve test samples that are representative of a batch of non-homogeneous material, as in the case with RCA. In this instance the sampling method that would apply, is the method where material is moving along a conveyor belt. The method states that the conveyor should be stopped and approximately a 1m length of material, along the width of the conveyor belt should be removed (Alexander & Mindess, 2005).

The amount of aggregate required for the experimental programme was in excess of a tonne and therefore this method was not viable as production would be halted. Instead material was removed by placing a large shovel below the conveyor feeding the material to the subsequent conveyor transporting the material to the vertical impact crusher. As the shovel head filled with material it was placed in a strong plastic bag. This was repeated until each bag had roughly 40kg of material. The amount of material sampled at each instance/batch was approximately 1.5 tonnes. A total of three batches of RCA were collected.

The collected material was relatively dirty, damp and not graded, hence it was decided that the material should be cleaned, allowed to dry and graded. This process would allow for consistency between the different batches of RCA and could still be considered a practical recycling method. The RCA in this instance would result in a superior secondary material compared to an unwashed material. The material was cleaned by emptying each bag over a large sieve raised off the ground with aperture sizes less than 4mm. Each sample bag was washed for at least 30 seconds under a constant flow of water from a hose. The material was then placed on a large plastic sheet to dry.

Once the RCA had been sufficiently dried, it was placed in steel drums for sieving. The material was sieved so that the individual stone sizes and amounts could be obtained and later combined to produce a nominal size of 19mm. The material was sieved by using a 400mm diameter sieve machine with sieve sizes (mm) arranged in decreasing order: 26.5, 19, 13.2, 9.5, 6.7, 4.75 and a pan. The material retained on each of the sieves was removed and placed in new plastic bags. This was done until enough material was collected for the next stage in the RCA preparation process. Dust produced from the sieving of the material was removed by a dust extractor placed over the top sieve.

The different material sizes were then combined to form a nominal stone size of 19mm. SANS 1083:2006 Table 2 specifies the limits for the combination of stone sizes for a nominally graded coarse aggregate. Table 4.1 defines grading of the RCA used in the investigation.

Table 4.1 Grading of RCA according to SANS 1083:2006 for a 50kg batch of material.

Sieve size (mm)	Percentage passing respective sieves size (%) ^a	Actual percentage passing (%) ^b	Actual Percentage retained (%)	Mass per 50kg (kg)
26.5	100	100	0	3.75
19	100 - 85	92.5	7.5	33.75
13.2	0 - 50	25	67.5	7.5
9.5	0 - 25	10	15	5
6.7	0 - 5	0	10	0

^a According to SANS 1083:2006

^b Intended grading in this investigation

The actual percentage passing was chosen as the average between the upper and lower limits for the percentage passing values. It must be noted that the percentage passing the 9.5mm sieve was adjusted so that the grading of the RCA sample has a relatively good “S” curve described in detail in Chapter 5. By grading the RCA in this manner the possibility of the aggregate improving the concrete properties could be expected. To correctly blend the various stone sizes smaller batches of 50kg samples would be mixed to form a combined total of 500kg. The masses for the 50kg batches are

given in the last column of Table 4.1. The masses for the individual stones sizes were weighed off and then mixed using a shovel. The 26.5mm and 19mm stone were combined on the floor and mixed by scooping and mixing the material 25 times with the shovel. The 13.2mm stone was then added and the same method was followed, as well as for the 9.5mm stone. The 50kg batches were then accumulated by storing the now experimental RCA in a metal drum for the duration of the experimental programme.

A total of three batches were collected from Cape Brick at 6-8 week intervals. The first batch was collected in March, the second in early May and the final batch in late June of 2012. The preparation process described above was employed to prepare each of the experimental batches of RCA. However, due to an error, the percentages for the March sample were mistakenly calculated. The 9.5mm stone amounted to 6.25kg per 50kg batch instead of the intended 5kg. This would change the overall grading marginally and could be considered as negligible. By grading the RCA batches in this manner, the mix design for concrete will not have to be changed for each batch as grading plays an important role in the initial workability of fresh concrete.

4.1.3 Natural fine aggregate

South Africa has a variety of fine aggregate available for use in concrete. Fine aggregate or sand can be categorised into the following: river sands, beach sands, dune sands and pit or quarry sands. The sand used in this experimental programme is known as “Malmesbury” sand, due to the area in which the quarries are located. Grieve (2009a) describes the sand as a siliceous pit sand that has a good particle shape and continuous grading. This type of sand has a high variability in terms of other properties and in several instances requires that the material be reprocessed to remove rock fragments and proportions of clay and silt (Grieve, 2009a). There is a high presence of fines and organic matter associated with Malmesbury sand, where the fines affects the water requirements and latter may influence the setting time of the concrete. The sand is sold as “river” sand as the process by which the material was deposited resembles that as defined by river sands. Unfortunately the Malmesbury sand used in this study was not collected from a single batch. Three different Malmesbury sand batches are used in this study, and this is explained further in the mix design section.

4.1.4 Binders

The commonly available binders or cements in South Africa are CEM I and CEM II. The Pretoria Portland Cement (PPC) company supplied the binders with two options: CEM I 52.5 N Ordinary Portland cement (OPC) and CEM II 42.5N Surebuild cement. CEM I 52.5 N is 95 to 100% clinker and displays high strength gains at an early age, while the latter may contain up to 30% replaced cement extenders with a slower strength gain. PPC in the Western Cape also provides a cement extender; Ground granulated Corex® Slag (GGCS). Corex® slag is a by-product from the reduction

of iron ore to metallic iron (Kutegeza, 2004). An iron producing company in Saldanha Bay introduced a modern smelter known as a Corex plant to its production process, and the slag produced is mainly used in the Western Cape and has a similar chemical composition to that of ground granulated blastfurnace slag (GGBS), but is more reactive (Grieve, 2009b).

The Cement and Concrete Institute (C&CI) of South Africa (2009) provide guidelines on selecting cementitious materials for concrete. Table 4.2 describes various concrete applications and the respective guidelines for amount of cements and cement extenders which can be used in those applications. Three scenarios are viable for the possible applications of concrete containing RCA in this experimental programme, and the recommended cementitious material percentages are shown in Table 4.2.

Table 4.2 Combination of cementitious binders depending on application (adapted from C&CI, 2009)

Application	Guidelines for cementitious amounts
Conventional structural concrete. The cement is normally selected for economy.	The cement is normally selected for economy. Any of the SANS 50197-1 common cements should be suitable. Site blends of CEM I cement with 50% GGBS or 30% FA have been extensively and successfully used in South Africa. A site blend of CEM I cement and about 8% SF is technically feasible but there is relatively little local experience of its use.
Reinforced concrete in marine environment	Research done with South African materials has shown that the best results are achieved with extender contents of either 50 % GGBS, 10% SF, 40% GGBS + 10% SF, or 30% FA.
Concrete made with alkali-reactive aggregate	The cement should contain not less than 40% GGBS, or 20% FA, or 15% SF. However, the use of SF at high replacement level usually results in sticky concrete requiring the use of a super plasticizer.

From Table 4.2 it can be seen that 50% replacement of slag is a recommended practice for the concrete industry for these applications. Noted in Section 3.3 the inclusion of Corex® slag may improve the hardened concrete properties when using RCA. To control variability between the different batches of concrete the same cement and cement extender from the same batch were used throughout the experimental programme and were kept in a cool and dry environment.

4.1.5 Water

The role of water in concrete is to hydrate the cementitious materials to produce the cementing compounds. The quality of mixing water can influence strength and other concrete properties (Goodman, 2009). In South Africa the majority of the available natural water is suitable for use in concrete mixtures. Water may be classified as one of the following, potable, recovered from processes in concrete industry, underground sources, surface water, industrial waste water, brackish or sea water and sewage water (Goodman, 2009). In this experimental programme potable water was used directly from available taps in the laboratory. The curing water was similarly used from the same source and filtered and circulated by means of medium sized water pump.

4.1.6 Admixtures

No chemical admixtures were used in this study as the possible variation between the different RCA batches may negatively influence the workability of the fresh concrete and therefore would complicate the mix design.

4.2 Tests

To achieve the research objectives requires that tests need to be conducted on the aggregates, fresh concrete and hardened concrete to assess the validity of the hypothesis.

4.2.1 Aggregate tests

SANS 1083:2006 requires that the following properties of coarse aggregate from natural sources are required for suitability in concrete as seen in Table 4.3. Due to the fact that there is no defined standard for the use of RCA in concrete in South Africa, additional tests are necessary to further define the sample material's properties (Table 4.3). Many researchers have not examined the influence that the percentage replacement will have on the aggregate properties, as the main focus has always been on the influence in the concrete. The aggregate properties are examined for the percentage replacements: 0, 15, 30, 50 and 100%. The aggregates are labelled according to the month in which the concrete batch for that particular RCA sample was cast and the percentage replacement. Mass was taken as the measure of the percentage replacement for the aggregates, with labels, for example: MarR15A, MarR30A, MarR50A, MarR100A and RefN100A. Note that the last label indicates the reference NA at 0% replacement. 40kg samples of each percentage replacement were prepared for the aggregate properties tests.

Table 4.3 Aggregate properties assessed and relevant standards

Property	Standard/Method
Required	
Grading	SANS 201:2008
Dust content	SANS 201:2008
ACV	SANS 5841:2008
Flakiness Index	SANS 5847:2008
Additional	
Shape and surface texture	Visual
Compacted and loose bulk density	SANS 5845:2006
Relative Density	SANS 5844:2006
Fineness Modulus	SANS 201:2008
Water absorption	SANS 5843:2008
Constituents of coarse RCA	BS EN 933-11:2009
Water soluble cations and anions	CAF Method
Chemical mineralogy	XRF Analysis

The aggregate crushing value (ACV) test was used as an alternative to the 10% FACT value test, because trial tests showed that the aggregates should fall within the specified margins for this test. The chemical analyses for this study were done by the Central Analytical Facilities (CAF) at the University of Stellenbosch. The aggregate properties are categorised according to the geometrical, physical and chemical properties.

4.2.2 Fresh concrete tests

The fresh concrete was tested for workability and consistency through various tests. The fresh concrete tests include: slump, slump loss with time, air content, and fresh concrete density. Fresh concrete properties determine whether or not a concrete mixture was suitable for further testing. The tests are described further detail with the relevant standard in Chapter 6.

4.2.3 Hardened concrete tests

The hardened concrete was tested according to the properties of: mechanical, durability and dimensional. A total of eight concrete mixes were produced from each batch of RCA collected, as defined in the mix design. The concrete tests and standards are summarized in Table 4.4 along with the curing period, test specimen and specimen dimensions. There needed to be some flexibility with the curing period in the eventuality that a test could not be completed on the required day. The following limits were defined for the relevant curing period: 7 + 1 day, 14 + 1 days and 28 + 2 days.

Table 4.4 Hardened concrete properties, test specimens, curing period and quantities assessed

Test	Specimen type	Dimensions (mm)	Curing Period (days)	Quantity per test	Quantity total
Density	Cube	100x100x100	7, 14, 28	4	288
Mechanical Properties					
Compressive Strength	Cube	100x100x100	7, 14, 28	4	288
Tensile Strength	Cube	100x100x100	28	4	96
Durability Properties					
Oxygen Permeability	Disc	φ70x30	7, 28	4	192
Water Sorptivity	Disc	φ70x30	7, 28	4	192
Chloride Conductivity	Disc	φ70x30	7, 28	4	192
Dimensional Properties					
Modulus of Elasticity	Cylinder	φ100x200	28	3	72
Shrinkage	Cylinder	φ105x300	28	3	36
Creep	Cylinder	φ105x300	7	2	24

The creep and shrinkage tests were only conducted on four of the concrete mixtures containing cement without any cement extender. This was done due to time constraints and the amount creep frames available to complete the necessary tests. The durability tests were conducted at the University of Cape Town, due to the fact that the experimental setups are not currently available at the University of Stellenbosch. The standards and methods for certain tests are not provided by the South African Bureau of Standards (SABS), and therefore the use of international standards was necessary. Standards from different countries were used however, the methods for the shrinkage and modulus of elasticity are based on concrete engineering principles and standards are provided as a guideline. The standards and methods for the respective tests are given in Table 4.5.

Table 4.5 Hardened concrete properties and relevant test standards/methods

Property	Standard/Method
Density	SANS 6251:2006
Compressive Strength	SANS 5863:2006
Tensile Strength	SANS 6253:2006
Oxygen Permeability	Alexander et al. (2009a)
Water Sorptivity	Alexander et al. (2009a)
Chloride Conductivity	Alexander et al. (2009a)
Modulus of Elasticity	ASTM C469-10
Shrinkage	ASTM C157-08
Creep	ASTM C512-10

4.3 Mix Design

South Africa makes use of the Cement and Concrete Institute (C&CI) method for guidelines to designing concrete mixtures. The C&CI method is derived from the ACI Standard 211.1-91 (Addis & Goodman, 2009) and are based on the following concrete characteristics: strength, at a given age for fully compacted concrete at a particular water:cement (w:c) ratio, the amount of water required per unit volume of concrete, optimum stone content depending on stone characteristics and volume of compacted concrete made through a combination of materials. There are no specific guidelines for the inclusion of RCA in a concrete mixture and from the literature many researchers consider RCA as an additional coarse aggregate. The same method was used which would be utilised for natural aggregate.

Most researchers pre-saturate the RCA to a surface saturated dry (SSD) condition to reduce the effects that the material may have on the fresh and hardened concrete properties. For the purpose of this investigation the practical implications of following this method were not viable, not only for this investigation, even more so in concrete production industry. Consequently, all the materials used in this experimental programme were kept in an air dry condition, where they were stored in containers in a cool and dry environment. It is therefore not necessary to calculate the moisture content of any of the materials as they are assumed to have negligible moisture content.

The C&CI method is summarized below into the following steps (adapted from Addis & Goodman, 2009):

1. Specify the strength of the concrete;
2. Specify the coarse aggregate (stone) size and type;
3. Specify the required workability as a measure of the slump;
4. Define the binder(s) (cement and/or cement extender) type;
5. Select a fine aggregate (sand) type;
6. Characterise the concrete constituents (aggregates and binders);
7. Select a w:c ratio based on target strength;
8. Estimate water requirements;
9. Calculate the cement content, stone content and subsequent sand content;
10. Make a trial mixture of 10-15 litres;
11. Measure the slump, assess the stone content and cohesiveness;
12. Approve or reject mixture; or/and
13. Modify the mixture design.

The concrete for this study was assumed to be a general structural concrete of 30 to 40 MPa for a coastal region. The characteristics of the concrete constituents that were used in this investigation are given in Table 4.6. It must be noted the relative densities for the sand and RCA were different for each concrete mixture as these constituents were not kept constant throughout the experimental programme. It was therefore required that the control or reference mixtures had to be repeated for each batch of concrete made for the different RCA samples.

Table 4.6 Concrete constituent characteristics used in this investigation.

Constituent	Description	
Cement	Type	CEM I 52.5N
	RD	3.14
Cement Extender	Type	GGCS
	RD	2.9
Sand	Type	Malmesbury
	RD	2.61-2.63
	FM	2.2-2.5
	Quality	Good
Natural stone	Type	Greywacke
	Size	19mm
	RD	2.73-2.74
	CBD	1557
	K	0.94
Recycled stone	Type	RCA
	Size	19mm
	RD	2.59-2.66
	CBD	1541-1605
	K	0.94

To choose the correct w:c ratio, the cement supplier was contacted to provide updated water:cement ratio curves seen in Figure 4.2. For a 30 to 40 MPa concrete strength cast under laboratory conditions where the recommended degree of control margin was 8.2 MPa according to McDonald (2009), a w:c of 0.6 was chosen.

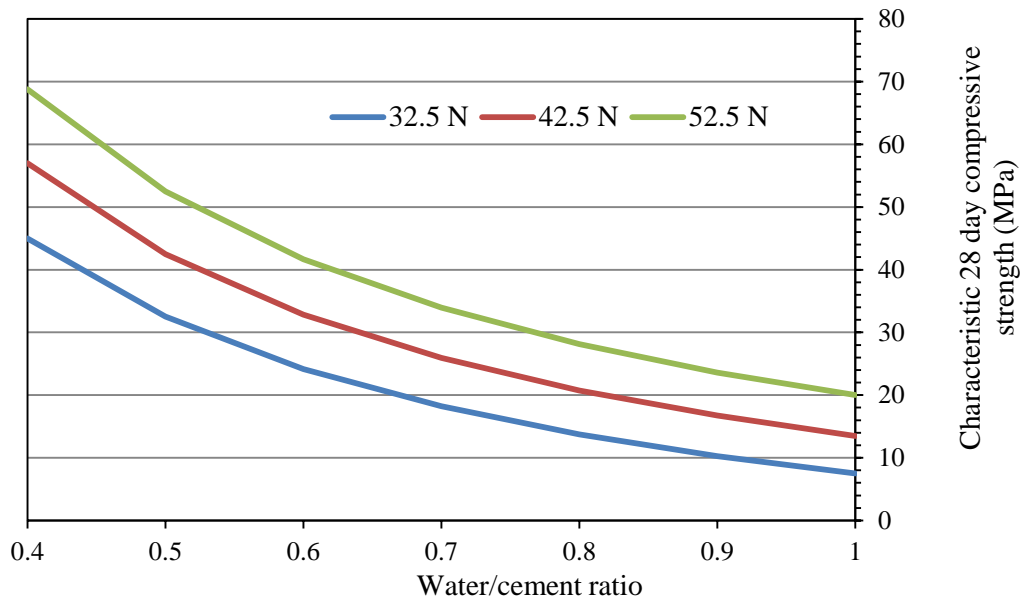


Figure 4.2 Water:cement ratio curves for different cements available from PPC (Crosswell, 2012)

For the workability and cohesiveness of the concrete mixtures to be consistent throughout the experimental programme and individual mixtures, trial mixtures were conducted on four concrete combinations. A target slump of 75mm was chosen and the mixtures should be cohesive. The four concrete mixtures were chosen for the potential of high variability and are described in Table 4.7.

Table 4.7 Different trial mixture combinations

Trial Concrete Mixtures
RCA 100% (CEM I ONLY)
NA 100% (CEM I ONLY)
RCA 100% (CEM I 50%/GGCS 50%)
NA 100% (CEM I 50%/GGCS 50%)

Once each of these mixtures were adjusted to meet the requirements of a good fresh concrete mixture and hardened concrete strength, the mixture proportions for different combinations were averaged and one single mixture was designed. Trial mixtures were made on this combination and modified to give the amounts provided in Table 4.8 as an example for a mixture containing 50% GGCS and 50% RCA replacement.

Table 4.8 Example of modified mix design

Constituents	kg/m ³	RD	litres
Water	180	1	180
Cement	150	3.14	47.8
Cement Extender	150	2.9	51.7
Natural Stone	485.3	2.73	177.8
Recycled Stone	471	2.65	177.8
Sand (CHOICE)	960	2.63	365
Total RCA Stone	956.3		1000

Most researchers base the percentage replacement on the mass; however by doing this the sand amount would not be consistent for each mixture according to the C&CI method. It was therefore decided that the percentage replacement would be based on the volume and the sand amount was initially chosen and kept constant. Trial mixtures were based on a 10l mix and the largest concrete mixture to be used in the experimental programme was 40l. The scaling from a small mixture to a larger mixture in terms of workability caused variation, with the slump increasing and cohesion questionable. The water amount was reduced to 175 kg/m³ and this resulted in a better concrete mixture.

Eight mixtures were prepared for comparison in the experimental programme. These mixtures were labelled according to the month the RCA concrete batch was produced, the percentage replacement and whether cement and/or cement extender was used. The concrete sample and mix proportions for March are given in Table 4.9 as an example, while the June and August concrete mixture proportions are given in Appendix B.

Table 4.9 March mix design for percentage replacements of RCA and binder

MarR15C				MarR50C			
Constituents	kg/m ³	RD	litres	Constituents	kg/m ³	RD	litres
Water	175	1.00	175	Water	175	1.00	175
Cement	292	3.14	93	Cement	292	3.14	93
Cement Extender	0	2.90	0	Cement Extender	0	2.90	0
Natural Stone	855	2.74	312	Natural Stone	503	2.74	184
Recycled Stone	146	2.65	55	Recycled Stone	486	2.65	184
Sand (CHOICE)	960	2.63	365	Sand (CHOICE)	960	2.63	365
Total Stone	1001		1000	Total Stone	989		1000

Table 4.9 continued...

MarR30C				MarR100C			
Constituents	kg/m ³	RD	litres	Constituents	kg/m ³	RD	litres
Water	175	1.00	175	Water	175	1.00	175
Cement	292	3.14	93	Cement	292	3.14	93
Cement Extender	0	2.90	0	Cement Extender	0	2.90	0
Natural Stone	704	2.74	257	Natural Stone	0	2.74	0
Recycled Stone	292	2.65	110	Recycled Stone	973	2.65	367
Sand (CHOICE)	960	2.63	365	Sand (CHOICE)	960	2.63	365
Total Stone	996		1000	Total Stone	973		1000

MarR30S				MarR100S			
Constituents	kg/m ³	RD	litres	Constituents	kg/m ³	RD	litres
Water	175	1.00	175	Water	175	1.00	175
Cement	146	3.14	46	Cement	146	3.14	46
Cement Extender	146	2.90	50	Cement Extender	146	2.90	50
Natural Stone	697	2.74	254	Natural Stone	0	2.74	0
Recycled Stone	289	2.65	109	Recycle Stone	963	2.65	363
Sand (CHOICE)	960	2.63	365	Sand (CHOICE)	960	2.63	365
Total Stone	986		1000	Total Stone	963		1000

MarN100C				MarN100S			
Constituents	kg/m ³	RD	litres	Constituents	kg/m ³	RD	litres
Water	175	1.00	175	Water	175	1.00	175
Cement	292	3.14	93	Cement	146	3.14	46
Cement Extender	0	2.90	0	Cement Extender	146	2.90	50
Natural Stone	1006	2.74	367	Natural Stone	995	2.74	363
Recycled Stone	0	2.65	0	Recycled Stone	0	2.65	0
Sand (CHOICE)	960	2.63	365	Sand (CHOICE)	960	2.63	365
Total Stone	1006		1000	Total Stone	995		1000

4.4 Mixing Procedure and Concrete Production

All the constituents for the concrete mixtures were assumed to be in an air dry condition before the addition of water. Four concrete mixtures were cast for each batch of RCA. The first mixture produced the test specimens for the compressive strength, tensile splitting strength and modulus of elasticity. The second would produce specimens for the durability tests. The third would be used for making shrinkage specimens and the last mixture would be used to make the creep specimens.

The concrete production for all the hardened concrete tests is summarized in Table 4.10 accompanied by the concrete volume. The mechanical, modulus of elasticity and durability mixtures were cast over four days, with each day comprising of four of the eight mixtures. The reason for this was due to the availability of moulds and the amount of testing per day that needed to be taken into account. The shrinkage and creep specimens were cast at a later date once the necessary procedures defined and apparatus needed were available. As stated Section 4.3 the sand was not kept constant for each monthly batch of concrete. The mechanical and modulus of elasticity (Emod) mixtures and durability mixtures were produced with the same sand material for each month. All the shrinkage and creep (dimensional) mixtures were produced using the same sand material which was available at the end of the experimental programme used in the August mixtures.

Table 4.10 Concrete mixtures for different batches and respective volumes

Concrete Mixture	Set 1	Set 2	Volume
Mechanical & Emod	R15C, R30C, R30S, N100C	R50C, R100C, R100S, N100S	40l
Durability	R15C, R30C, R30S, N100C	R50C, R100C, R100S, N100S	20l
Dimensional	R30C, R50C, R100C, N100C		12l

Prior to mixing the concrete all the materials were weighed. Due to the fact that different specimens were cast from each of the concrete mixtures, there was no manner to determine where the contaminants defined as “X” and “FL” in Section 5.1.6 that was present in the RCA would end up. The inclusion of these contaminants may lead to results which are not representative of the larger sample of RCA. Consequently the RCA that would be utilized each day was laid out on the floor and screened for these contaminants. The screening process involved using a strong magnet to remove magnetic items and visual inspection to remove the following items; plastics, rubber, non-magnetic metals, organics, papers, glass and wood as examples. No brick, tiles or similar items were however removed. Once this was completed the RCA was weighed.

All dry materials were added to a small concrete mixer in the order: sand, binders, stone and mixed for a minute. Water was then added and mixed for a further two minutes. After the relevant fresh concrete tests were completed the concrete was placed into the appropriate moulds and then vibrated. All concrete specimens were vibrated in a similar manner for consistency. First the mould was filled halfway and then vibrated for 15 seconds, then completely filled and vibrated for 30 seconds at high vibration. This method yielded concrete of a moderate compaction as some air bubbles were still present and the stone was within 5mm of the casting surface.

The moulds containing the concrete were then placed in a temperature controlled room of $21 \pm 1^\circ\text{C}$ and relative humidity of $65 \pm 5\%$. 24 hours after casting the concrete was removed from the moulds and placed in a curing tank with temperature $23 \pm 1^\circ\text{C}$ until testing.

4.6 Summary of the Experimental Programme

The experimental programme is summarised in Table 4.11. The aggregate, fresh concrete and hardened concrete tests were repeated for all three RCA batches i.e. March, June and August.

Table 4.11 Summary of experimental programme

Aggregate Tests								
Test/Property\Mixture	R15A	R30A	R50A	R100A	N100A	FA ^a		
Geometrical Properties								
Grading	*	*	*	*	*	*		
Dust content	*	*	*	*	*	*		
Fineness modulus	*	*	*	*	*	*		
Flakiness Index	*	*	*	*	*			
Shape and surface texture				*	*			
Constituents of coarse RCA				*				
Physical Properties								
Compacted and loose bulk density	*	*	*	*	*			
Relative density	*	*	*	*	*	*		
ACV	*	*	*	*	*			
Water absorption	*	*	*	*	*			
Chemical Properties								
Water soluble cations and anions	*	*	*	*	*			
Chemical mineralogy	*	*	*	*	*			
Fresh Concrete Tests								
Test/Property\Mixture	N100C	R15C	R30C	R50C	R100C	N100S	R30S	R100S
Slump	*	*	*	*	*	*	*	*
Slump loss	*	*	*	*	*	*	*	*
Air content	*	*	*	*	*	*	*	*
Density	*	*	*	*	*	*	*	*
Hardened Concrete Tests								
Test/Property\Mixture	N100C	R15C	R30C	R50C	R100C	N100S	R30S	R100S
Mechanical Properties								
Density	*	*	*	*	*	*	*	*
Compressive Strength	*	*	*	*	*	*	*	*
Tensile Strength	*	*	*	*	*	*	*	*
Durability Properties								
Oxygen Permeability	*	*	*	*	*	*	*	*
Water Sorptivity	*	*	*	*	*	*	*	*
Chloride Conductivity	*	*	*	*	*	*	*	*
Dimensional Properties								
Modulus of Elasticity	*	*	*	*	*	*	*	*
Shrinkage	*		*	*	*			
Creep	*		*	*	*			

^aFA = Fine aggregate

Chapter 5

Aggregate Properties

The aggregate properties for the monthly batches of RCA (March, June and August) were examined. The aggregate properties are assessed for the percentage replacements: 0, 15, 30, 50 and 100%. The testing procedures for the relevant standards and methods are described first in more detail and thereafter the results are presented. The results are presented according to the three main aggregate properties, namely: geometrical, physical/mechanical and chemical. Included in Appendix C are calculation examples for the various aggregate properties assessed as well as the apparatus used for each test.

5.1 Test Methodologies

5.1.1 Sieve analysis (grading, dust content & fineness modulus)

To determine the grading, dust content and fineness modulus of both fine and coarse aggregate, procedures in SANS 201:2008 were followed. A single sample, approximately 500g of fine aggregate was washed through the 1180 μ m and 75 μ m sieves consecutively until the water was clear. The material on the 1180 μ m sieve was returned to the original sample mass and the material on the 75 μ m sieve was weighed once dry. The remaining material was placed in an oven for 24 hours until dry, weighed and then graded. Grading of the fine aggregate was done through the following sieve sizes: 4750, 2360, 1180, 600, 300, 150 and 75 μ m. The material retained on each sieve was weighed to determine the grading, dust content and fineness modulus. The grading was calculated as the percentage material passing the respective sieve, while the fineness modulus is calculated by summing the cumulative percentages retained and dividing the result by 100. The dust content was calculated according to Equation 5.1.

$$\text{dust content} = \frac{(a - b) + c}{M_{Ff}} \quad [Eq 5.1]$$

where a = original test sample mass

b = mass of material after drying

c = mass of material passing the 75 μ m sieve

M_{Ff} = mass of material after sieving, plus (a – b)

The coarse aggregate sieve analysis was completed in a similar manner, except the original material mass was roughly 5 kg and was initially washed through the 1180, 425 and 75 μ m sieves consecutively. The material retained on the 1180 and 425 μ m sieves was returned to the original sample and the material of the 75 μ m was dried and then weighed. The coarse material was graded through the 26.5, 19.0, 13.2, 9.5, 6.7 and 4.75mm sieves successively. The grading and fineness modulus are determined similar to the fine aggregate, while the dust content is calculated according to Equation 5.2.

$$\text{dust content} = \frac{d - (e + f)}{M_{Fc}} \quad [Eq 5.2]$$

where d = mass of original test sample

e = mass of material after drying

f = mass of material retained on the 75 μ m sieve

M_{Fc} = mass of total test sample, after sieving, plus (d – e)

A material loss of 1% was permitted for the test.

5.1.2 Particle shape, Flakiness Index and surface texture

The particle shape and surface texture was classified and described according to the descriptions provided Tables 3.2 and 3.3 in Section 3.1.1 through a visual analysis of the relevant coarse aggregates.

The Flakiness Index (FI) was completed according to the SANS 5847:2008 procedure. The coarse aggregate samples from the sieve analysis were used to determine the FI value. The material retained on each sieve was weighed and the percentage retained of the total mass was determined. Material retained amounting to less than 10% of the total mass may be discarded; however in this experiment all the material retained on each sieve was assessed. The material was then gauged using an apparatus shown in Figure C.1 in Appendix C, where the mass passing the relevant slot was determined. The FI was then calculated as defined in Table 5.1.

Table 5.1 Flakiness Index (FI) calculation example

Sieve size	Individual mass percentage retained	Percentage mass passing slot	Flakiness Index
mm	a	b	$\sum(a \times b)/100$
26.5	10	20	2
19	67.5	35	23.625
13.2	15	30	4.5
FI =			30

5.1.3 Loose bulk, compacted bulk and relative density

The loose and compacted bulk densities are done in accordance with SANS 5845:2006 for the coarse aggregates. The loose bulk density (LBD) was determined by filling a container of known volume to the brim with a sample of aggregate in an air-dry condition. The mass was weighed and divided by the volume to determine the LBD to the nearest 1 kg/m³. The compact bulk density (CBD) was determined in the same manner, except the material was added into the container in three equal layers, where each layer was tamped 25 times using a tamping rod before the next layer was added. The methods for the LBD and CBD were repeated three times for each aggregate sample and the average between the results was calculated as the overall LBD and CBD.

The relative density was determined with reference to SANS 5844:2006 for both the coarse and fine aggregate. A sample of approximately 500g was weighed in an air-dry (AD) condition, differing from the prescribed SSD condition. Any foreign materials such as metals, wood and plastics are removed, due to the influence that these objects may have on the test results. The foreign materials form a small percentage when compared to the total amount of material and could be considered as not representative. The sample was then placed in a dry pycnometer which was also weighed and then water was added to cover the sample. A low pressure vacuum was used, while agitating the pycnometer and contents, to remove any entrapped air. The pycnometer was then filled completely with water and the mass was determined. The contents were removed and the pycnometer was then filled only with water and weighed. The relative density was determined using Equation 5.3.

$$RD = \frac{m_a}{m_a + m_b - m_c} \quad [Eq 5.3]$$

where m_a = mass of sample

m_b = mass of water (pycnometer mass zeroed)

m_c = mass of sample plus water (pycnometer mass zeroed)

The relative density sample size was small relative to the larger batches of aggregate, and therefore may not be representative. To account for this variability, six samples are measured for each of the individual aggregate amounts. Three of the samples were chosen randomly, while the other three were sampled according to the quartering and coning method and then combined to calculate the average relative density.

5.1.4 Aggregate crushing value

To determine the Aggregate Crushing Value (ACV) the prescribed method in SANS 5841:2008 was utilised. This test method was only used on coarse aggregate, and if the ACV result was greater than 30% the test method SANS 5842:2006 for the 10% FACT value should be used. To determine the ACV, the coarse material was sieved through a 13.2mm sieve and the material retained on the 9.5mm was measured as the test sample. All test samples were washed by agitating the samples under a jet of water to remove any adhered dust.

Once dry a 10kg sample for each percentage replacement was prepared by combining the natural and RCA material in a large bowl until thoroughly mixed. From the 10kg batch, a container was filled in three equal layers, tamping each layer 25 times with a tamping rod. The material was weighed and then added to the combination of base plate and crushing cylinder (Figure C.7 Appendix C) in the same manner as stated above, making sure no material was lost due to tamping. The crushing cylinder is placed in a compression machine and loaded to $400 \text{ kN} \pm 5 \text{ kN}$ in $10 \text{ min} \pm 15 \text{ s}$.

The material was then carefully removed from the crushing cylinder, using light strokes with the tamping rod. The material was sieved through a 2.36mm sieve until the material passing was minimal and then weighed. To determine the ACV, the mass of the material passing the 2.36mm sieve (m_b) was divided by the original mass before crushing (m_a) as given by Equation 5.4.

$$ACV = \frac{m_b}{m_a} \times 100 \quad [Eq 5.4]$$

This test method was repeated three times for each aggregate sample.

5.1.5 Water absorption

The water absorption of the coarse aggregate was calculated with guidance from SANS 5843:2008. Approximately 8kg of each individual aggregate sample was added to a clean container filled with water. The material was soaked for 24 hours and then placed in a large towel to dry the aggregate to an SSD state. A test sample of roughly 2kg was removed and the mass was determined. The test sample was then placed in an oven for 24 hours to dry after which it was weighed. The water absorption was determined according to Equation 5.5 and given as the mass percentage.

$$\text{Water absorption} = \frac{m_a - m_b}{m_b} \times 100 \quad [\text{Eq 5.5}]$$

where m_a = mass of SSD sample

m_b = mass of dry sample

The test was repeated three times for each aggregate sample.

5.1.6 Constituents of recycled concrete aggregate

To classify the constituents of RCA the British/European Standard BS EN 933-11:2009 was used as reference. It provides the method to identify and quantify by visual inspection the amount of various constituents that may be found in a sample of RCA. A test sample of at least 20kg of dry material was weighed and recorded as M_0 . The sample was then sieved through a 63mm and 4.75mm sieve respectively, weighing the material retained on the former of the sieves recorded as M_{63} and weighing the material passing the latter recorded as $M_{4.75}$. The M_{63} and $M_{4.75}$ materials were discarded and remaining mass was recorded as M_1 .

The clay and soil was then separated from the remaining mass. The standard was not clear in determining this mass, and therefore a method was prescribed by the author. The sample was immersed in a clean container filled with water. The material was agitated to remove adhered dust/clay and to release floating particles. The floating particles (FL) were removed, dried and their volume was determined. This was done by placing them in a graduated cylinder filled with a known volume of water. A plunger was used to push the particles beneath the water to allow for total immersion and measure the volume of water displaced (V_{FL}).

The non-floating particles were collected and dried. Once dry, the particles were spread over a flat surface and the items belonging to X as described in Table 5.2 were removed. These items were weighed and recorded as mass M_X . The water remaining in the container was washed through the

75 μ m sieve. The material retained on the sieve was dried and weighed and recorded as mass $M_{0,075}$ and was added to the mass of M_X .

The remaining non-floating material was weighed and recorded as M_2 . The sample may be reduced to simplify sorting to at least a 1000 particles by a recognized reduction method. Guidance on the minimum mass was provided in the standard and approximately 10kg was used for the final sorting and recorded as M_3 . The material was then sorted as described in Table 5.2, the masses weighed and recorded as M_{Rc} , M_{Ru} , M_{Rb} , M_{Ra} and M_{Rg} .

Table 5.2 Non-floating constituents of coarse RCA

Constituent	Description
Rc	Concrete, concrete products, mortar and concrete masonry units
Ru	Unbound aggregate, natural stone and hydraulically bound aggregate
Rb	Clay masonry units (i.e. bricks and tiles), calcium silicate masonry units and aerated non-floating concrete
Ra	Bituminous materials
Rg	Glass
X	Other: Cohesive (i.e. clay and soil), miscellaneous: metals (ferrous and non-ferrous), non-floating woods, plastics, rubbers, and gypsum plaster

The calculations for the different constituents are given in Equations 5.6 to 5.12 and rounded to one decimal place, except for the percentages above or equal to 10% which have no decimal.

$$\mathbf{FL} \text{ (cm}^3\text{/kg)} = 100 \times (V_{FL}/M_1) \quad [\text{Eq. 5.6}]$$

$$\mathbf{X} \text{ (\%)} = 100 \times (M_X/M_1) \quad [\text{Eq. 5.7}]$$

$$\mathbf{Rc} \text{ (\%)} = 100 \times (M_2/M_1) \times (M_{Rc}/M_3) \quad [\text{Eq. 5.8}]$$

$$\mathbf{Ru} \text{ (\%)} = 100 \times (M_2/M_1) \times (M_{Ru}/M_3) \quad [\text{Eq. 5.9}]$$

$$\mathbf{Rb} \text{ (\%)} = 100 \times (M_2/M_1) \times (M_{Rb}/M_3) \quad [\text{Eq. 5.10}]$$

$$\mathbf{Ra} \text{ (\%)} = 100 \times (M_2/M_1) \times (M_{Ra}/M_3) \quad [\text{Eq. 5.11}]$$

$$\mathbf{Rg} \text{ (\%)} = 100 \times (M_2/M_1) \times (M_{Rg}/M_3) \quad [\text{Eq. 5.12}]$$

Foreign materials (X) including floating materials were removed from the RCA before mixing the concrete. The mass total of woods plastics, glass, metals (ferrous and non-ferrous) and other items were determined. The volumetric mass of floating items for the total foreign materials was calculated by submerging the material under water and following the same procedure as described above for floating particles (FL).

5.1.7 Chemical analysis for water soluble cations and anions

Test samples were prepared by quartering and coning a sample of each aggregate combination (R15A, R30A, R50A, R100A and RefN100A) from $\pm 40\text{kg}$ to $\pm 500\text{g}$. The test sample was checked for any foreign material which may not be representative of the sample population and removed. The samples were then crushed into a fine powder (particle size $< 70\mu\text{m}$) with a jaw crusher and milled in a tungsten-carbide Zibb mill. The jaw crusher and mill were cleaned with clean uncontaminated quartz between two samples to avoid cross contamination. Test samples for the XRF analyses were also taken from the milled powder.

Gordon (2012) describes the methods determining the water soluble cations and anions. 10g of the test sample was added to 50ml of distilled water and this mixture was then shaken on a horizontal shaker for 1 hour. The mixture of sample and distilled water was then centrifuged. The clear solution part of the filtrate was analysed for cations by atomic absorption spectroscopy and the anions by ion chromatography. To convert results to mg/kg or ppm (parts per million) multiply the result by 5.

5.1.8 XRF analysis

The X-ray fluorescence (XRF) analyses were completed using test samples prepared in the same manner as described in Section 5.1.7. Sanchez-Garrido (2012) describes that glass disks were prepared for XRF analysis using 10g of high purity trace element and Rare Earth Element-free flux ($\text{LiBO}_2 = 32.83\%$, $\text{Li}_2\text{B}_4\text{O}_7 = 66.67\%$, $\text{LiI} = 0.50\%$) mixed with 1g of the powder sample. Whole-rock major element compositions were determined by XRF spectrometry on a PANalytical Axios Wavelength Dispersive spectrometer. The spectrometer is fitted with an Rh tube and with the following analyzing crystals: LIF200, LIF220, LIF420, PET, Ge and PX1. The instrument is fitted with a gas-flow proportional counter and a scintillation detector. The gas-flow proportional counter uses a 90% Argon, 10% methane mixture of gas. Major elements were analyzed on a fused glass disk at 50kV and 50mA tube operating conditions. Matrix effects in the samples were corrected for by applying theoretical alpha factors and measured line overlap factors to the raw intensities measured with the SuperQ PANalytical software. The concentration of the control standards that were used in the calibration procedures for major element analyses fit the range of concentration of the samples. Amongst these standards were NIM-G (Granite from the Council for Mineral Technology, South Africa) and BE-N (Basalt from the International Working Group). The loss on ignition (LOI) is the weight loss or gain at 1000°C .

5.2 Results

Geometrical Properties

5.2.1 Sieve analysis (grading, dust content and fineness modulus)

The grading results from the sieve analysis for the different batches of RCA collected throughout the experimental programme are shown in Figures 5.1 to 5.3. Included in these figures is the grading for the natural aggregate or reference material (RefN100A) as well as the original intended grading for the RCA (Graded R100A). The March sample displays a higher amount of 9.5mm sized stone, which is attributed to the error as stated in Section 4.1.2. The grading curves for all the monthly samples exhibit the same trend, where the increasing percentage replacement results in a greater amount of smaller stones and consequently an improved continuous grading compared to that of the reference material. The June and August samples indicate that the intended grading was achieved for the 100% recycled material. The improved continuous grading resulting from the addition of RCA will improve the workability of the fresh concrete and should result in lower air content due to better packing ability.

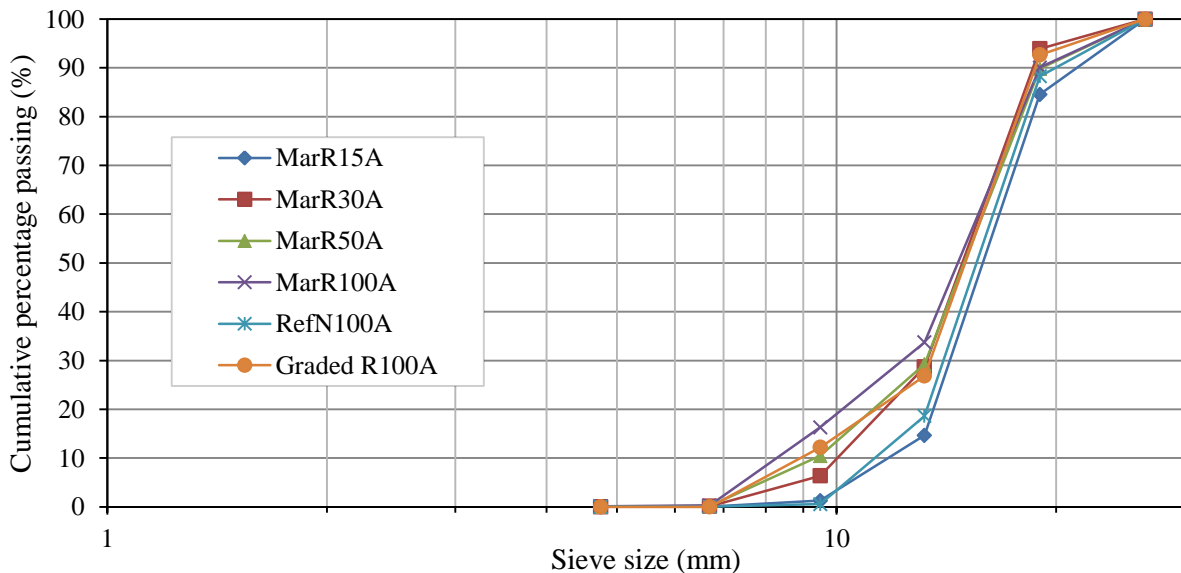


Figure 5.1 Grading curves of the RCA samples prepared from the March period

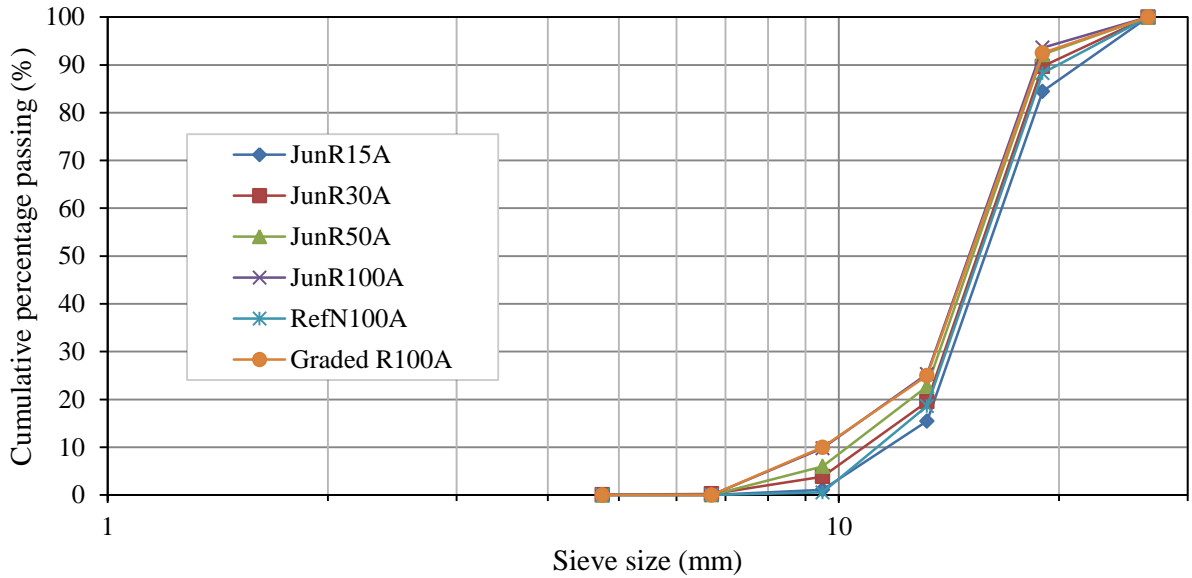


Figure 5.2 Grading curves of the RCA samples prepared from the June period

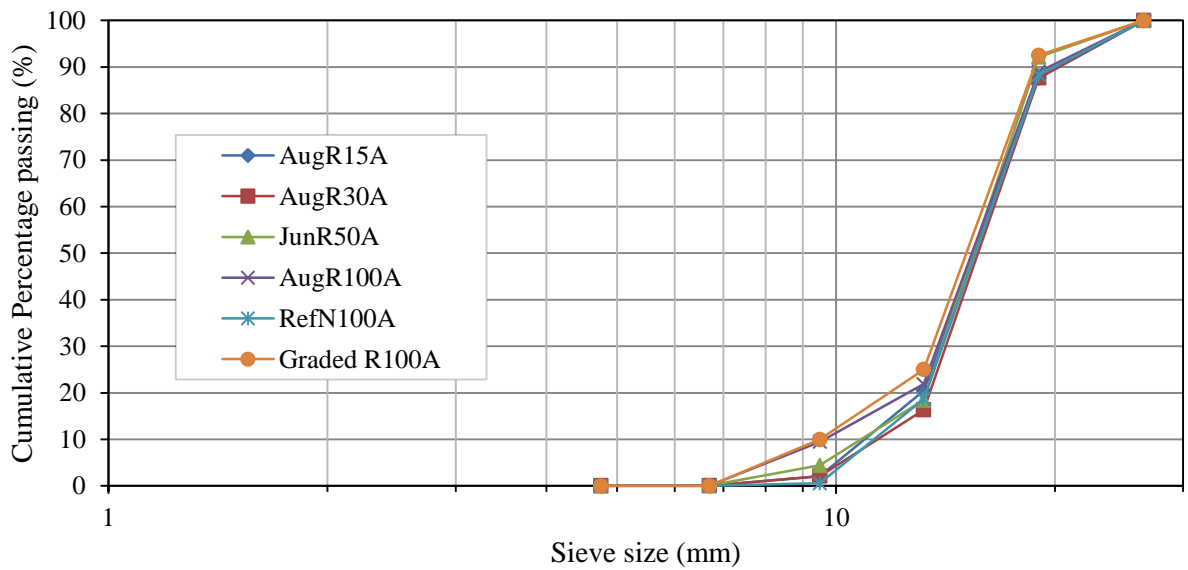


Figure 5.3 Grading curves of the RCA samples prepared from the August period

The grading curves for the natural fine aggregate (Malmesbury sand) are included, as the sand also plays an important role in the workability of the fresh concrete. The results from the sieve analysis are shown in Figure 5.4 and shows that the March sand has a better continuous grading compared the other two sands.

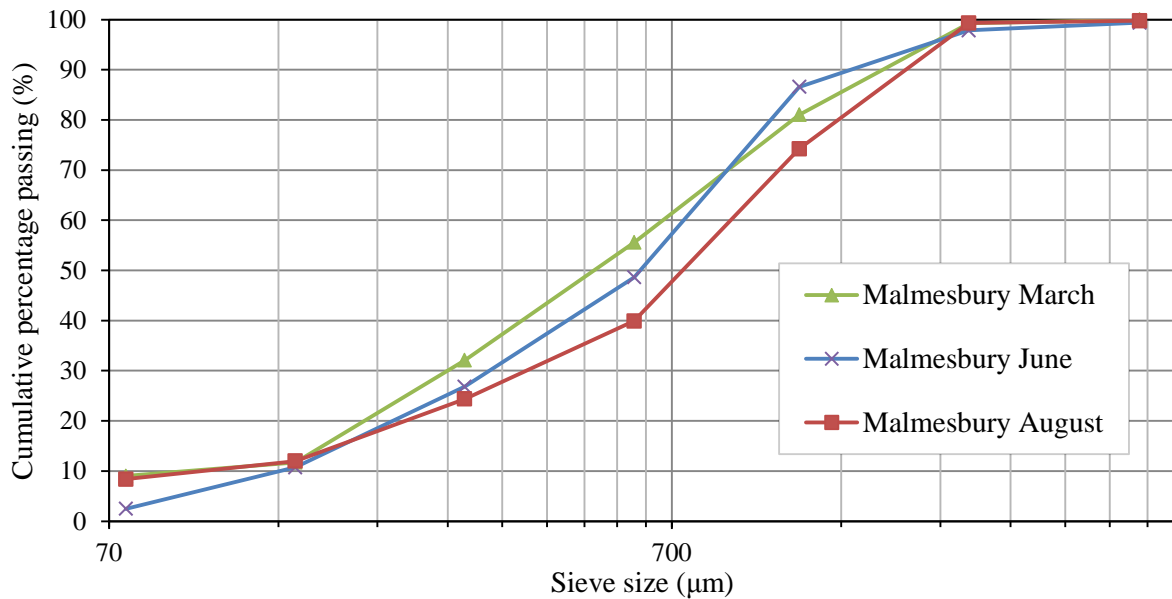


Figure 5.4 Grading curves for the natural fine aggregate

From the sieve analysis the fineness modulus (FM) and dust content were also determined and summarised for both the fine and coarse aggregate in Table 5.3. The results for the fine aggregate show that the August material is the coarsest of the three, with a FM of 2.5. All the fine aggregates fall within the medium sand fineness as noted in Table 3.4 in Section 3.1.2. The coarser the fine material, the lower the water requirement as is noticed in the fresh concrete property results in Chapter 6.

The FM of the coarse aggregate is not as important as that of the fine aggregate. The data shows that as the percentage replacement increases the FM decreases. This is a consequence of an increase in smaller stone sizes and will result in a material that is less harsh in fresh concrete.

The dust content is higher than the prescribed limit of 5% in SANS 1083:2006 for the March and August fine aggregate samples, however in subclause 4.2.3.2, it states that the maximum dust content limit may be adjusted to 10% provided the material passes the methane blue absorption and clay content tests. Assuming that the supplier providing the materials has completed these checks, the dust content is within the 10% limit. The dust content for the coarse aggregate is lower than the prescribed 2% according to SANS 1083 for all the individual aggregate samples. From the results, as the percentage replacement increases, the dust content increases. It was stated in Section 3.1.2 that the RCA has higher dust content when compared to natural aggregates and should reduce the bleeding and segregation potential of fresh concrete.

Table 5.3 Dust content and FM for fine and coarse aggregates

Sample	Dust Content (%)	Fineness Modulus
Fine Aggregate		
March Sand	8.42	2.20
June Sand	2.44	2.30
August Sand	7.84	2.50
Coarse Aggregate		
RefN100A	0.24	3.93
March		
MarR15A	0.22	3.99
MarR30A	0.31	3.71
MarR50A	0.30	3.70
MarR100A	0.13	3.60
June		
JunR15A	0.29	3.99
JunR30A	0.40	3.87
JunR50A	0.44	3.79
JunR100A	0.55	3.71
August		
AugR15A	0.37	3.90
AugR30A	0.46	3.94
AugR50A	0.50	3.85
AugR100A	0.61	3.80

5.2.2 Particle shape, Flakiness Index and surface texture

The visual inspection of the coarse aggregate shows that the aggregates varied in both shape and texture and this is illustrated in Figure 5.5. In Figure 5.5a, the reference material displays an angular, elongated and flaky shape with a rough surface texture. The recycled material generally has an irregular, sub-angular and cubical shape as seen in Figures 5.5b to 5.5d. The surface texture is rough, porous and highly porous, in the case of the stone, stone & mortar and brick & mortar particles, respectively. The RCA shape and surface texture is determined by the methods of crushing, where the employment of different crushing methods improves the shape and surface texture by removing the adhered mortar. The larger particle shape resembles that of the natural aggregate, whilst the smaller particles are more cubical and sub-rounded.



Figure 5.5 Photographs of coarse aggregate used in experimental programme

The flakiness index (FI) value gives an indication of particle shape in terms of flatness. Greywacke generally has a high FI value, as a result of crushing properties. In this case the FI value for RefN100A is 25 and as the percentage replacement increases the FI value decreases. It is interesting to note that from the data shown in Figure 5.6, at 15% and 50% there is some variability with the FI value. At 0%, 30% and 100% replacement the values are identical for the monthly samples of RCA. The FI value at 30% is 20 and decreases to 7 for 100% replacement. The SANS 1083:2006 limits the FI value to 35, which means that all the material would meet this specification. This low FI value can be attributed to the rounder and less angular nature of the RCA material, and should improve the workability and water requirement of fresh concrete. A higher FI value may improve the tensile strength of hardened concrete, as it decreases the possibility of forming continuous failure cracks.

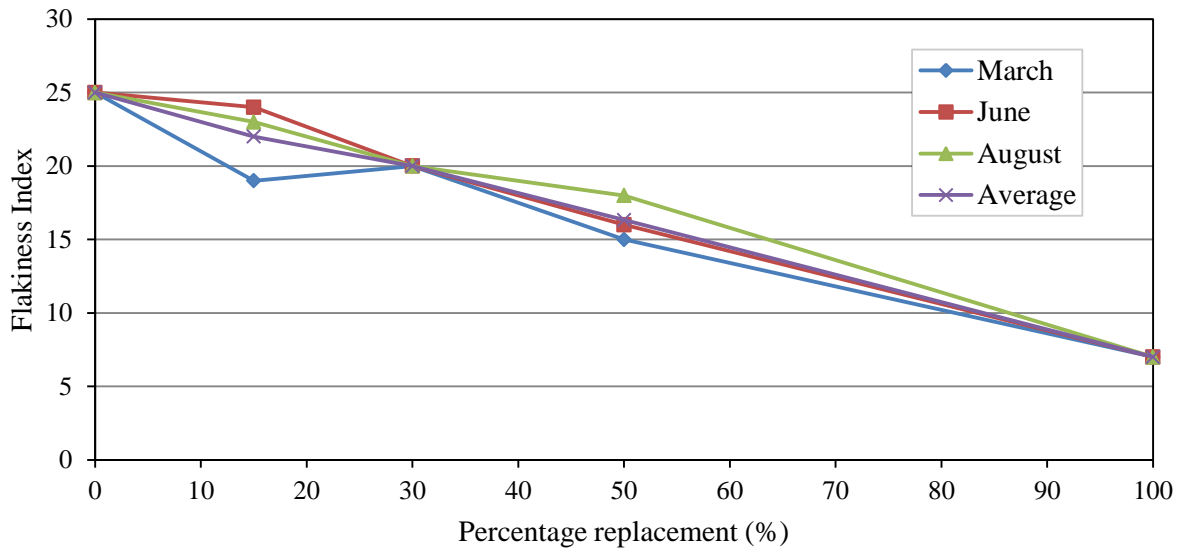


Figure 5.6 Graph to show the influence of percentage replacement of the FI value for coarse aggregate

Physical Properties

5.2.3 Constituents of recycled concrete aggregate

The results from the constituents analysis completed on the RCA from each month are presented in Figures 5.7 to 5.9 with symbols defined in Table 5.2. The March and June samples had similar compositions as the March samples containing slightly higher proportions of brick and stone/mortar combination. The RCA collected in August had the worst composition with significantly higher amounts of brick and stone/mortar combination. The higher proportions of lower density particles will result in a lower relative density, but not necessarily a lower compacted density.

The lower percentage constituents in the March RCA sample consisted of 0.08% bituminous materials, 0.09% foreign non-floating materials and 1.58% clay masonry items. The floating material found in the March RCA sample amounted to 0.21 cm³/kg. The June RCA had 0.07% foreign non-floating materials, 1.09% clay masonry items and 1.29% bituminous materials. The floating items found in the June RCA totalled 0.90 cm³/kg. The August RCA sample lower percentage items comprised of 0.03% glass, 0.12% bituminous materials, 0.27% foreign non-floating materials and 6.38% clay masonry units. The August RCA had 0.50 cm³/kg of floating materials.

The foreign (X) items consisted mainly of metals, plastics, polymers and wood and are discussed in more detail later in this section. The floating particles mainly consisted of wood and plastics. Considering the limits in Table 3.48 of BS 8500-2:2006, all the RCA used in this investigation would have met the requirements listed in the table, except possibly the August sample. The clay masonry content of 6.38% is slightly higher than the maximum allowable amount of 5%.

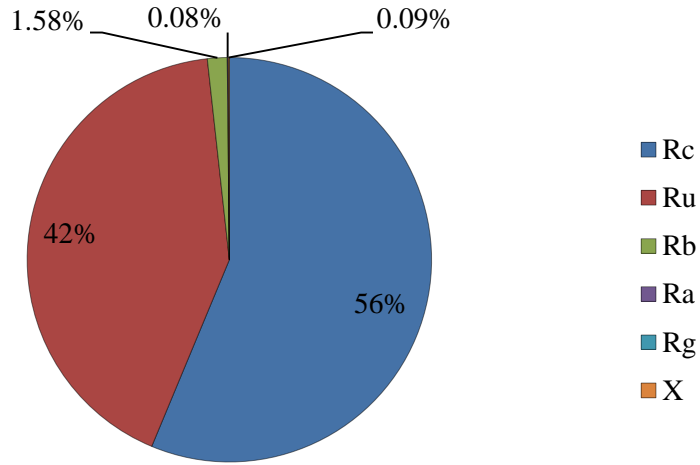


Figure 5.7 Constituent composition for the 100% RCA collected in March

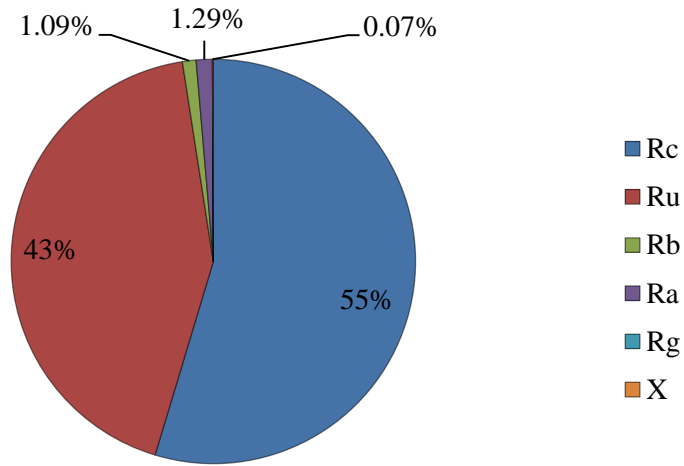


Figure 5.8 Constituent composition for the 100% RCA collected in June

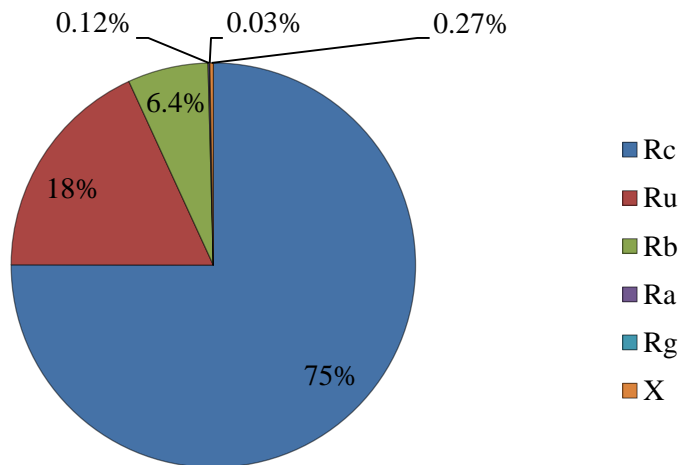


Figure 5.9 Constituent composition for the 100% RCA collected in August

The RCA collected in March comprised of $\pm 1/3$ C&D waste from a demolition project in the city of Cape Town and $\pm 2/3$ C&D waste from a demolition project in the Cape Town harbour. The June RCA comprised of mainly the C&D waste from the same harbour project in March. The August RCA sample was derived from a city demolition project. The composition of the different RCA samples reflect the possible original C&D waste, where city projects could contain more brick items, due to brick partitioning walls and the harbour C&D waste could be collected from large concrete elements. The potential chemical contaminants in C&D waste from projects in close proximity to the sea could be of concern and is discussed in Section 5.2.7.

Assessing the amount of constituents Rc (concrete) and Ru (unbound aggregate) was difficult as the latter, although primarily consisting of stone, a fine layer of assumed old cement paste was attached to most of the stone particles. Seen in Figure 5.10 the Ru particles (left) have an almost “cement” like layer across the surface of the aggregate. The Rc particle (right) have this layer of “cement”, but have a definite bound cement paste attached to the stone. The attached cement paste in some instances only covered a small portion of the stone. There was no clear description differentiating this observation, so it was assumed that Rc particles would be assessed as particles with a definite attached cement paste, irrelevant of the amount attached. Ru particles were then assessed as described above.

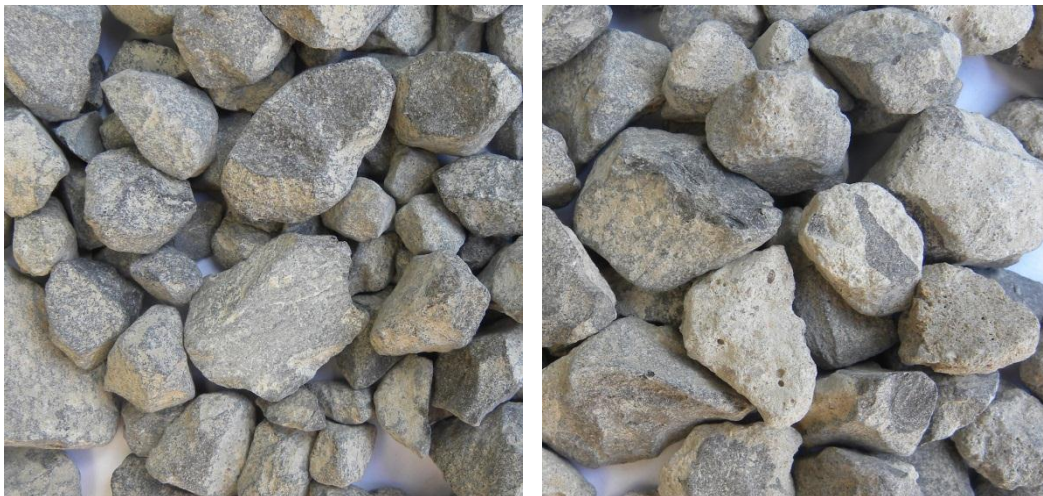


Figure 5.10 The difference between the Ru (stone) and Rc (stone/mortar) particles

As stated in Section 4.4, prior to mixing the foreign (X) items including glass were removed from the RCA. The amount of RCA to be used for each batch of concrete mixtures per day was roughly weighed off and placed on the ground. The items were removed by visual inspection and sorted according to the items under (X) listed in Table 5.2. The RCA to be used in each mixture was then accurately weighed off. The foreign material collected from each RCA batch was individually assessed and then combined to produce the amounts recorded in Table 5.4.

To calculate the mass percentage of foreign items within an RCA batch, the approximate total mass of RCA used for the concrete mixtures for each month was determined as ± 295 kg. The foreign materials also consisted of floating items whose volume was determined for each RCA batch. The floating material is presented as a volume of the total foreign materials mass and a volume of total RCA mass.

Table 5.4 The total foreign material removed from the RCA before mixing the concrete

Month/ Foreign Items	March		June		August	
	Amount (g)	(%)	Amount (g)	(%)	Amount (g)	(%)
Glass	0.0	0.0	0	0.0	44.7	9.1
Ferrous metals	162.9	71.8	184.2	52.7	303.8	62.0
Non-ferrous metals	14.0	6.2	11.8	3.4	38.7	7.9
Plastics, polymers, rubber	32.4	14.3	89.5	25.6	76.5	15.6
Wood, paper	17.7	7.8	64.1	18.3	26.1	5.3
Total Foreign Material^a	227.0	100.0	349.6	100.0	489.8	100.0
Large RCA sample (± 295 kg)	0.08 %		0.12 %		0.17 %	
Floating material	50 cm ³		152 cm ³		84 cm ³	
Floating material/TFM ^b	0.22 cm ³ /g		0.43 cm ³ /g		0.17 cm ³ /g	
Floating material/TRM ^c	0.17 cm³/kg		0.52 cm³/kg		0.28 cm³/kg	

^a floating and non-floating items

^b TFM = Total Foreign Material Mass

^c TRM = Total RCA Mass (± 295 kg)

From the data presented in Table 5.4 it is clear that the amount of non-floating foreign material determined for the small RCA sample (± 20 kg) is similar to the amount determined from the large RCA sample (± 295 kg), taking into account that the floating material is included in the large sample assessment. A large RCA sample would be a better representation for the possible foreign material found in the RCA, which is recommended by EN 933-11:2009.

The amount of floating material present in the RCA differs between the large and small samples. The small RCA sample over estimates the amount of floating material present in the RCA. For example, the small RCA sample from August had 0.50 cm³/kg of floating material, while the large RCA sample had 0.28 cm³/kg of floating material. The large RCA sample is more representative and will be more accurate in assessing the amount of floating materials.

Assessing the individual foreign items present in the RCA, it is evident that the metal constitutes the greatest mass of all the items. As stated in the small RCA sample assessment, the wood and plastic items represent the largest amount of the floating items. When examining the foreign material as both floating and non-floating items combined, it can be noted that although the total mass of the foreign items may be the highest, the total amount of floating items may not reflect this mass. As an example,

comparing the June and August RCA samples, the total mass of foreign materials (489.8g) was greater in the August sample, but the amount of floating foreign materials (0.43 cm³/g) was greater in the June sample.

An important observation was made during the foreign material assessment. Seen in Figure 5.11 are photographs of the total foreign material collected from the June RCA (left) and August RCA (right). The floating items such as wood are large in size and contribute the greatest to volume of floating materials. Of concern is the size of metals present in the RCA, as seen in the photograph on the right. These items should be removed by magnets along the recycling processing stream, but some pass these magnets and end up in the RCA. The metals have been exposed to moist conditions and it is obvious from the photograph that corrosion has started taking place. The concern raised by this observation is that if such an item was located near the surface of the concrete, it would be more susceptible to further corrosion and may lead to localised spalling or increase the potential for corrosion of nearby steel reinforcing. Items such as wood could swell in moist conditions causing spalling, because the material would possibly float close to the surface of the concrete. Measures should be in place to reduce the amount of floating and non-floating material as far as possible through simple or specialised recycling techniques.



Figure 5.11 Photographs of the total foreign material collected from the RCA in June (left) and August (right)

5.2.4 Loose bulk, compacted bulk and relative density

The relative density (RD) of RCA is the primary indicator of the physical properties and to whether or not the material is acceptable after the visual inspection. The RD values are highly variable due to the small sample size necessary for the test. Even with the correct sampling technique, the variability is a problem especially in the cases where higher percentages of lower density materials are present.

Figure 5.12 gives both a graphical and numerical representation of the relative densities calculated for the individual aggregate samples.

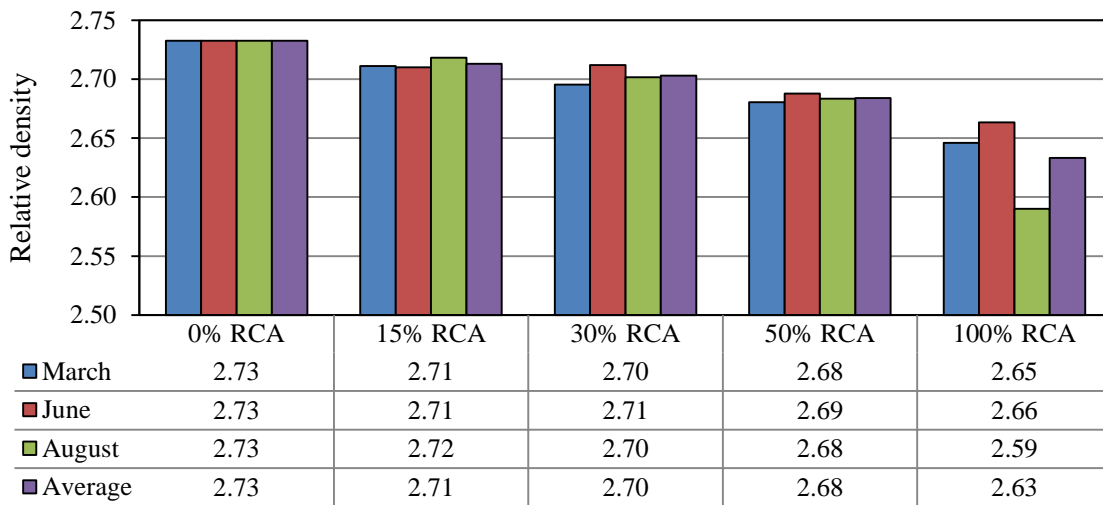


Figure 5.12 Bar graph representing the relative densities for the aggregate samples

From the data presented, it is evident that with increasing replacement percentage, the RD value decreases. The RD for a combination of materials can be calculated based on the individual relative density and the amount (percentage) by which the materials are combined. This is calculated using Equation 5.13 as provided and adapted from Addis & Goodman (2009).

$$RD = \frac{100}{\frac{\%_a}{RD_a} + \frac{\%_b}{RD_b}} \quad [Eq. 5.13]$$

where $\%_a$ = percentage of material a

$\%_b$ = percentage of material b

RD_a = RD of material a

RD_b = RD of material b

The difference between the calculated value and the measured value is presented in Table 5.5. The difference between the two results is marginal, with the August RCA samples showing a slightly higher difference which could be related to the greater percentage of lower density materials or an error in the experimental analysis of 100% RCA sample.

Table 5.5 Calculated RD values and difference between experimental results

Percentage Replacement	Calculated March	Difference March	Calculated June	Difference June	Calculated August	Difference August
0%	2.73	0.00	2.73	0.00	2.73	0.00
15%	2.72	0.01	2.72	0.01	2.71	-0.01
30%	2.71	0.01	2.71	0.00	2.69	-0.01
50%	2.69	0.01	2.70	0.01	2.66	-0.02
100%	2.65	0.00	2.66	0.00	2.59	0.00

The RD is important in determining the mixture proportions for the mix design and to maintain a concrete density that is within the suitable range. For materials which have a significantly low RD value it can be assumed that a high proportion of lower density materials are present and may be the basis for rejection before further testing. A greater presence of lower density materials would typically result in higher water absorption due to the porous nature associated with these materials.

The loose bulk and compact bulk densities (LBD & CBD, respectively) are important in determining the packing capacity of the material. Table 5.6 provides the values determined for the LBD and CBD and Figure 5.13 provide a graphical representation of the results. The values for the RCA materials ranged from 1401 to 1462 kg/m³ and 1541 to 1605 kg/m³ for the LBD and CBD, respectively at 100% replacement, while the natural aggregate had an LBD and CBD of 1405 kg/m³ and 1557 kg/m³, respectively. The results for both densities showed that March had the highest, and then June and August had the lowest values. The LBD and CBD values for the August RCA samples are low when compared to the June RCA, because of the presence of lower density materials. The March sample has the highest LBD and CBD when compared to June, due to the higher proportion of smaller stone which would result in a reduction of voids.

Table 5.6 Values for the LBD and CBD for monthly samples of RCA

Percentage Replacement	March		June		August		Average	
	LBD	CBD	LBD	CBD	LBD	CBD	LBD	CBD
0%	1405	1557	1405	1557	1405	1557	1405	1557
15%	1422	1587	1409	1557	1395	1548	1409	1564
30%	1428	1588	1417	1575	1402	1559	1416	1574
50%	1440	1597	1432	1584	1402	1555	1425	1578
100%	1462	1605	1452	1600	1401	1541	1438	1582

Examining the percentage replacement influence on the LBD and CBD values showed that with increasing replacement, the LBD and CBD increased as well, except in the case of August RCA. The relative density for the materials is lower than that of the reference material as previously discussed.

However, the improved continuous grading increases the packing capacity. The August sample displays how a much lower relative density can affect the packing capacity, even with a continuous grading.

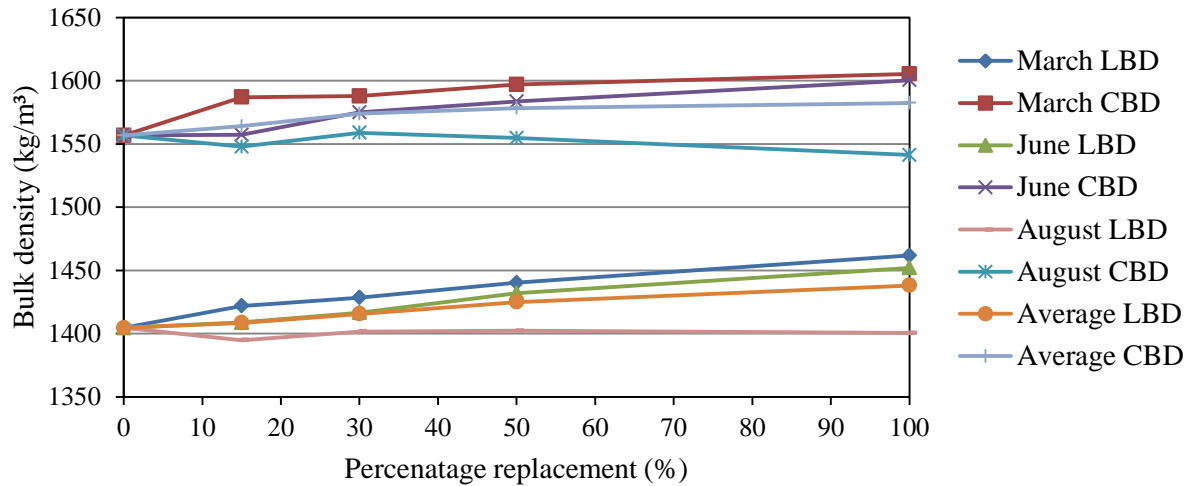


Figure 5.13 LBD and CBD values for different RCA percentages from each month

5.2.5 Water absorption

The water absorption results provided consistent data with low variability between the averages of the three test samples per individual aggregate sample. The reference material had the lowest water absorption (WA) percentage at 0.52% and the highest value was achieved with the August RCA sample at 2.59% (Table 5.7). A trend can be determined from the WA results, with the WA increasing with increasing percentage replacement. The higher WA values for RCA can be attributed to the presence of brick particles as seen in the August sample and also the combined stone & mortar and individual mortar particles present in the March and June samples. The March and June RCA samples had similar WA percentages, but were still relatively low when compared to examples described in Section 3.1.5.

Table 5.7 Measured water absorption percentages for RCA

RCA %	March	June	August	Average
0%	0.52	0.52	0.52	0.52
15%	0.59	0.67	0.79	0.68
30%	0.80	0.82	1.15	0.92
50%	1.13	1.01	1.71	1.28
100%	1.67	1.44	2.59	1.90

From Figure 5.14 it can be seen that there is an almost linear increase in WA with increasing percentage replacement. The samples with a higher WA are associated to the same samples with a lower RD. With the fact that the WA is relatively low the impact on the workability of fresh concrete will be minimal and the influence on the water:binder ratio may become apparent in Chapter 7.

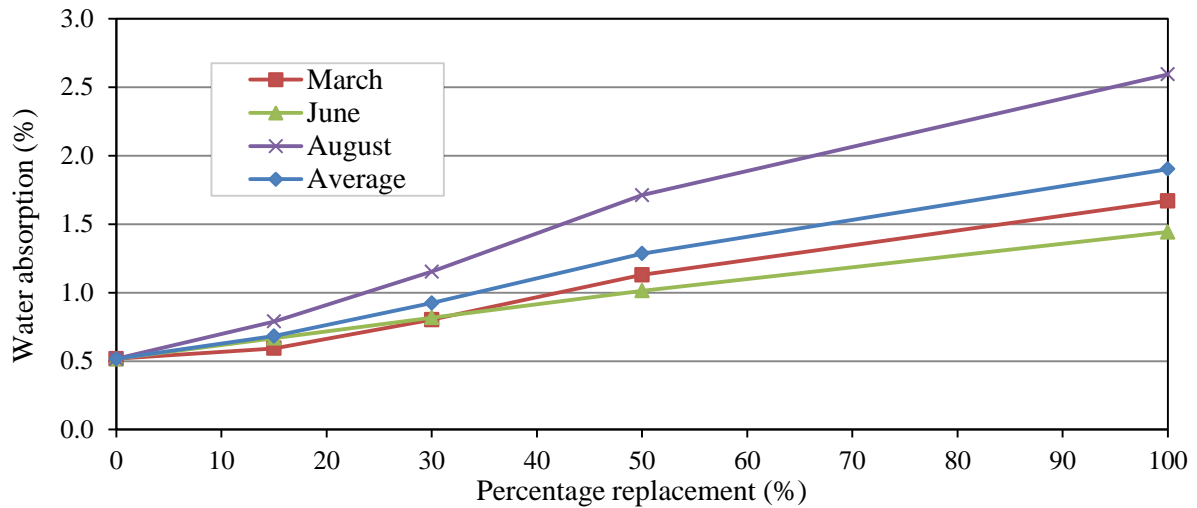


Figure 5.14 Water absorption versus the percentage replacement for monthly RCA samples

5.2.6 Aggregate strength - Aggregate crushing value

The ACV results are shown in Figure 5.15 for the individual aggregate samples. There is no clear trend for the change in percentage replacement, however the August aggregate sample results displayed an increasing trend with increasing replacement. The March and June samples ACV results are relatively similar for all percentages when compared to the reference material. The highest value from the ACV results is 15.2% for AugR100A and the lowest 10.8% for MarR50A. The comparable margins are small as the test is repeated three times for each sample with a coefficient of variance below 5% for every sample measured.

The results show that RCA strength is therefore comparable to that of natural aggregate, except in the case where the higher percentages of fragile materials such as brick become significant, as was the case with the August sample. The fragile materials are weaker in strength and produce finer particles when crushed. The SANS 1083:2006 recommends an ACV value below 30%, which confirms that all the aggregates for this experimental programme would meet the requirements from this standard.

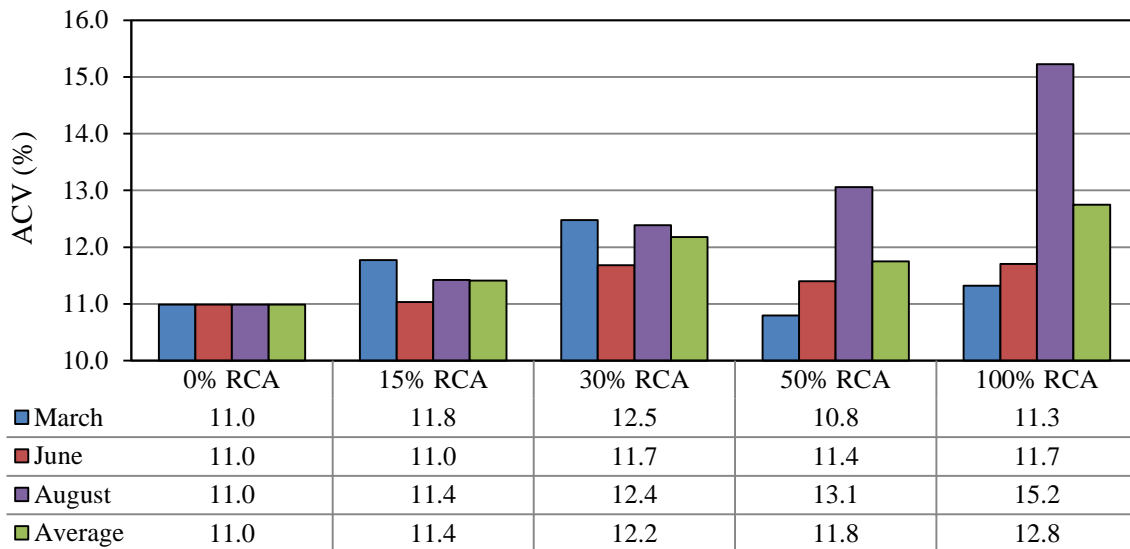


Figure 5.15 Aggregate Crushing Value (ACV) results for coarse RCA samples

Chemical Properties

5.2.7 Chemical analysis for water soluble cations and anions

The chemical analysis results for water soluble cations and anions for the different percentages of RCA used in each month is given in Tables 5.8 to 5.10. The results show variable results with some ions presented. The small test sample ($\pm 500\text{g}$) amount may not be representative and the percentages of RCA and NA may have changed particularly in the lower percentages. Considering the attached mortar on the particles, particles with larger portions of attached mortar may have been more present in some samples than others. The test was conducted on only one sample for each percentage. Nevertheless, examining the overall amount of ions between the percentages will give an indication to the possible amounts of ions present in a batch of RCA.

Table 5.8 Water soluble ions present in the RCA samples from March

Sample	RefN100A	MarR15A	MarR30A	MarR50A	MarR100A
Ca (mg/l)	1.9	62.7	11.1	8.1	12
Mg (mg/l)	2.3	0.1	0.1	0.1	0.1
Na (mg/l)	6.1	8.3	16.1	12.9	26.1
K (mg/l)	18.3	22.4	36.5	36.3	53.4
Cl (mg/l)	2.7	3.7	4.3	6.1	9
SO ₄ (mg/l)	8.2	10.6	29.5	31.4	9.9
Total	39.5	107.8	97.6	94.9	110.5

Table 5.9 Water soluble ions present in the RCA samples from June

Sample	RefN100A	JunR15A	JunR30A	JunR50A	JunR100A
Ca (mg/l)	1.9	9.6	10.1	86.4	18.3
Mg (mg/l)	2.3	0.1	0.1	0.1	0.1
Na (mg/l)	6.1	7.9	9.4	15.1	17.9
K (mg/l)	18.3	25.7	33.6	34.1	32.8
Cl (mg/l)	2.7	3.3	3	8.9	8.3
SO ₄ (mg/l)	8.2	16.4	23.1	6	49.5
Total	39.5	63	79.3	150.6	126.9

Table 5.10 Water soluble ions present in the RCA samples from August

Sample	RefN100A	AugR15A	AugR30A	AugR50A	AugR100A
Ca (mg/l)	1.9	15	6.7	15.7	38.5
Mg (mg/l)	2.3	0.1	0.1	0.1	0.1
Na (mg/l)	6.1	9.6	11.7	15.7	17
K (mg/l)	18.3	32.1	40.4	39.5	28
Cl (mg/l)	2.7	4.1	2.8	3.4	3.7
SO ₄ (mg/l)	8.2	39.1	22.7	11.5	10
Total	39.5	100	84.4	85.9	97.3

From the data presented it is clear that the RCA increases the amounts of all the soluble ions investigated, except in the case of magnesium (Mg) ions. The amount of calcium (Ca) ions is higher in the August samples possibly due to the higher amount of stone/mortar combination. As noted in Section 3.1.7 higher amounts of Ca ions are present in the cement paste. The potassium (K) ions are consistently the highest amount in all the samples. The potassium (K) and sodium (Na) ions form in hydration of cement along with calcium (Ca), sulphate (SO₄) and chloride (Cl) ions in lower concentrations to raise the pH. Assessing the total amount of the ions present in the samples investigated shows that highest amount is about 150 mg/l. Table 3.13 in Section 3.1.7 from the ACI Building Code 318 rates the exposure level of concrete with sulphate dissolved in water. Considering this information, if concrete was exposed to concentrations of sulphate at 150 mg/l the exposure class would be negligible. The total amount of water soluble ions is 150 mg/l and therefore is not of great concern in raising the pH greater than normal. To assess the percentage of sulphate ions the highest amount is considered. 10g of ground sample was diluted in 50ml of distilled water which would equate to 200 g/l. The highest amount of sulphate present in all the samples from the months examined was about 50 mg/l which amounts to 0.025%. This is well below the threshold of 0.2% defined in Table 3.46 from the BS EN 12620.

The chloride (Cl) content was the highest in the months of March and June taking into consideration that the samples originated from C&D waste from the Cape Town harbour. The chloride content for fine aggregates used in concrete is specified in SANS 1083:2006 and percentages are given below as the maximum mass percentage:

- Prestressed concrete: 0.01%
- Reinforced concrete: 0.03%
- Non-reinforced concrete: 0.03%

The highest amount of chloride ions present was 9 mg/l and dividing this by the amount of diluted sample resulted in a percentage of 0.0045%. The amount of chloride ions is also not a concern in the RCA used in this investigation. The water-soluble ions in the RCA should not under normal circumstances affect the durability of concrete at these concentrations. The XRF analysis will examine the mineral composition of the samples and together with the water-soluble ions a conclusion can be made relating the two.

5.2.8 XRF analysis

The XRF analyses on the samples of aggregates provided more consistent data. Clear trends developed in the amounts of the different minerals as the percentage of RCA increased. Seen at the end of this section are the results from the XRF analyses conducted on the same samples which were prepared for the water-soluble cations and anions in Tables 5.12 to 5.14. Seen in Table 5.11 are differences which were found between the 100% NA and 100% RCA in the major mineral oxides.

Table 5.11 Difference between the N100A and R100A samples in terms of mineral composition

Mineral	March	June	August	Average	Change
Al ₂ O ₃ (%)	-1.92	-2.72	-3.47	-2.70	Decrease
CaO (%)	2.88	2.99	3.99	3.29	Increase
Cr ₂ O ₃ (%)	0.00	0.00	0.00	0.00	NS
Fe ₂ O ₃ (%)	-1.11	-0.98	-1.61	-1.23	Decrease
K ₂ O (%)	-0.52	-0.78	-0.98	-0.76	Decrease
MgO (%)	-0.66	-0.75	-1.00	-0.80	Decrease
MnO (%)	-0.01	-0.02	-0.02	-0.02	NS
Na ₂ O (%)	0.09	0.10	-0.32	-0.04	V
P ₂ O ₅ (%)	0.00	0.00	0.00	0.00	NS
SiO ₂ (%)	0.03	0.97	1.05	0.68	Increase
TiO ₂ (%)	-0.07	-0.10	-0.05	-0.07	NS
LOI (%)	1.01	1.33	2.08	1.47	Increase

NS = Not Significant

V = Varied

From the information presented in Table 5.11 the difference in mineral composition is marginal at less than 5% for any mineral. The SiO₂ representing the quartz is the most abundant mineral present which is consistent for greywacke aggregate. The increase of CaO which is present in much greater quantities typically in cement (Table 3.16 in Section 3.1.7) could be as a result of attached mortar which may contain unhydrated cement. The August sample had the highest quantity of stone/mortar combination which is reflected in the result of the CaO quantity. The increase in CaO may result in a decrease in alumina Al₂O₃ due to the relationship between the two in the hydration of cement. The XRF analysis shows that although the RCA samples originated from different sources, they are compositionally similar. The loss on ignition (LOI) represents the total of volatiles content of the rock (including the water combined to the lattice of silicate minerals) and the gain on ignition related to the oxidation of the rock (mostly due to Fe). The increase in LOI could be as a result of trapped moisture or minerals combined with water molecules. The presence of higher portions of brick in the August sample along with the stone/mortar combination could have contributed to a higher LOI.

Table 5.12 Mineral composition of the aggregates samples from March

Sample	RefN100A	MarR15A	MarR30A	MarR50A	MarR100A
Al ₂ O ₃ (%)	14.08	12.48	13.36	11.83	12.16
CaO (%)	1.15	3.47	2.58	2.95	4.03
Cr ₂ O ₃ (%)	0.00	0.00	0.00	0.00	0.00
Fe ₂ O ₃ (%)	5.89	5.12	5.28	4.65	4.78
K ₂ O (%)	3.21	2.67	2.79	2.54	2.69
MgO (%)	2.85	2.54	2.53	2.27	2.19
MnO (%)	0.09	0.11	0.09	0.10	0.08
Na ₂ O (%)	2.05	2.03	2.20	2.01	2.14
P ₂ O ₅ (%)	0.00	0.00	0.00	0.00	0.00
SiO ₂ (%)	68.36	68.41	68.65	71.48	68.39
TiO ₂ (%)	0.76	0.69	0.69	0.65	0.69
LOI (%)	1.71	2.44	1.86	2.18	2.72
Sum Of Conc. (%)	100.15	99.97	100.03	100.64	99.88

Table 5.13 Mineral composition of the aggregates samples from June

Sample	RefN100A	JunR15A	JunR30A	JunR50A	JunR100A
Al ₂ O ₃ (%)	14.08	12.19	13.24	13.10	11.36
CaO (%)	1.15	1.65	2.42	3.37	4.14
Cr ₂ O ₃ (%)	0.00	0.00	0.00	0.00	0.00
Fe ₂ O ₃ (%)	5.89	4.86	5.50	5.33	4.92
K ₂ O (%)	3.21	2.55	2.89	3.10	2.42
MgO (%)	2.85	2.21	2.75	2.55	2.11
MnO (%)	0.09	0.07	0.11	0.08	0.07
Na ₂ O (%)	2.05	2.32	2.22	2.39	2.15
P ₂ O ₅ (%)	0.00	0.00	0.00	0.00	0.00
SiO ₂ (%)	68.36	71.97	68.89	67.13	69.33
TiO ₂ (%)	0.76	0.69	0.69	0.73	0.66
LOI (%)	1.71	1.41	2.05	2.57	3.04
Sum Of Conc. (%)	100.15	99.92	100.76	100.34	100.19

Table 5.14 Mineral composition of the aggregates samples for August

Sample	RefN100A	AugR15A	AugR30A	AugR50A	AugR100A
Al ₂ O ₃ (%)	14.08	14.13	11.87	13.57	10.61
CaO (%)	1.15	1.67	3.47	3.38	5.15
Cr ₂ O ₃ (%)	0.00	0.00	0.00	0.00	0.00
Fe ₂ O ₃ (%)	5.89	6.14	4.93	5.59	4.29
K ₂ O (%)	3.21	3.23	2.64	2.91	2.22
MgO (%)	2.85	3.03	2.26	2.66	1.86
MnO (%)	0.09	0.08	0.07	0.08	0.07
Na ₂ O (%)	2.05	1.81	2.01	1.91	1.73
P ₂ O ₅ (%)	0.00	0.00	0.00	0.00	0.00
SiO ₂ (%)	68.36	66.83	69.54	66.79	69.41
TiO ₂ (%)	0.76	0.71	0.69	0.71	0.70
LOI (%)	1.71	2.46	2.88	3.13	3.79
Sum Of Conc. (%)	100.15	100.10	100.36	100.74	99.83

To assess the alkali-silica reactivity potential of RCA the XRF analysis and results from the water-soluble ions are considered. Since there is no significant composition difference between the RCA samples and the reference material (greywacke), the ASR potential will likely be similar. Comparing the composition of greywacke and the samples assessed for calibration of the XRF analysis, the greywacke is almost identical to granite and granodiorite (Table 5.15). It was established in Section 3.1.7 that all of these rocks contribute to the ASR due to the presence of strained/crystalline quartz (SiO₂). The quartz or silica (SiO₂) reacts with the alkaline pore solution of the cement paste to produce an expansive gel. The water-soluble ions, although low in concentration will contribute to the increase in pH of new concrete and with the amount of silica present, so ASR is possible.

Table 5.15 Mineral composition of the reference materials used to calibrate the XRF analysis

Sample	Granite	Basalt	Basalt (depleted)	Granodiorite
Al ₂ O ₃ (%)	12.08	10.05	14.53	14.29
CaO (%)	0.78	14.03	9.29	2.18
Cr ₂ O ₃ (%)	0.00	0.05	0.68	0.01
Fe ₂ O ₃ (%)	2.02	12.61	8.97	2.20
K ₂ O (%)	4.99	1.40	1.43	3.98
MgO (%)	0.06	12.95	7.73	0.74
MnO (%)	0.02	0.19	0.16	0.06
Na ₂ O (%)	3.36	3.18	2.79	3.44
P ₂ O ₅ (%)	0.01	1.06	0.26	0.10
SiO ₂ (%)	75.70	38.38	52.17	72.28
TiO ₂ (%)	0.09	2.59	1.34	0.26
LOI (%)	0.79	2.45	0.00	0.00
Sum Of Conc. (%)	99.11	98.95	99.35	99.54

An interesting observation was made with the samples used in the chloride conductivity tests in Chapter 7. The samples were not discarded after the completion of the test. A period of time had passed and when the samples were examined a reaction had taken place as seen in Figure 5.16. It is not clear what kind of reaction is taking place, but in the presence of a high concentration of NaCl (5.0 M) it can be assumed that is possibly an ASR reaction. The pH of the pore solution in the bulk cement paste may have increased due to the high concentration of the NaCl and with aggregates which have a tendency for an ASR reaction the assessment may be plausible. The reaction was more apparent in the samples containing only OPC (left) and less visible in the mixtures which contained Corex® slag (right). The inclusion of a cement extender reduces the ASR potential in concrete.



Figure 5.16 Potential ASR reaction taking place in the OPC mixture (left) and less visible in slag mixture (right)

5.3 Concluding Summary

The properties of NA compared to RCA have been covered in this chapter. The aggregates were assessed according to the geometrical, physical and chemical properties. The method of recycling and the source of the original C&D waste govern the outcomes of these properties. The RCA collected at three different instances were combined at 0, 15, 30, 50 and 100% with NA to determine the influence of percentage replacement on the aggregate properties. The RCA combinations were compared to the 100% NA or reference material and although differing in relative amounts according to the various properties, would still be considered acceptable in most standards referring to RCA usage.

The RCA was intentionally graded to control the grading for the mixture design and to compare the different monthly batches relative to one another. The increase in RCA percentage resulted in an improved continuous grading with higher proportions of smaller particles. The higher portions of smaller particles were also indicated by the decreasing FM. The improved grading would result in a better packing ability. The dust content increased with increasing percentage replacement varying between 0.24% for NA and 0.61% for 100% RCA. Although the dust content was higher in the RCA, it was still within the limits defined by SANS 1083:2006, RILEM TC 121 and JIS A 5021.

The RCA particles had an irregular, sub-angular and cubical shape with an FI value of 7 at 100% replacement. The reference material was angular, elongated and flaky with an FI value of 25. The NA particles were rough in texture, while the RCA particles had a rough and porous surface texture associated to the adhered mortar and masonry particles. A higher FI value would improve the tensile strength by restricting the formation of continuous cracks through the concrete.

The RCA constituent composition typically had about a 55% stone/mortar combination particles, 40% stone and the lower proportions were made up of clay masonry items, bituminous material and glass. One batch of RCA had a significantly different composition, with 75% of the RCA consisting of stone/mortar and 6.4% amounting from masonry items. The constituent composition is dependent on the source of the original material and the recycling process. The foreign items or contaminants were below 0.2% for RCA batches and consisted of metals, polymers, plastics and wood etc. A larger sample of RCA should be assessed to accurately determine the amount of foreign items found within an RCA batch. The floating items consisting generally of wood and plastics were below the 2 cm³/kg limit defined in BS EN 12620. The amount of foreign items, especially larger items, should be limited to avoid localised corrosion and spalling.

The physical properties are dependent on the geometrical properties. The relative density decreased with increasing replacement percentage due to the higher presence of lower density materials such as brick and adhered mortar. The lowest RD measured was 2.59, however a reasonable concrete density could still be achieved when using this RCA. After a visual inspection, the RD could be used to reject a RCA batch due to the higher water absorption associated with a lower RD. The LBD and CBD increased with increasing RCA percentage due to the improving packing capacity. The LBD and CBD were lower when RCA with a lower relative density was assessed. At 100% replacement the LBD and CBD was between 1401 to 1462 kg/m³ and 1541 to 1605 kg/m³ respectively. The reference material had a LBD and CBD of 1405 kg/m³ and 1557 kg/m³ respectively.

The water absorption increased with increasing RCA replacement. The highest water absorption was 2.59% as was isolated to the higher presence of clay masonry items and stone/mortar particles. The water absorption percentage was below the 3.5% limit defined by JIS A 5021 and 3% in the RILEM recommendation for recycled aggregates. The ACV was similar for all RCA combinations, except marginally higher for RCA with higher percentages of lower density particles. The lower density particles are fragile and crush at a lower force compared to the stone particles. The highest ACV determined was 15% and is significantly lower than the 30% limit defined in the SANS 1083:2006.

The chemical and mineralogical analysis of the RCA compositions had interesting outcomes. From water-soluble cations and anions analysis, the RCA combinations increased the amounts of the six ions analysed. The individual amounts from the various ions were not significantly high, with the highest total combination of all six ions amounting to 150 mg/l. The RCA samples which originated from C&D waste from a demolition project in the Cape Town harbour had higher amounts of chloride ions, but not considerably high with the highest amount of 9 mg/l.

The mineralogical composition of the RCA samples was similar to that of the reference material. The difference between the mineral oxides percentages for the various RCA combinations was not significant (below 5%). The CaO mineral increased with increasing RCA replacement, indicating the increasing presence of cement paste. The LOI also increased with increasing RCA percentage signifying the presence of water bound substances in materials such as brick and cement paste. The mineralogical analysis also showed that although the RCA batches originated from different C&D waste sources, the compositions were similar. Assessing the RCA batches for potential ASR showed that there is a greater possibility for this reaction when using RCA. The RCA samples had compositions almost identical to that of greywacke (reference material) and grandoirite which are aggregates which have displayed ASR potential when used in concrete.

From the investigation, the physical are dependent on the geometrical properties, while taking into consideration that the geometrical properties are dependent on the source and method of recycling the original C&D waste. The chemical properties are dependent on the physical properties of the RCA. The various properties assessed for the RCA batches examined in this investigation fall within the limits defined by the standards and specifications in Section 3.4. For example, according to the RILEM recommendation the RCA samples could be classified as Type II and may be used in a maximum concrete class of C50/C60. The influence that the aggregates should have on the fresh and hardened concrete properties will be minimal taking into account the assessment completed.

Chapter 6

Fresh Concrete Properties

This chapter discusses the properties relating to concrete in a fresh or plastic state. The influence that the aggregate properties have on the fresh concrete results is covered along with the possible influence that the fresh concrete properties may have on the hardened concrete. The fresh concrete properties are assessed by examining the workability and loss of workability through a slump test and slump loss test respectively. The fresh density is included as well as the air content, where the latter has a greater influence on the hardened concrete properties.

6.1 Test Methodologies

6.1.1 Workability (slump & slump loss)

The consistency of fresh concrete was measured in accordance with SANS 5862-1:2006. The cone mould and base plate were moistened before each slump test and care was taken so that no excessive free surface water was present. The cone was placed on the base plate and filled in approximately three equal layers, where each layer was tamped using a tamping rod 25 times. Tamping the first layer was done without striking the base plate, and for the second and third layers the rod extended 1/3 into the previous layer. The top of the cone was levelled and then the cone removed to measure the resulting slump. The slump was measured from the top of the over turned cone to the highest point of the concrete.

The slump loss assessment used to measure the possible loss of workability was completed in the same manner as stated above. The slump was taken at 15 minute intervals from the initial slump for a period of one hour. The pan mixer drum was covered by a sheet of plastic to prevent possible evaporation. The concrete was re-mixed for approximately 30 seconds before each slump test. The base plate with concrete on top was struck to give an indication of cohesiveness. The cohesiveness is an indication of segregation, and a mixture was considered cohesive when the constituents of the concrete settled into a solid mass when the base plate was struck.

The temperature of the ambient air was taken at the start of each test, because the experimental programme was conducted over a period with seasonal changes.

6.1.2 Fresh density

The fresh density of concrete was completed with guidance from SANS 6250:2006. The fresh density of each concrete mixture was determined by filling a 100x100x100mm cube mould with fresh concrete. The mass of the cube mould was measured before filling and the concrete was added in two layers with the first layer vibrated for 15 seconds on a vibrating table and the second layer for 30 seconds. Care was taken to ensure that the mould was filled to the brim and no excess concrete was present on the mould itself. The mass of the mould and fresh concrete was weighed and the fresh density was calculated. The fresh density was calculated from three samples taken from each batch of concrete.

6.1.3 Air content

The air content was determined according to SANS 6252:2006 with the use of a Type B measurement device. The Type B meter was calibrated to measure the air content correctly and ensure accurate readings. The fresh concrete was added in three equal layers, with each layer tamped 25 times using a tamping rod with the same method as for the slump test. The surface was levelled to the rim of the container and excess concrete on the edge of the container was removed and cleaned. The container was closed and the lid tightened, ensuring an adequate seal. Water was introduced through the receiver and the container was lightly tapped to remove excess air. The water level reading was zeroed and the respective valves closed and air was pumped into the container until the required pressure (9 kPa) was reached. The displaced water reading (A_1) was taken and the air released to measure the residual air (G). This process was repeated three times and the air content was calculated according to Equation 6.1 as an average of the three results

$$\text{Air content} = A_1 - G \quad [Eq 6.1]$$

6.2 Results

6.2.1 Workability (slump & slump loss)

The initial slump values from the different monthly concrete mixtures varied significantly. The March and June concrete batches had initial slump values which were considered reasonable. The August concrete batches however displayed higher slump values (Table 6.1). The June concrete mixtures displayed consistent initial slumps with 75 ± 25 mm and the March mixtures containing Corex® slag showed higher initial slumps when compared to the mixtures containing only OPC. The grading of the RCA and NA had an influence on the initial slump of the concrete; however by keeping the grading similar, this factor could be isolated.

Table 6.1 Initial and final slump values for monthly concrete batches

Concrete Mixture	March		June		August	
	0 min	60 min	0 min	60 min	0 min	60 min
N100C	90	45	70	45	200	160
R15C	100	60	60	40	125	120
R30C	105	70	80	35	160	150
R50C	100	70	70	45	155	155
R100C	100	50	90	50	150	85
N100S	120	70	100	65	140	120
R30S	145	80	80	65	160	110
R100S	125	65	85	45	100	65

The higher initial slump values in the August concrete samples can therefore be attributed to the natural fine aggregate used, which was coarser than the fine aggregate used in the other months. The increase in material coarseness meant that less water was required to maintain the same workability of mixtures with finer material. The temperature ranges for the March, June and August samples were: 17 to 21°C, 15 to 17°C and 10 to 16°C, respectively. This may also have had an influence in the initial slump readings, but would have a greater influence on the slump loss. The mixtures with higher initial slump values displayed slumps which in most cases either sheared or collapsed (Figure 6.1). A shear slump shows a lack of cohesion, however when the base plate was struck all the concrete samples in this experimental programme, had constituents which remained together. The stone did not displace to the bottom of the concrete and when compacted on a vibrating table, the stone could be found within 5mm of the concrete surface.



Figure 6.1 Photographs showing the initial slump tests for a sheared (left) and collapsed (right) slump

In terms of slump loss or loss of workability, the March and June batches of concrete showed a slump loss between about 50 to 70% based on the initial slump value after an hour (Figures 6.2 & 6.3). The August concrete mixtures had slump loss which ranged between about 50 to 100% as seen in Figure 6.4. The March concrete samples had a greater rate of slump loss after 15 minutes compared to the June concrete samples which had most of the slump loss at 15 minutes. The August fresh concrete had the highest rate of slump loss at 15 minutes and then remained constant with some of the mixtures showing higher workability. The inconsistent slump loss rates of the August concrete mixtures could be ascribed to the high initial slump values and the coarser fine material. The August mixtures would have had excess water and therefore loss of workability would be low, compared to mixtures where insufficient water was initially available for mixing.

Comparing the individual mixtures showed that the R100C mixture generally had the highest slump loss with all the monthly samples. The R15C and R50C concrete mixtures mostly had the lowest slump loss when compared to the other individual mixtures. Interestingly the N100C mixture displayed slump loss rates similar to the R100C mixture across the monthly concrete batches. The concrete mixtures with slag cement replacement had slump loss rates between the lowest and highest slump loss values.

The influence that the aggregates have on the consistency of the concrete mixtures is evident from these observations. The fact that the R100C and N100C mixtures showed similar slump loss rates, illustrates the influence of the grading and water absorption of the aggregates. Although the RCA has higher water absorption, the grading of the RCA is more continuous and therefore counteracts the absorption effects. The particle shape and surface texture may similarly influence the results for the slump tests. In the case of R50C, the mixture generally had the lowest initial slump values and the least loss of slump. The combination of RCA and NA at this percentage meant that there was a combination of round and angular shaped particles, rough and porous texture with addition of the improved grading and water absorption may have influenced the outcome for the results of the slump test.

The slump test is influenced by many external factors such as: mix volume, type of mixer, environmental conditions and human influence. This was noted when conducting the slump tests for the other mixtures for the durability, shrinkage and creep concrete specimens. The main slump tests were conducted on the largest of the four concrete batches for each month. For the purposes of this study these factors are not examined and the outcomes from these additional tests are included in Appendix D for reference.

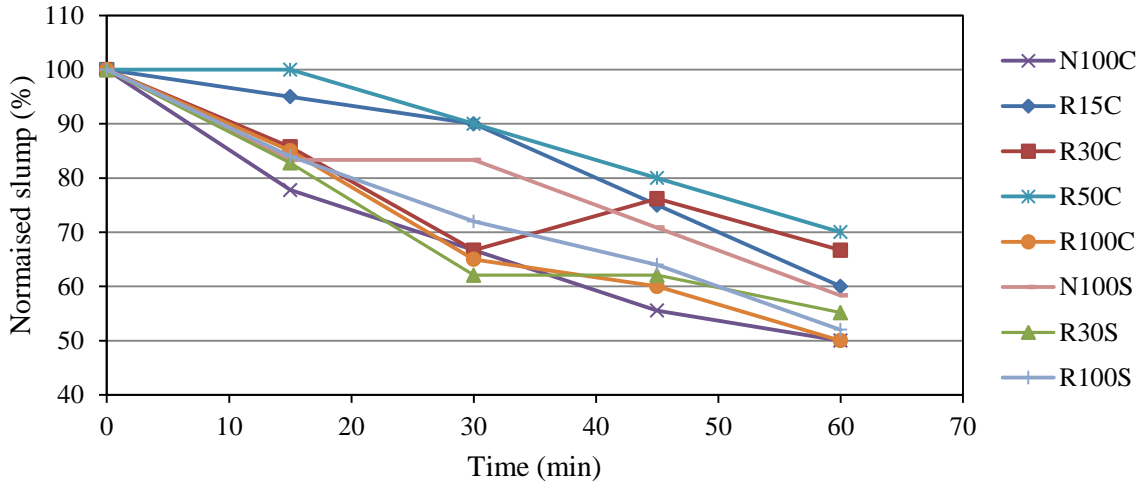


Figure 6.2 The slump loss based on the initial slump value for the March concrete batches

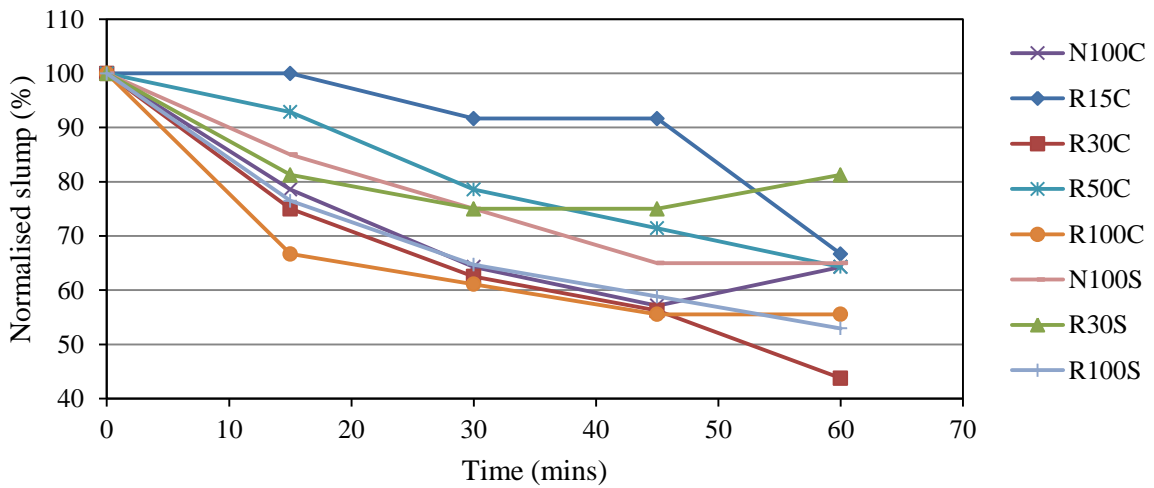


Figure 6.3 The slump loss based on the initial slump value for the June concrete batches

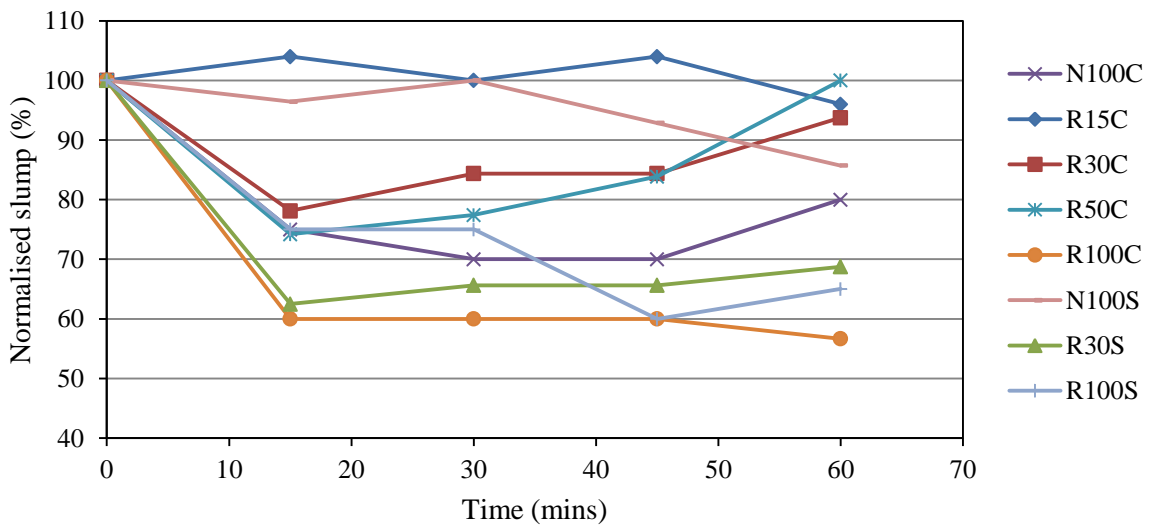


Figure 6.4 The slump loss based on the initial slump value for the August concrete batches

6.2.2 Air content

The results from the air content analysis of the different monthly batches of concrete displayed similar trends. Table 6.2 provides the results for the individual samples for each of the monthly batches of concrete. From this data it is apparent that the June and March samples' air content percentages had similar values, while the August samples had relatively higher values. The reason for the difference in air content percentages could be attributed to the coarseness of the fine aggregate and the excess water relating to the case of the August concrete mixtures.

Table 6.2 Measured air content results for monthly concrete batches

Sample	March (%)	June (%)	August (%)	Average (%)
N100C	4.5	4.1	5.8	4.8
R15C	4.5	4.2	5.4	4.7
R30C	4.9	4.2	5.7	5.0
R50C	4.9	4.9	7.8	5.9
R100C	5.5	5.9	7.4	6.3
N100S	3.7	3.8	3.7	3.7
R30S	3.6	3.9	5.0	4.2
R100S	4.0	4.6	5.2	4.6

Figure 6.5 shows the trend which developed across the monthly batches of concrete for the individual mixtures. It can be clearly seen that on average as the percentage replacement increases the air content increases, except in the case for R15C which shows a minor decrease. Interestingly it would be assumed that if the aggregate had a more continuous grading, the resulting air content would be lower than an aggregate which had a lesser continuous grading, due to the better packing ability identified by the bulk density. However in this case the RCA, which had a more continuous grading than the NA, had a higher air content. The reason for this consequence may be isolated to the fact that the porous and rough nature of the RCA may entrap air when mixed in concrete. The effect of replacing the OPC with a slag cement extender resulted in a lower air content for all the mixtures when compared to the mixtures containing only OPC and with the increase in percentage replacement, the air content also increased.

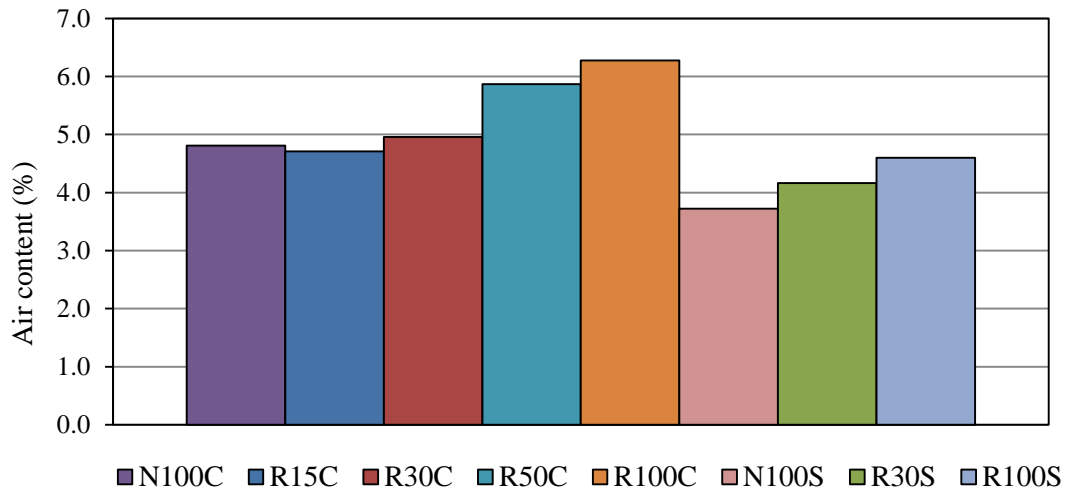


Figure 6.5 Average air content percentage for the individual concrete mixtures from each month

The air content will affect the workability of fresh concrete by enabling the constituents to move with less friction between the individual particles. This is evident in the case with the August concrete mixtures where higher slump values were recorded. The effect of adding finer particle induced the “fine-filler effect” and therefore filling available voids and was observed in the mixtures where Corex® slag was used as a cement replacement.

6.2.3 Fresh compacted density

The fresh compacted density results for the monthly batches of concrete displayed similar trends when comparing the individual concrete mixtures, with some exceptions. Table 6.3 gives the numerical results for the individual mixtures for each of the monthly concrete batches and Figure 6.6 provides a graphical representation of the average result for the individual mixtures. Table 6.3 clearly shows that the June samples generally had the highest fresh densities and August had the lowest fresh concrete density results. The relative density of the aggregates contributed the greatest to these outcomes, with the bulk density further influencing the fresh compacted density. The August mixtures also had the highest air content which may have also contributed to the lower fresh density. The June concrete mixtures had coarse RCA and FA with RD values of 2.66 and 2.64, respectively, while the August constituents had RD values of 2.59 and 2.61, respectively for coarse RCA and FA.

Table 6.3 Measured fresh compacted density results for monthly concrete mixtures

Sample	March (kg/m ³)	June (kg/m ³)	August (kg/m ³)	Average (kg/m ³)
N100C	2332	2333	2295	2320
R15C	2345	2346	2320	2337
R30C	2329	2343	2277	2316
R50C	2314	2324	2276	2305
R100C	2328	2278	2233	2279
N100S	2345	2364	2320	2343
R30S	2342	2360	2333	2345
R100S	2319	2296	2258	2291

The bulk density was generally higher for the R100A than the N100A which should result in a higher density when used in concrete; however this is not the case. The bulk density is influenced more by the grading and the RD of the aggregate which was noted in Section 5.2.4. The R100C mixture in the March concrete batch was the only mixture which deviated significantly from the other and because the aggregate had a higher bulk density because of the additional small stone size.

Figure 6.6 shows that the increasing replacement of RCA generally results in a decrease in fresh density. Comparing the outcomes from the air content analysis and the fresh density provides an explanation for the reason in the contradiction stated above. With the increase in air content percentage for the increasing percentage replacement results in a decreased fresh density. The influence of the air content is clear as the R15C mixture showed a deviation in air content trend and likewise displayed a deviation in the fresh compacted density test. The lower air content in the mixtures where OPC was replaced with slag resulted in mixtures with higher fresh densities compared mixtures containing only OPC. The difference between R100S and R100C is not significant, but the R100C mixture had the lowest overall density.

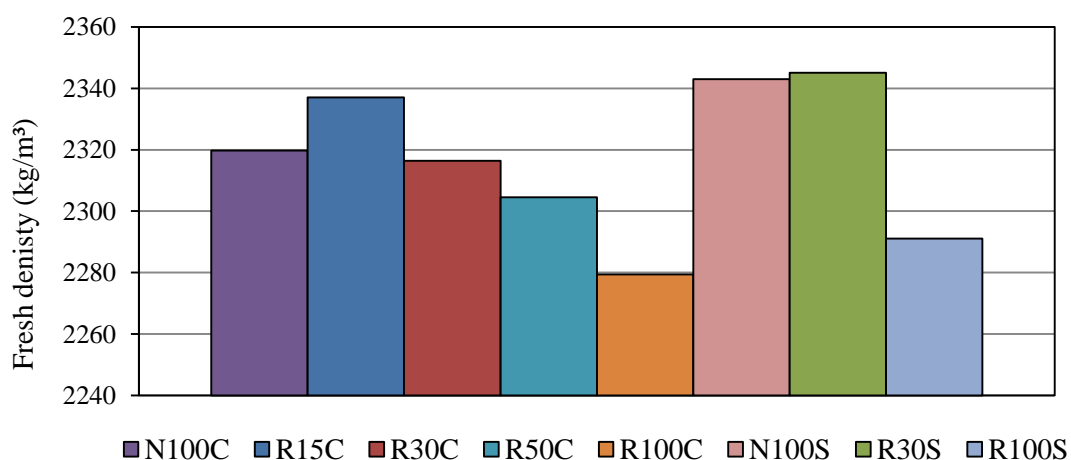


Figure 6.6 Average fresh compacted density results for individual concrete mixtures from each month

6.3 Concluding Summary

The fresh concrete properties play the most important role in the concrete production process. Ensuring that the mixture design and the constituent proportions are correct will produce concrete that is cohesive and consistent. The fresh concrete properties are dependent on the aggregate properties and by utilising aggregates which are geometrically sound will reduce the influence on the fresh concrete. The fresh concrete was tested for workability or slump, loss of workability (slump loss), air content and the fresh compacted density.

The measured slump value was within the target slump range of 75 ± 25 mm for most of the mixtures. The influence of percentage replacement on the initial slump value was negligible. The slag mixtures displayed more workability (i.e. higher slump) than the OPC mixtures. The influence which the fine aggregate has on the fresh concrete workability was evident in this investigation. The one batch of concrete was produced with sand which was coarser (higher FM) than the other sand used in the concrete mixtures. The sand thus required less mixing water to produce the target slump and in this case the concrete was highly workable (slump > 150mm) and less cohesive. The importance of mixture design with the constituents at that instance is apparent. Controlling the mixture design by using materials which are similar is possible, however trial mixtures should be carried out to guarantee equivalent workability.

The slump loss between the concrete mixtures showed that the physical properties which negatively influence the concrete can be counteracted by geometrical properties which will reduce the loss of workability. The 100% RCA and 100% NA mixture had similar slump loss rates, supporting the previous statement. Although the RCA had a higher water absorption than the NA, the RCA grading which was more continuous improved the loss of workability. The surface texture and particle shape also contributed to the slump loss rate. The mixture consisting of 50/50 RCA and NA would have had a combination of particles which were rough to porous and angular to sub angular. This mixture had the lowest initial slump value and least loss of slump.

The increase in RCA replacement percentage resulted in an increase in air content. The slag mixtures had the lowest air content and the air content likewise increased with higher percentages of RCA. The lower air content in the slag mixtures can be attributed to the “fine-filler effect” of cement extender particles. The average air content for the OPC mixtures ranged between 4.7 to 6.3% and the slag mixtures ranged between 3.7 to 4.6%. Aggregates with a better grading should have a lower air content due to improved packing ability. The 100% RCA mixtures with the better grading had the highest air content and therefore it was attributed to the porous nature of the aggregate particles which entrap air during mixing. The effect of excess mixing water resulted in a higher air content than in mixtures with sufficient mixing water.

The fresh concrete density decreased with increasing percentage replacement and was influenced by the air content and density of the aggregates. The air content increased with increasing RCA replacement and the RD decreased, resulting in a lower fresh concrete density. This was reflected by the slag mixtures which had the lowest air content and highest fresh compacted density.

The higher percentages of RCA negatively influenced the fresh concrete properties, although not significantly. The mixtures containing 15% RCA displayed the best fresh concrete results. However, the amount of NA replaced by this amount of RCA is minimal and it would be possible to use between 30 to 50% RCA replacement without considerably influencing the fresh concrete properties. The hardened concrete test specimens were moderately compacted in a fresh state without segregation of the constituents.

Chapter 7

Hardened Concrete Properties

The hardened concrete properties relating to the mechanical strength, durability performance and dimensional stability are assessed in this chapter. The influence which the aggregate and fresh concrete properties have on the hardened concrete properties is discussed. The mechanical properties which were assessed were the compressive and splitting tensile strength. The oxygen permeability, water sorptivity and chloride conductivity were the tests conducted to evaluate the durability performance. The dimensional properties examined were the modulus of elasticity, shrinkage and creep of the hardened concrete. The test methodologies are first stated and the results for the respective tests are discussed thereafter.

7.1 Test Methodologies

7.1.1 Compressive strength and hardened concrete density

To determine the compressive strength of the concrete mixtures produced, SANS 5863:2006 was used. Test specimens consisted of 100mm cubes which were cast and water-cured at $23\pm 1^{\circ}\text{C}$ for a period of 7, 14 and 28 days. On the day of testing the samples were removed from the curing tank and excess surface water was removed so that the samples would be in an SSD condition. Each individual sample was weighed and the dimensions were recorded before testing. The weight and dimensions of each sample were used to determine the hardened concrete density.

The sample was placed in a Contest compression machine as seen in Figure E.1 in Appendix E and the load was applied to the surface perpendicular to the casting surface. The load was applied at a rate of 3 ± 1 kN/s. A total of four specimens were tested for each mixture and each curing period. The compressive strength was determined as the maximum applied force over the cross sectional loading area of the specimen. The compressive strength was also determined for the mixtures which produced the shrinkage and creep specimens at 28 days and 7 days curing, respectively.

7.1.2 Tensile splitting strength

The tensile splitting strength of the concrete mixtures was completed in accordance with SANS 6253:2006. The test specimens consisted of 100mm cubes which were cured for 28 days. On the day of testing the same procedure to determine the dimensions and weight of the specimens were followed similar to the compression test before the specimen was tested.

The tensile splitting test was completed using the Zwick Z250 testing machine, where the test specimen was placed between two loading plates as seen in Figure 7.1. Hardboard packing strips were placed between the sample and loading plates with dimensions as follows:

- Width: $a = 15 \pm 2\text{mm}$;
 Thickness: $t = 4 \pm 1\text{mm}$; and
 Length: $l = \text{not less than length of specimen}$

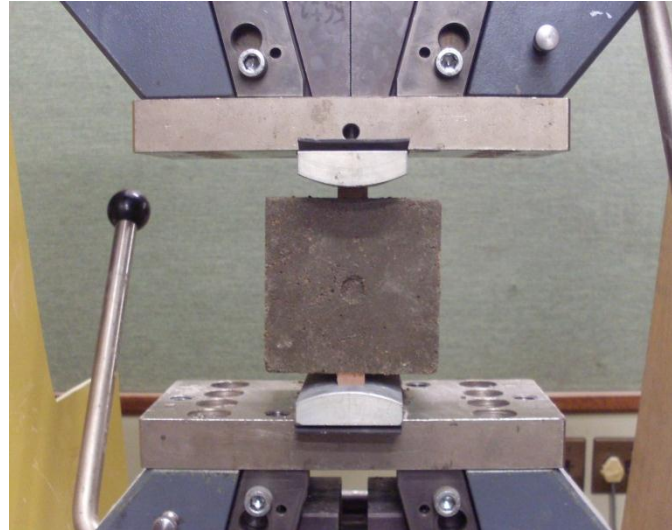


Figure 7.1 Tensile splitting setup for testing cube specimens

A small preload was applied to the samples to position the specimen correctly before continuing with the test. A load of $0.03 \pm 0.01 \text{ MPa/s}$ was applied to the surface perpendicular to casting until the specimen failed/split. A total of four specimens were tested for each concrete mixture and the tensile splitting strength is determined with Equation 7.1 as the average of the four specimens.

$$f_{ct} = \frac{2 \times F}{\pi \times l \times d} \quad [\text{Eq. 7.1}]$$

where f_{ct} = tensile splitting strength (MPa)

F = maximum load at failure (N)

l = length of specimen (mm)

d = cross sectional dimension of specimen (mm)

7.1.3 Oxygen permeability

The Oxygen Permeability Index (OPI) tests were completed with guidance from the UCT Durability Index Testing Procedure Manual 2009 Part-2 (Alexander et al, 2009a). Test specimens were prepared in accordance with Part-1 of the manual. The oxygen permeability was tested at 7 and 28 days curing. Cylindrical cores were drilled from 100mm cube specimens using a water cooled diamond tipped core barrel and coring drill. The cores were drilled from the face perpendicular to casting and the cylindrical specimens should have a diameter of 70 ± 2 mm.

Using a wet saw concrete cutter, 5mm was removed from either side of the cylindrical specimen. The edge on the outer face of the cylindrical core was marked using a permanent marker for reference. 30 ± 2 mm cylindrical discs were then cut from either side of the cylindrical core to produce the actual test specimens used in the durability index tests. A total of four disc specimens were cut for each test. The four disc specimens were then clearly marked along the outer edge and placed in an oven at $50 \pm 2^\circ\text{C}$ for 7 days ± 4 hours to be conditioned. Some of the test samples used in this experimental programme were unfortunately conditioned for 6 days due to time constraints and the availability of testing apparatus at the University of Cape Town (Table 7.7).

After conditioning the test specimens were removed from the oven and the specimens which had the least damage (chipped edges) were chosen and were placed in a desiccator for 2 to 4 hours to cool down. Once cooled down the specimens were placed in a compressible rubber collar within a rigid sleeve with the reference/outer face facing down. The tightly fitted specimen and collar were then placed on top of the pressure chamber ensuring that the collar was centered and no gaps were visible. Once correctly placed the screw on top of the coverplate was tightened by hand and then with a spanner.

The oxygen chamber (Figure 7.2) was first purged by running oxygen through the inlet valve escape through the outlet valve. The outlet valve was then closed and the oxygen pressure allowed to increase up to 100 ± 5 kPa. Readings were recorded using a computer connected to each OPI pressure gauge for 6 hours ± 15 minutes or when the pressure had dropped below 50 ± 2.5 kPa. The same specimens used in the OPI test were used again for the water sorptivity test.

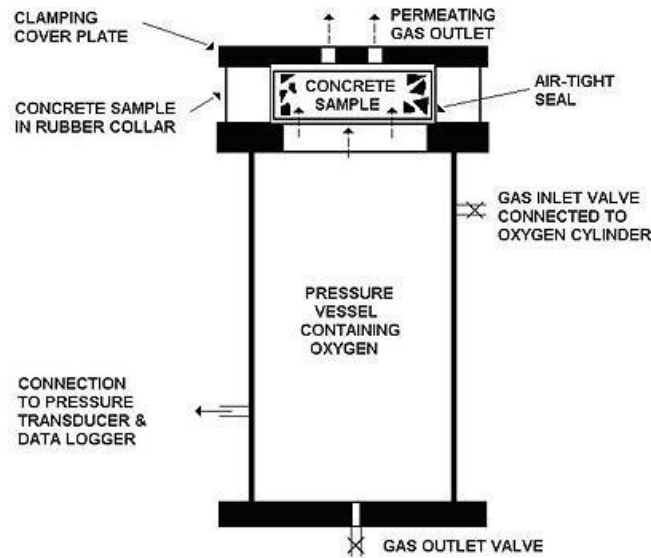


Figure 7.2 Diagram showing the OPI test setup (Alexander et al, 1999)

To calculate the OPI value the coefficient of permeability (k) was calculated using Equation 7.2. The line of best fit was needed to calculate the value for z , which was done by linear regression of $\ln(P_0/P_t)$ against time, forcing the regression line through the origin (0,0). The slope of linear regression (z) was calculated using Equation 7.3.

$$k = \frac{\omega V g dz}{RA\theta} \quad [Eq. 7.2]$$

where k = coefficient of permeability

ω = molecular mass of oxygen (32 g/mol)

V = volume of oxygen under pressure in pressure chamber (4.6l)

g = gravitational acceleration (9.81 m/s²)

R = universal gas constant (8.313 Nm/K·mol)

d = average specimen thickness (m)

A = cross sectional area of specimen (m²)

θ = absolute temperature (assumed 296.15° K)

z = slope of line determined by linear regression of $\ln(P_0/P_t)$ against time

$$z = \frac{\sum[\ln(\frac{P_0}{P_t})]^2}{\sum[\ln(\frac{P_0}{P_t})]} \quad [Eq. 7.3]$$

where P_0 = initial pressure at the start of test (t_0) measure in kPa

P_t = subsequent reading in pressure at time t from t_0 measured in kPa

t = time

Every reading recorded for each specimen in the analysis was used in the linear regression calculation and to ensure reasonable results the correlation coefficient was calculated using Equation 7.4. If the correlation coefficient was less than 0.99 the test was disregarded.

$$r^2 = 1 - \frac{\sum [t_i - t_{p,i}]^2}{\sum t_i^2 - (\sum t_{p,i})^2 / n} \quad [Eq. 7.4]$$

where t_i = time at any given pressure

$t_{p,i}$ = predicted time at the same pressure reading (based on linear regression)

n = number of data points considered

The coefficient of permeability (k) was calculated for each specimen and the OPI value was determined using the average k value from the four samples as shown in Equation 7.5.

$$OPI = -\log_{10}[(1/4) \cdot (k_1 + k_2 + k_3 + k_4)] \quad [Eq. 7.5]$$

7.1.4 Water sorptivity and porosity

The samples from the OPI test were used for the water sorptivity test as stated in the UCT Durability Index Testing Procedure Manual 2009 Part-3 and therefore were prepared and conditioned in the same manner (Alexander et al. 2009a). The test specimens were sealed along the outer edge with packaging tape and it was ensured that the edge closest to the reference face was sealed properly. Ten layers of paper towel were placed one on top of the other and calcium hydroxide saturated water was poured over the stacked paper towels (Figure 7.3). The air bubbles beneath the layers of paper towel were removed and the solution level was to be about 2mm up the side of the specimen. An additional towel was dampened, which was used to dry the excess solution from the specimens during the test.

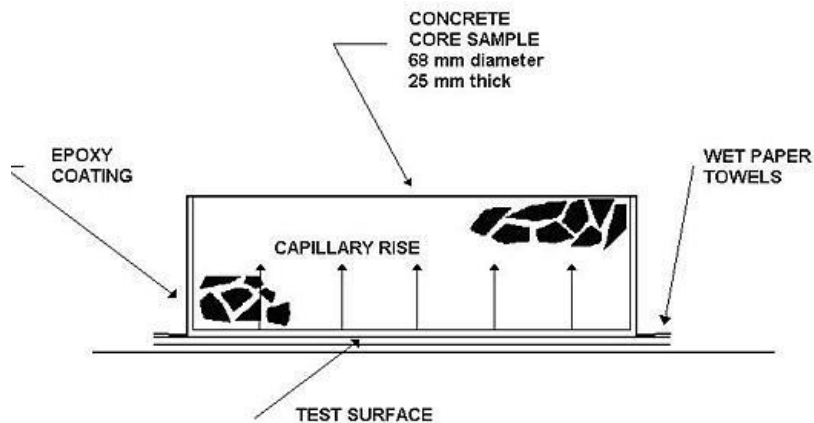


Figure 7.3 Diagram to show the setup for the water sorptivity test (Alexander et al, 1999)

The test specimens were weighed to determine initial mass and then placed with the reference side down in the solution. The specimens were weighed to the nearest 0.01g at 3, 5, 7, 9, 12, 16, 20 and 25 minutes after patting the damp side of the specimens with a damp towel to an SSD condition. The drying and weighing of a specimen took about 10 seconds after which the specimen was returned face down onto the tray of solution.

Once the test was completed the test specimens were placed into a vacuum saturation tank in an orderly manner to maximise the exposed surface area. The air was evacuated between -75 and -80 kPa for 3 hours \pm 15 minutes. After the depressurisation calcium hydroxide saturated water was allowed to flow into the tank until the solution completely covered the specimens. The tank was depressurised to the same pressure as before for 1 hour \pm 15 minutes, after which the pressure was released and the specimens allowed to soak for 18 \pm 1 hours. After the soaking period the specimens were removed from the solution, dried to an SSD condition and immediately weighed to the nearest 0.01g.

The porosity (n) of each specimen was calculated as a percentage by using Equation 7.6.

$$n = \frac{M_{sv} - M_{s0}}{Ad\rho_w} \times 100 \quad [Eq. 7.6]$$

where M_{sv} = vacuum saturated mass (g)

M_{s0} = initial mass at time t_0 (g)

A = cross sectional area (mm^2)

d = average thickness of specimen

ρ_w = density of water ($10^{-3}\text{g}/\text{mm}^3$)

The water sorptivity was calculated using Equation 7.7. The line of best fit was needed to calculate the value for F , which was done using linear regression using the equations defined by Alexander et al. (2009a). The correlation coefficient was determined for each specimen to check whether the data correlated well. In this case, if the correlation coefficient was below 0.98, the last mass recorded in the test was rejected. The correlation procedure was repeated until the value was equal or above 0.98, or there were five data points remaining, after which point the test would become invalid.

$$S = \frac{Fd}{M_{sv} - M_{s0}} \quad [Eq. 7.7]$$

where F = slope of line of best fit (grams/ $\sqrt{\text{hour}}$)

d = average specimen thickness (mm)

M_{sv} = vacuum saturated mass (g)

M_{s0} = initial mass at time t_0 (g)

The water sorptivity was calculated for each specimen and the average value was calculated from three or more valid results.

7.1.5 Chloride conductivity

The chloride conductivity test was completed in accordance with the UCT Durability Index Testing Procedure Manual 2009 Part-4 (Alexander et al., 2009a). The test specimens were prepared and conditioned in the same manner as the OPI and water sorptivity tests. The specimens were removed from the oven and allowed to cool for 2 to 4 hours. The specimens were then placed in a vacuum saturation tank and arranged in an orderly fashion to maximise the exposed surface area. The air was evacuated between -75 and -80 kPa for 3 hours \pm 15 minutes. After the depressurisation, salt solution (5M NaCl) was allowed to flow into the tank until the solution completely covered the specimens. The tank was depressurised to the same pressure as before for 1 hour \pm 15 minutes, after which the pressure was released and the specimens allowed to soak for 18 \pm 1 hours.

After the soaking period the specimens were removed from the solution and placed in a rubber collar contained within a rigid plastic ring. The connecting points from the anode and cathode chambers were removed and the luggin capillaries and chambers were filled with the salt solution. The cathode chamber was then screwed to the rigid plastic ring, after which the anode chamber was then also screwed to the plastic ring ensuring that no solution leaks from the conduction cell (Figure 7.4). The conduction cell was placed horizontally and connected to an ammeter and voltmeter. The DC power supply was adjusted until the voltmeter reading was approximately 10 volts (V) and the current reading was then recorded simultaneously.

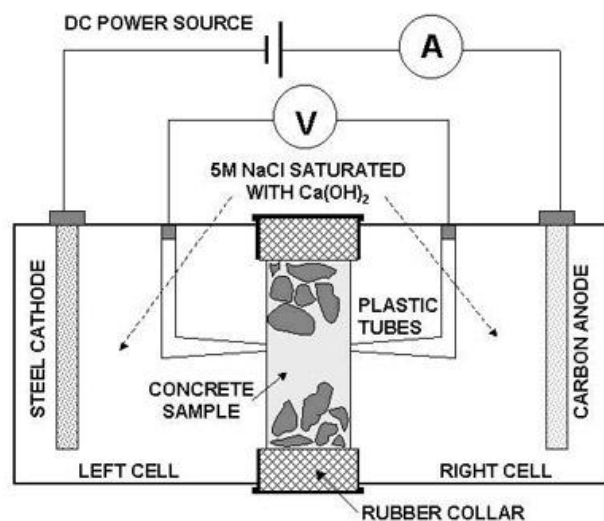


Figure 7.4 Schematic drawing of the chloride conductivity setup (Alexander et al, 1999)

To calculate the chloride conductivity σ (mS/cm) of each specimen, Equation 7.8 was used and the average between four specimens was calculated as the overall conductivity for that concrete sample.

$$\sigma = \frac{id}{VA} \quad [Eq. 7.8]$$

where i = electric current (mA)

V = voltage difference (V)

d = average specimen thickness (cm)

A = cross sectional area of specimen (cm²)

7.1.6 Modulus of elasticity

The modulus of elasticity was determined with guidance from ASTM C469-02. Three cylindrical specimens ($\phi 100 \times 200$ mm) were cast and tested at 28 days for each concrete mixture from the monthly batches. The casting face needed to be ground to ensure a plane bearing surface. Initially the surfaces were ground using a hand grinder. This was found to give unreliable ultimate load readings. To correct this, a grinding device was constructed which would accurately prepare the testing surface. Seen in Figure E.11 in Appendix is the grinding device which was adapted to be used on cylindrical specimens and then used to grind the casting surface to be plane.

Three 10mm linear variable differential transducers (LVDTs) were secured to the center of each specimen. The LVDTs were held in place using the apparatus seen in Figure 7.5 and equally spaced by spacing bars between the top and bottom rings of the apparatus. The LVDTs were secured by tightening screws to the specimens and the spacing bars were then removed. A load cell capable of testing the required loads was placed on top of the specimen.



Figure 7.5 Modulus of elasticity experimental setup

The load cell and LVDTs were connected to a Spider8 electronic measuring system to collect the data. The load was applied at a rate of 91 kN/min approximately half the cube compression test rate of load applied. The test was conducted until the cylinder had failed under the ultimate load.

Equation 7.9 was used to calculate the modulus of elasticity based on the chord method discussed in Section 3.3.3. The strain for each LVDT was calculated by dividing the displacement of the LVDT by the length between the screws holding the testing apparatus to the specimen. This gauge was approximately 70.5mm. The stress was calculated by dividing the applied force by the cross-sectional area under the load. The average strain between the three LVDTs for the loading sequence was calculated and used as the overall strain. The modulus of elasticity was calculated by averaging the modulus of elasticity for each specimen.

$$E_c = \frac{\sigma_1 - \sigma_0}{\varepsilon_1 - \varepsilon_0} \quad [Eq. 7.9]$$

where σ_1 = stress at $\pm 35\%$ of ultimate load/stress
 σ_0 = stress at 0.0005 strain
 ε_1 = strain at $\pm 35\%$ of ultimate load/stress
 ε_0 = strain of ± 0.0005 mm/mm

7.1.7 Shrinkage

The shrinkage of the concrete examined in this investigation was tested with guidance from ASTM C157-06 and RILEM: CPC 9 (1975). Three cylindrical specimens ($\phi 105 \times 300$ mm) were produced for each concrete mixture. At 26 days curing the specimens for the monthly concrete batch were removed from the curing tank. The specimens' casting surfaces were ground using the same machine used in the elastic modulus method and allowed to dry for ± 30 minutes. During this time, the positions of the targets to be used to measure the uniaxial deformation were marked along the face of the specimens. The targets were spaced at 120° apart and located on the center of the specimen. Once the surface for the first set of targets was dry the targets were glued into position using quick setting concrete glue and a positioning apparatus seen in Figure in Appendix E. The glue was allowed to dry for ± 15 minutes. This process was repeated until all the faces had the targets fixed onto them. The specimens were allowed to dry for an additional 30 minutes before placing all the specimens back into the curing tank.

At 28 days the specimens were removed from the water and the top and bottom faces were sealed using heated wax and applied in layers using a brush to prevent axial moisture loss. The sealing process was done in such a way that only the individual mixture specimens produced on the same day were removed to ensure equal sealing and measuring time. The first measurement was taken ± 15

minutes once removed from the curing tank and sealed using the apparatus seen in Figure 7.6. The LDVT attached to the apparatus was connected to a Spider8 electronic measuring system. The reading was manually recorded from the computer to an accuracy of 0.001mm. Care was taken to ensure that the measured values were correct by checking the zeroed reading before and after the measurement was taken. If the difference between the zeroed readings was greater than 0.002mm the reading was retaken. The measuring apparatus was zeroed/calibrated using a steel reference bar with a gauge length of 101mm.

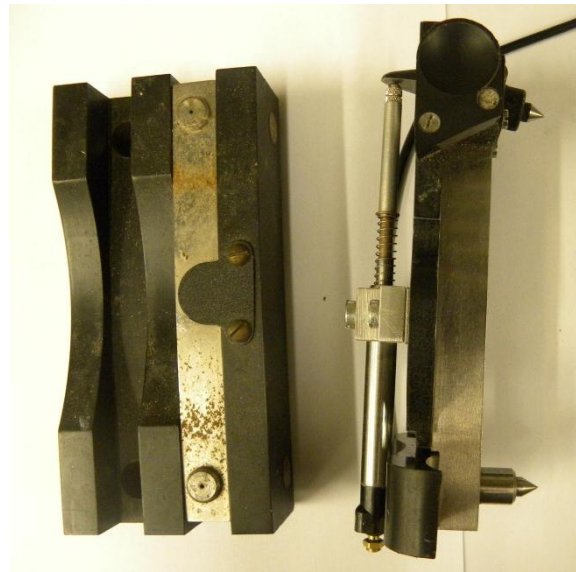


Figure 7.6 The apparatus used to measure the shrinkage and creep of concrete (right) and the steel reference bar with gauge length of 101mm (left)

Readings were taken at 0, 3, 6, 18, 30, 42 and 54 hours initially, then daily for a week and then at increasing increments until 90 days. The specimens were kept in a climate controlled room with temperature $21 \pm 3^\circ\text{C}$ and relative humidity of $65 \pm 5\%$. The shrinkage strain was calculated by dividing the change in length by the original length between the targets. The original length was calculated using the length of the positioning apparatus (gauge length = 101mm) plus the offset due to placing the targets, which was less than 1mm (Equation 7.10). The data was examined and where necessary a maximum of three readings of the nine total readings were removed to correct the coefficient of variation of the results.

$$\varepsilon_{sh} = \frac{L_{ti} - L_{t0}}{L_o + L_{t0}} \quad [\text{Eq. 7.10}]$$

where L_{ti} = measured length at time i
 L_{t0} = measured length at time 0
 L_o = length of positioning device

The shrinkage specimens from each month were tested for the same period in the same time frame and any change in temperature or humidity would be noticed throughout the specimens. Included in Appendix E are the actual results from the shrinkage reading before the adjustments were made.

7.1.8 Creep

A creep apparatus was designed and constructed over a period of 6 months during the experimental programme. The creep apparatus or creep frame design is not discussed in detail due to the extent of the design and construction methods. The design particulars are however discussed to provide insight into the creep frame mechanisms and method of testing. The design particulars are listed below with a brief description of the related problems and solutions and a diagram of the creep frame is seen in Figure 7.7 (left). A total of four creep frames were designed and built and mounted on a table seen in Figure 7.7 (right).

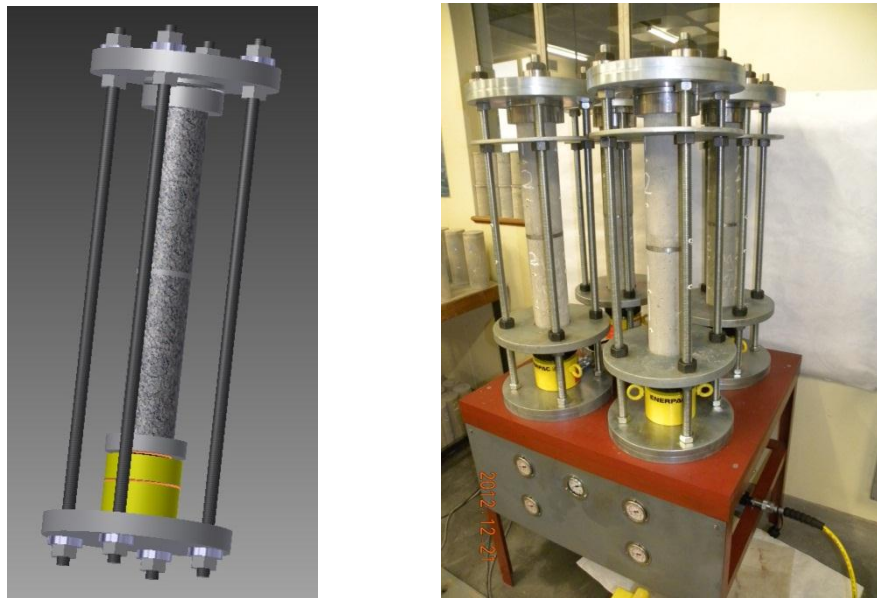


Figure 7.7 Individual creep frame design (left) and final creep test setup (right)

- Loading conditions/concrete strength

The creep frame was loaded using hydraulic jacks. The jacks used were capable of loading up to 606 kN (safety factor not included). Creep specimens are usually tested at 30 to 40% of the ultimate concrete load. This meant that concrete cylinder specimens with the smallest diameter of 100mm could be tested which had an ultimate strength of ± 100 MPa (40% ultimate load). To design the load bearing elements, a safety factor of 1.25 was used on the hydraulic jack capacity of 606 kN. The load was assumed to be purely axial and applied at the center of the creep frame.

- Load bearing elements

Four fully threaded steel rods were used to distribute the load equally. The load bearing plate between the specimens was difficult to design due to the unknown nature of the loading and boundary conditions. The area of loading on the plate and the size of the holes for the rods were the areas with the greatest problems. To assess the load bearing elements, finite element analyses (linear and non-linear) were conducted on these elements for different load cases and boundary conditions. The loading area on the plate had to be large enough to distribute the load so that high stresses were avoided. The areas where holes were to be drilled had high stress concentrations which were at ultimate load greater than the yield stress. These areas of high stress were extremely localised and solutions were found.

- Hydraulics

As the specimens deformed under load, the applied load would decrease due to displacement of the specimens. To correct this problem an accumulator was used which would hold a load under deformation of the specimen for a long period of time. The accumulator had a capacity of 350 bar and the hydraulic jack at ultimate load had a capacity of 700 bar. This meant that the applied load of the system was restricted because of the accumulator capacity. Recalculating the ultimate load meant that only 303 kN could be applied. The ultimate strength of concrete was then limited to just over 55 MPa. The hydraulic system was designed in such a way that the same load was applied to all the specimens because only one accumulator was used. Pressure gauges were used to check the pressure in the entire system as well as the individual creep frames.

- Specimens

The creep frame was designed in such a manner that it is capable of testing cylindrical or prism specimens with a maximum diameter/width of 150mm. The creep frame was also designed to test possibly two specimens at an instance with a maximum height of 650mm.

- Bearings

Since the load was assumed to be axial, a bearing had to be manufactured to correct the applied load direction if the specimen face was not perpendicular to the longitudinal face. A small degree of rotation was allowed and the bearing was designed and manufactured from steel discs which are located between the specimen and the bearing plate at the top of the creep frame. The hydraulic jack had a pivot bearing already included in its design.

- Safety mechanisms

Safety was the most important factor because of the possible high pressures that were being used in the hydraulic system. The possible scenarios of failure were considered and methods of avoiding these failures were employed. This included a pressure release valve in the case of over loading to quickly displace the hydraulic fluid. A steel plate was used to enclose the hydraulic piping beneath the table. Certain high grades of steel were used in different elements for load induced stresses. The hydraulic jacks did not have a safety mechanism to prevent the loading piston from stopping when nothing was resisting it (Figure 7.8a). To prevent this mode of failure a relatively thick plate was used through which a large hole was drilled to allow the specimen through, but not the loading piston (Figure 7.8b). A plate was also used at the top of the creep frame to prevent the bearing from falling due to its weight.



a) Piston failure mechanism

b) Steel plates to prevent failure

Figure 7.8 Possible piston failure mode and designed safety mechanism

The concrete specimens were only cured for 7 days and tested for 14 days under loading conditions because of the available time remaining in the investigation. The specimens were prepared in the same manner as the shrinkage specimens for measuring the deformation. Two days before testing the specimens were removed from the curing tank. The casting surface was ground and the targets were attached to the sides of the specimens (Figure E.15 in Appendix E).

After 7 days curing, three cube specimens and a single cylinder specimen identical to the specimens used for the creep test were tested to determine the concrete strength. Since a single cylinder specimen was tested, the strength from the cube specimens was needed to determine the strength of the concrete. The ratio of cube strength to cylinder strength was calculated and determined to be about

75%. The cube strength was multiplied by this factor and the average between this calculated result and the actual cylinder strength was established as the concrete strength. Since the creep frames were only able to test a single load between all the specimens, 35% of the ultimate concrete strength was calculated for each specimen and the average was determined as the load applied to the specimens. The calculated values described above are given in Table 7.1 and the applied loads for March, June and August were 6.0 MPa, 7.0 MPa and 7.0 MPa respectively.

Table 7.1 Determination of creep specimen strength and applied creep load

Mixture	f_{cu} (MPa)	f_c (MPa)	f_c/f_{cu} (%)	75% f_{cu} (MPa)	Average ^a (MPa)	35% Average ^b (MPa)
March						
N100C	26.4	19.9	75.4	19.8	19.9	6.9
R30C	19.9	14	70.4	14.9	14.5	5.1
R50C	18.8	14.8	78.7	14.1	14.5	5.1
R100C	29	22.4	77.2	21.8	22.1	7.7
Average	23.5	17.8	75.4	17.6	17.7	6.2
June						
N100C	26.1	16.5	63.2	19.6	18.0	6.3
R30C	28.5	20.3	71.2	21.4	20.8	7.3
R50C	28.3	19.7	69.6	21.2	20.5	7.2
R100C	28.2	22.5	79.8	21.2	21.8	7.6
Average	27.8	19.8	71.0	20.8	20.3	7.1
August						
N100C	23.1	18.1	78.4	17.3	17.7	6.2
R30C	25.2	21.3	84.5	18.9	20.1	7.0
R50C	26.8	19	70.9	20.1	19.6	6.8
R100C	29.2	22.5	77.1	21.9	22.2	7.8
Average	26.1	20.2	77.7	19.6	19.9	7.0

^a Average of 75% cube strength and actual cylinder strength

^b 35% of the average of 75% cube strength and actual cylinder strength

The first measurement was taken ± 15 minutes once removed from the curing tank. Readings were taken at 0, 3, 18 and 30 hours initially, then daily for a week and at incrementing periods until 14 days. The specimens were kept in a climate controlled room with temperature of $21 \pm 3^\circ\text{C}$ and relative humidity of $65 \pm 5\%$. The creep strain was calculated by dividing the change in length by the original length between the targets. The original length was calculated using the length of the positioning apparatus (gauge length = 101mm) plus the offset due to placing the targets, which was less than 1mm (Equation 7.11). The data was examined and where necessary a maximum of three readings of the nine total readings were removed to correct the coefficient of variation of the results.

$$\varepsilon_{cr} = \frac{L_{ti} - L_{t0}}{L_o + L_{t0}} \quad [\text{Eq. 7.11}]$$

where L_{ti} = measured length at time i
 L_{t0} = measured length at time 0
 L_o = length of positioning device

7.2 Results

Mechanical properties

7.2.1 Compressive strength and hardened concrete density

The compressive strength results for each of the monthly batches of concrete showed varied strength development, but individual mixtures performed similarly. Tables 7.2 and 7.3 provide numerical data for the 7 and 28 day compressive strength analyses, respectively. From Table 7.2 the early age compressive strengths of mixtures consisting of only OPC and containing RCA were in most cases lower or relatively equal to that of the control mixture containing only NA (N100C) in the March and June concrete batches. Conversely, the August mixtures containing RCA had higher early age strengths than the control mixture. The influence of the higher water absorption percentage for the August RCA is evident in this instance. The mixtures containing Corex® slag as a cement replacement showed opposite strength development. The mixtures generally had lower strengths than the OPC mixtures, which was to be expected, however with the inclusion of RCA, higher strengths developed than the control mixture (N100S).

Table 7.2 Compressive strength results for 7 days curing

Month	March		June		August	
	Strength (MPa)	COV (%)	Strength (MPa)	COV (%)	Strength (MPa)	COV (%)
N100C	29.3	5.9	26.5	5.2	20.2	3.0
R15C	28.8	7.7	23.1	3.7	21.4	3.6
R30C	26.4	13.4	27.1	2.9	21.9	2.5
R50C	24.8	6.4	25.3	4.0	22.2	4.7
R100C	25.5	3.2	26.7	2.6	24.5	2.4
N100S	21.9	2.1	23.3	1.5	22.4	3.9
R30S	22.4	4.7	23.9	3.7	21.8	6.3
R100S	24.9	5.2	25.9	3.2	25.7	3.4
Average	25.5	6.1	25.2	3.3	22.5	3.7

To explain the variation between the individual mixtures from each month a box and whisker plot is utilised. The box represents the interquartile range (IQR), with the upper boundary the third quartile (75th percentile) and the lower boundary the first quartile (25th percentile). The line through the IQR is the 50th percentile or median. The point in the IQR represents the average recorded value for the data. The whiskers extend to the lowest recorded value (Min) within 1.5IQR from the first quartile and extend to the highest recorded value (Max) within 1.5IQR from the third quartile. If the minimum or maximum value does not fall within the 1.5IQR it is considered an outlier.

Figure 7.9 is a box and whisker plot of the compressive strength variation for the 7 day concrete strength between the individual concrete mixtures for each month. The strength variation for the March mixtures is similar to the June mixtures, but the majority of the strengths are in the upper percentile whereas the June strengths are in the lower percentile. The overall average strength between the June and March concrete mixtures is almost identical. The August mixtures, although having a much lower strength variation within upper and lower percentiles, have a much lower overall average strength than that of the March and June mixtures. With the fact that the variation is lower the possibility of having outliers is possible. The August sample has only one outlier, which was the R100S mixture. The variation between the four specimens for each individual mixture in each month is between 1.5% and 13.2%, with the latter being an extreme case. This low variation shows that the mixtures containing RCA are produced without large deviation between samples, even in the case where the strength was lower.

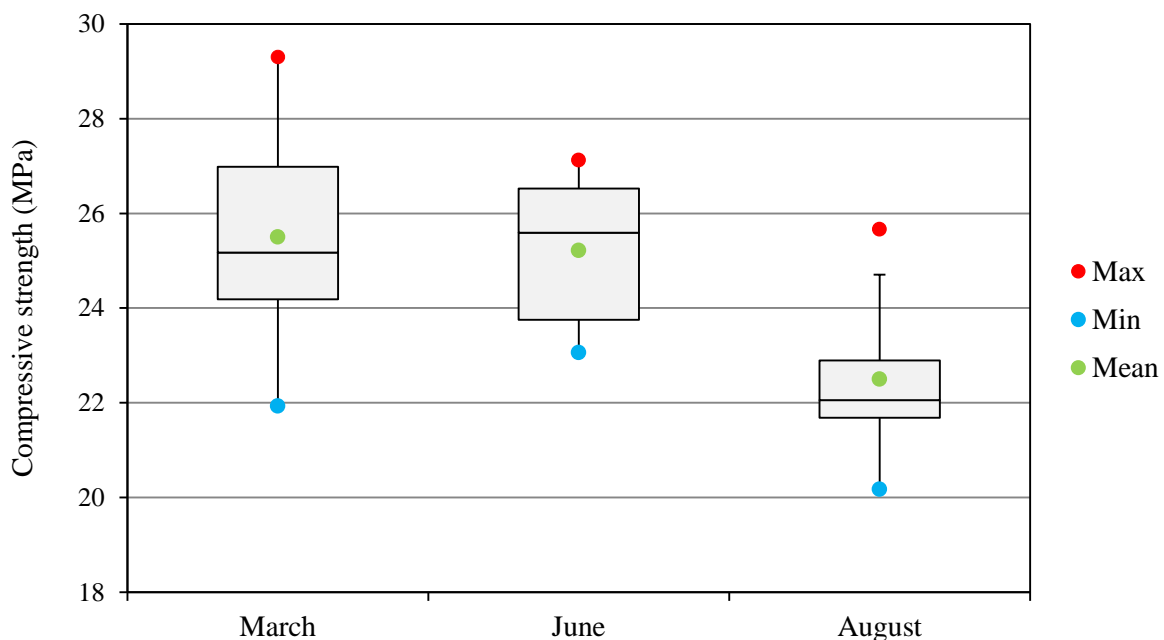


Figure 7.9 Box and whisker plot for the compressive strength variation at 7 days between concrete mixtures for each month

Shown in Table 7.3 are the 28 day compressive strength results for the monthly batches of concrete. Table 7.3 shows an opposing trend to the 7 day compression results, where for the most part, mixtures containing RCA were either greater or relatively equal to that of the control mixture for each month, in both the OPC and slag mixtures. The March mixtures produced mixtures with individual strengths which were generally higher than the other two months. The August concrete mixtures had the lowest individual concrete mixture strengths, with an overall combined strength of the mixtures about 15% lower than March and June combined mixtures. The mixtures with 100% RCA and slag cement replacement produced the highest strengths in each month. This showed that the cement extender has lower early age strengths when compared to mixtures only having OPC and higher later age strengths. The variation between the samples in each mixture for each month improved with coefficient of variation values ranging between 0.7 and 6.3. The lower variation between the test samples, further confirms that the RCA did not cause major deviations in this case study.

Table 7.3 Compressive strength results for 28 days curing

Month	March		June		August	
Sample	Strength (MPa)	COV (%)	Strength (MPa)	COV (%)	Strength (MPa)	COV (%)
N100C	35.7	1.8	33.5	5.5	26.6	1.4
R15C	36.5	1.6	31.9	3.4	28.9	5.4
R30C	32.9	0.7	33.2	2.7	27.8	1.5
R50C	36.0	2.6	34.5	3.6	27.5	3.2
R100C	35.4	2.5	34.9	2.0	30.2	3.1
N100S	35.7	1.4	34.7	1.2	33.2	4.4
R30S	35.7	4.1	35.9	2.6	32.9	5.8
R100S	38.6	2.3	39.6	2.2	34.3	6.3
Average	35.8	2.1	34.8	2.9	30.2	3.9

The overall variation between the concrete mixtures in each month is displayed by the box and whisker plot in Figure 7.10. Figure 7.10 shows different results when compared to the 7 day compressive strength results. The March and June concrete mixtures at 28 days have lower variation when compared to the 7 day strength results and the August mixtures show a much higher variation than what was recorded at 7 days. The March concrete mixtures had the lowest variation between mixtures, with upper and lower outliers resulting from the R100S and R30C mixtures respectively. The June concrete mixture only had one outlier which occurred in the R100S mixture. The August samples had no outliers, because the variation between the mixtures was high with the standard deviation nearly 3 MPa and the coefficient of variation about 10%.

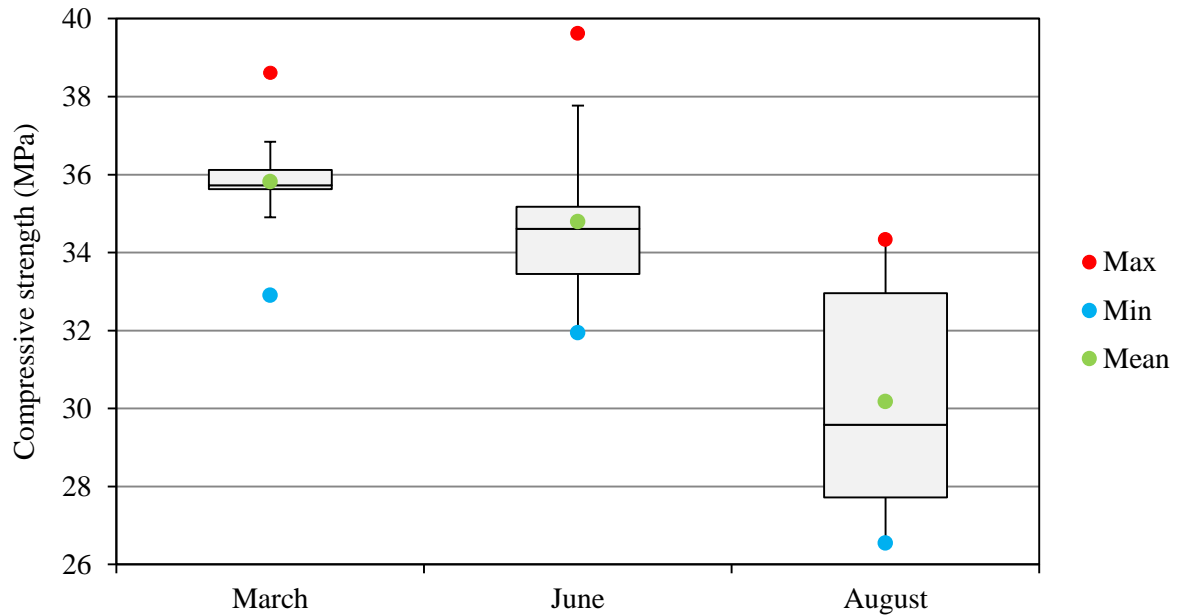


Figure 7.10 Box and whisker plot for the compressive strength variation at 28 days between concrete mixtures for each month

To determine the influence of the aggregates on each of the monthly batches of concrete, Figures 7.11 to 7.13 are included to show the strength development from 7, 14 to 28 days. Firstly the overall difference in strength between the monthly concrete batches can be related to the air content. The air content percentages in the March and June fresh concrete were fairly similar and lower than the August fresh concrete results (Table 6.2). The air content as noted in Section 3.2.3 can dramatically influence the concrete strength which is refuted in the outcomes of the above data. The air content in the R100C mixtures was the highest, however these mixtures produced higher strengths compared to the NA mixtures which means that other factors are influencing the strength in mixtures containing RCA.

The workability or consistence and cohesiveness of the concrete mixtures may have also played a role in the compressive strength results. The August mixtures were highly workable, due to the coarser fine aggregate used resulting in excess water. These mixtures therefore displayed a lesser degree of cohesion and consistence when compared to the other two months.

The water absorption of the aggregates influences the concrete strength by altering the w:c ratio. Aggregates in an air dry condition allowed for the water absorption to influence the concrete strength. The RCA used in the August concrete mixtures had higher water absorption percentages for all the percentage aggregate replacement ratios and this resulted in higher early age strengths when compared to the control mixture for that month. The higher water absorption is associated to the higher percentage of brick and combination of stone and mortar present with the RCA in August.

A plausible reason for the higher strength gain in R100C mixture in August could be the re-hydration of the old cement paste. With the excess water, higher water absorption and higher percentage of stone/mortar present this may be credible.

The improved compressive strength results in the June and especially the March concrete mixtures containing RCA could be attributed to the grading and therefore bulk density of the aggregate. The March RCA had a greater proportion of smaller stone than the June RCA and consequently resulting in a better bulk density through an improved packing capacity. Additionally, the particle shape allowed for the aggregates to move easier in the concrete and created a scenario for the ideal concrete mixture containing RCA.

The strength development showed varied results for each of the monthly concrete batches. The N100C, R15C and R30C mixtures from the March concrete batch showed an almost linear increase in strength from 7 to 28 days (Figure 7.11). The R50C, R100C, N100S and R100S mixtures displayed minor strength improvement at 14 days, but then improved significantly up to 28 days. The June mixtures all had an identical strength development, except for the R100S mixture (Figure 7.12). The strength development rate was higher between 7 and 14 days, but decreased between 14 and 28 days, while the R100S mixture showed a linear strength development between 7 and 28 days. The August concrete mixture had a similar strength development rate as that of the June mixtures (Figure 7.13). The numerical data for the compressive strengths at 14 days are included in Appendix E for reference.

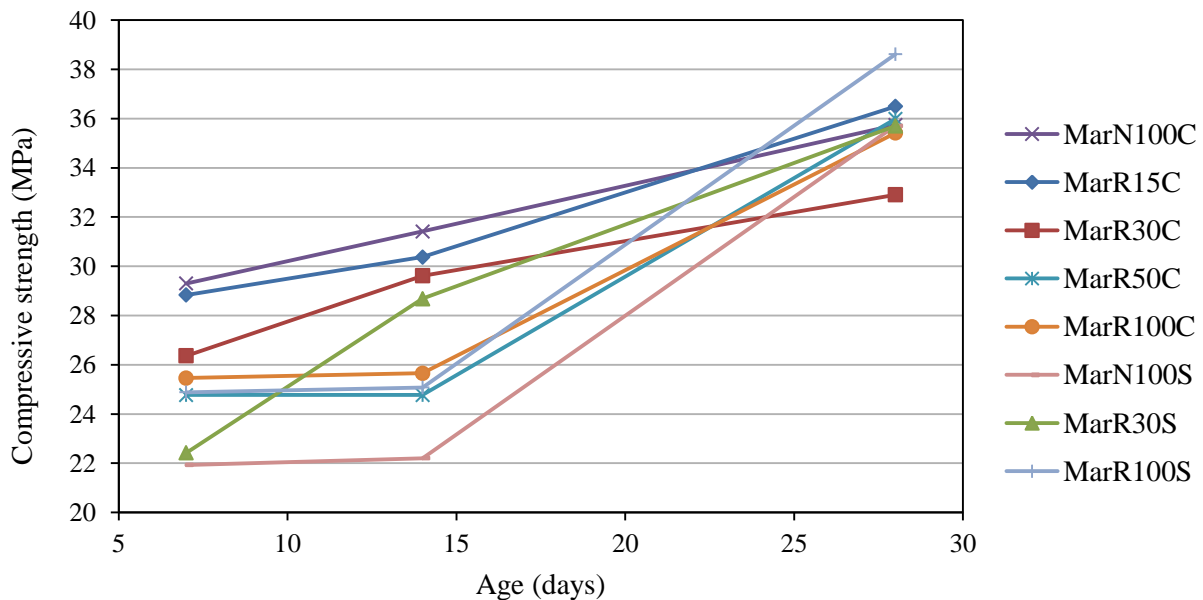


Figure 7.11 Compressive strength developments for March concrete mixtures

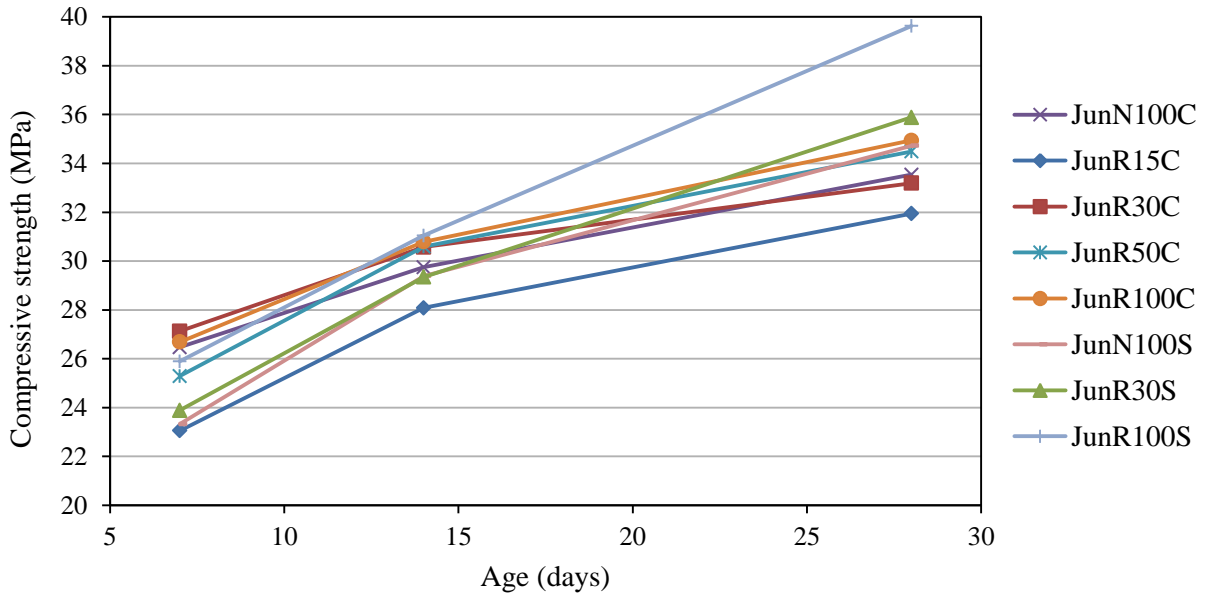


Figure 7.12 Compressive strength developments for June concrete mixtures

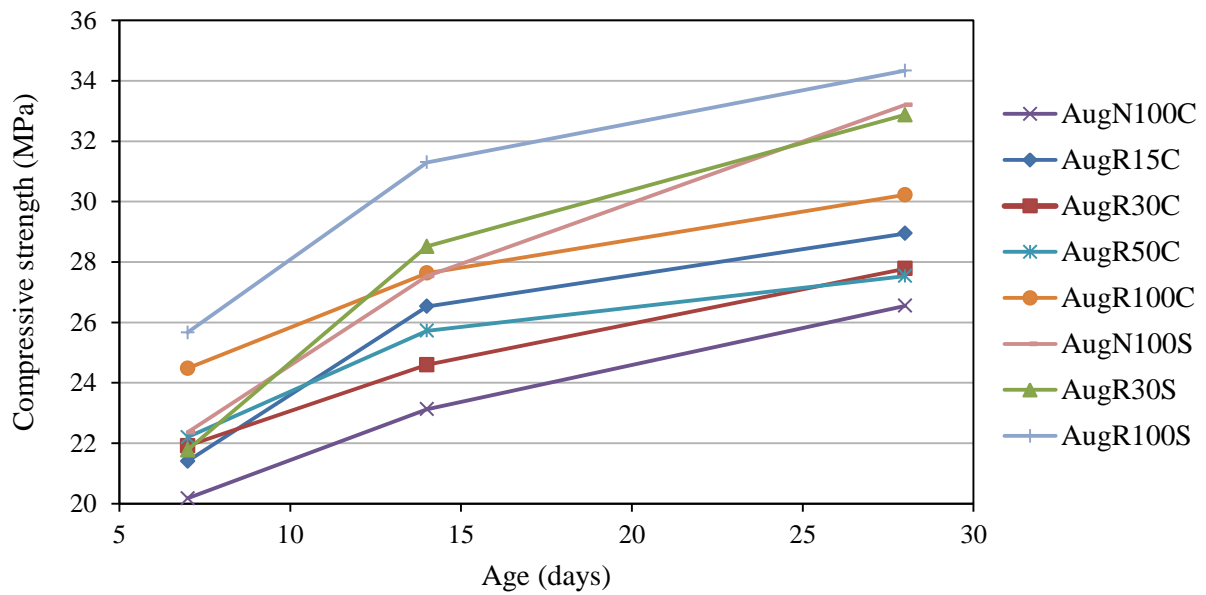


Figure 7.13 Compressive strength developments for August concrete mixtures

Compressive strength specimens were produced for the shrinkage and creep specimens with the results presented in Table 7.4. These mixtures were produced using the same fine aggregate as in the August mixtures as stated in Section 4.3. The influence that the fine aggregate will have on the compressive strength can therefore be neglected. The 7 day results for the March mixtures showed inconsistent data with the R30C and R50C mixtures significantly lower than the N100C and R100C mixtures. The June and August 7 day results showed less variation between the mixtures. To compare the mixtures the 28 day results are considered.

The compressive strength was higher in the mixtures containing RCA than the control mixture. Overall the RCA mixtures had similar strengths with the August R100C mixture having the highest overall strength due to the higher water absorption of the aggregates. The March mixtures overall performed better than the other months confirming the packing capacity argument. The outcome from this data shows that the compressive strength increases with the use of RCA and consistent strengths can be achieved due to the low variation between individual specimens.

Table 7.4 Compressive strength from shrinkage and creep mixtures

Mixture	7 days ^a (MPa)	COV (%)	28 days ^b (MPa)	COV (%)	Difference (MPa)
March					
N100C	26.4	2.3	32.1	2.8	5.7
R30C	19.9	8.5	35.3	2.5	15.4
R50C	18.8	5.3	35.1	1.9	16.3
R100C	29.0	6.2	35.6	0.3	6.6
Average	23.5	5.6	34.5	1.9	11.0
Std Dev.	4.3		1.4		
June					
N100C	26.1	0.8	28.2	0.4	2.1
R30C	28.5	2.1	32.5	2.9	4.0
R50C	28.3	2.5	33.3	5.8	5.0
R100C	28.2	3.9	32.6	2.3	4.4
Average	27.8	2.3	31.7	2.8	3.9
Std Dev.	1.0		2.0		
August					
N100C	23.1	0.4	28.4	2.6	5.3
R30C	25.2	0.8	33.1	1.9	7.9
R50C	26.8	3.4	32.6	3.6	5.8
R100C	29.2	1.7	36.5	3.8	7.3
Average	26.1	1.6	32.7	3.0	6.6
Std Dev.	2.2		2.9		

^a Creep cube specimens

^b Shrinkage cube specimens

The hardened concrete density results are given in Table 7.5 for the individual concrete mixtures for each month. Interestingly, the June mixtures had generally the highest concrete densities, while the March mixtures had the highest fresh concrete densities. This contradicts the packing capacity statement that was made for the compressive strength results. The reason for this may have resulted from lower RD values for the fine and coarse aggregate used in these mixtures. The August concrete

mixtures had the lowest densities due to the higher proportion of brick and combination of stone and mortar reducing the RD of the aggregate. The hardened concrete density at 7, 14 and 28 days showed no significant difference.

Table 7.5 Hardened concrete density after 28 days curing

Sample	March (kg/m ³)	June (kg/m ³)	August (kg/m ³)	Average (kg/m ³)
N100C	2352.5	2360.4	2331.7	2348.2
R15C	2351.8	2356.9	2322.3	2343.7
R30C	2323.3	2352.2	2298.4	2324.6
R50C	2341.6	2353.6	2281.0	2325.4
R100C	2291.5	2319.4	2278.3	2296.4
N100S	2335.6	2384.9	2361.4	2360.6
R30S	2365.1	2400.7	2354.1	2373.3
R100S	2310.2	2371.9	2286.7	2322.9

Figure 7.14 shows the trend which is observed from the average hardened concrete densities at 28 days for the individual concrete mixtures for each month. The trend is similar to that of the fresh concrete densities, where by as the percentage replacement increases the hardened concrete density decreases. From the OPC mixtures the R15C mixture had the highest fresh concrete density (Figure 6.6), but the R15C mixture was slightly lower than the control mixture in the hardened concrete densities. The mixtures containing slag reflect the results from fresh concrete densities, where the densities are higher than that of the OPC mixtures and the R30S mixture is slightly higher than the N100S mixture.

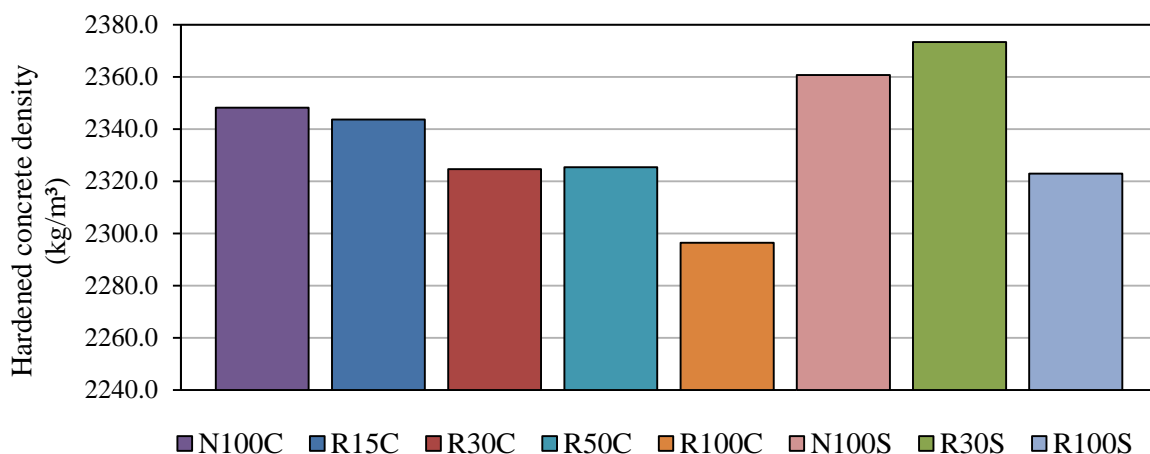


Figure 7.14 Average hardened concrete density for individual concrete mixture from each month

7.2.2 Tensile splitting strength

The tensile splitting strength for the individual concrete mixtures from the different concrete batches produced no clear trend. Examining the individual mixtures from March showed that the R100C mixture had the lowest tensile strength, while the N100S mixture had the highest (Figure 7.15). The coefficient of variation between the mixtures was about 4%, which showed the mixtures performed similarly.

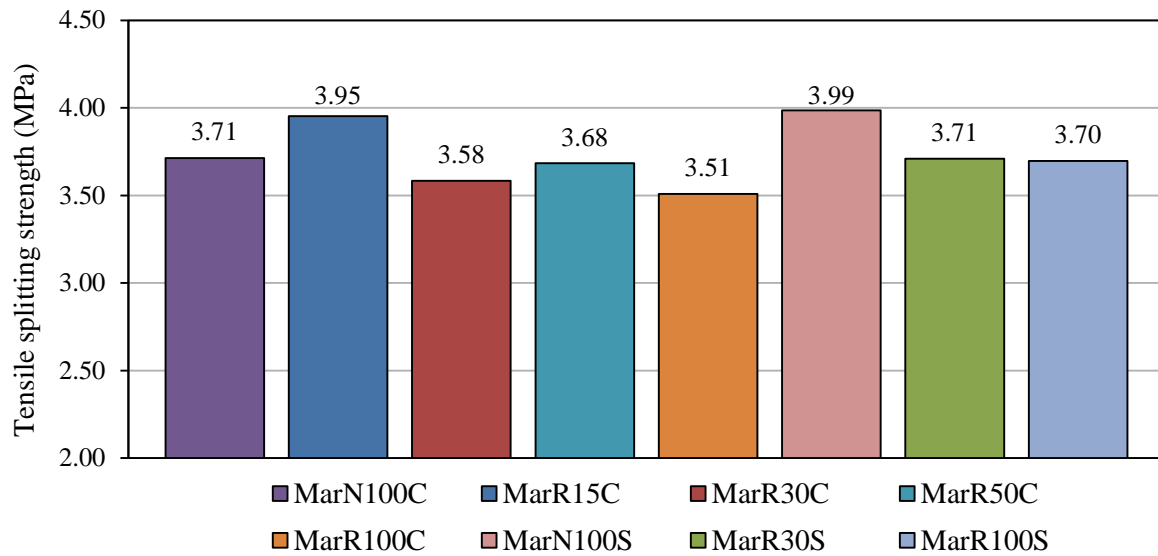


Figure 7.15 Tensile splitting strength for individual mixtures from March

The June concrete mixtures similarly had the lowest tensile strength with the R100C mixture and the highest with the N100S mixture (Figure 7.16). The overall coefficient of variation between the mixtures was about 3%, which shows that the mixtures performed relatively the same. The strengths between the individual mixtures compared to March show lower values. The August mixture had the lowest overall strengths when compared to March and June. The mixtures containing Corex® slag produced strengths which were relatively the same when examining the monthly data. The August concrete mixtures had a higher coefficient of variation of about 9% which showed that the mixtures differed in strength, which would explain the fact that the R50C mixture had the lowest strength (Figure 7.17). The N100S mixture however again had the highest tensile splitting strength.

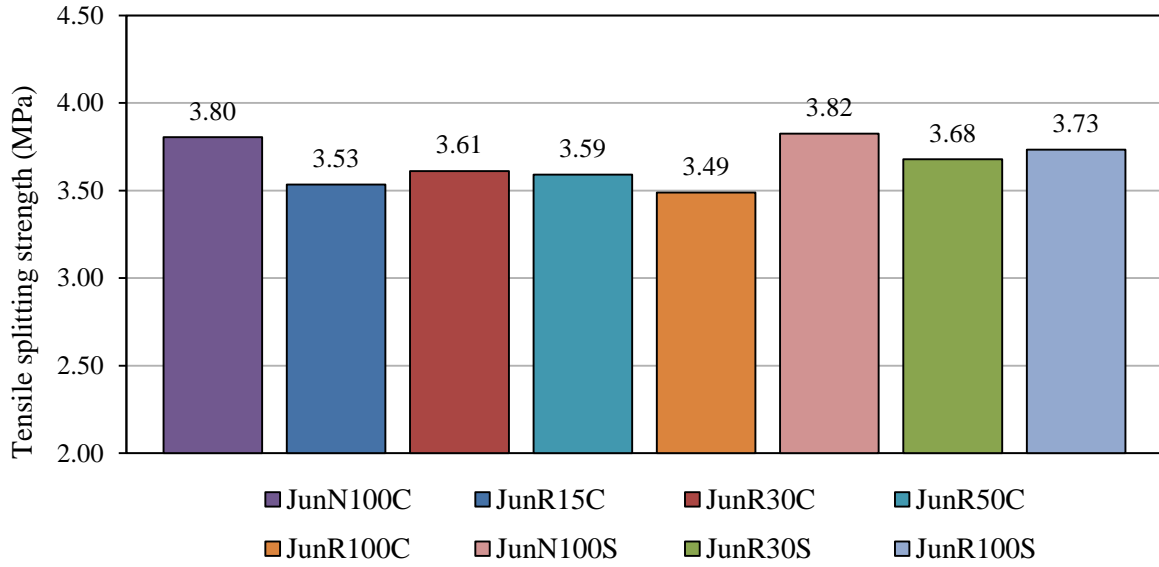


Figure 7.16 Tensile splitting strength for individual mixtures from June

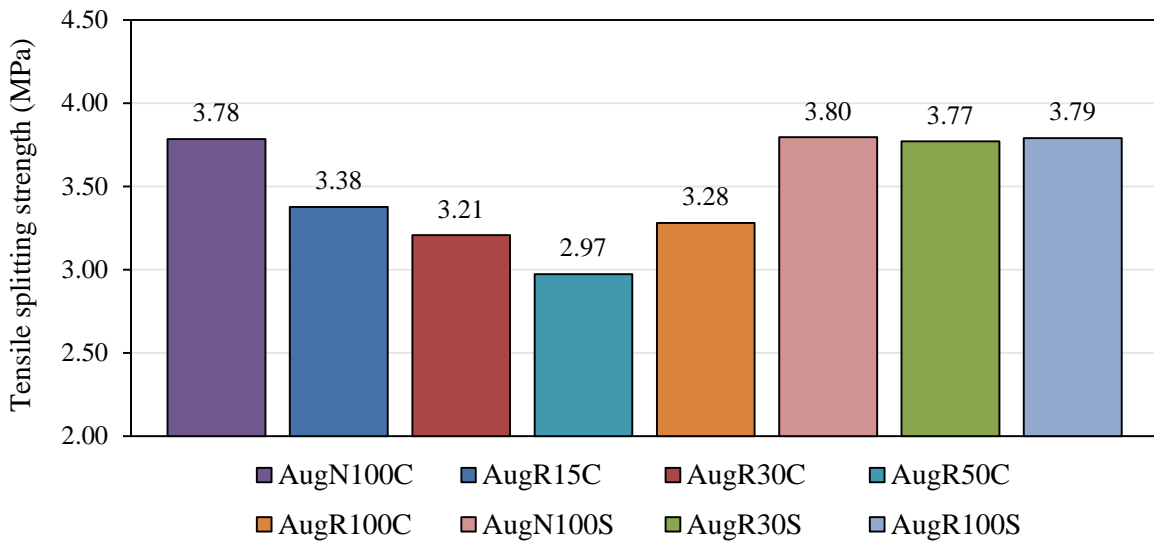


Figure 7.17 Tensile splitting strength for individual mixtures from August

The higher tensile strength in the N100S mixture can be attributed to the inclusion of slag cement extender which was noted in Section 3.3.1. Also the mixtures containing lower to no percentages of RCA performed better than mixtures with higher proportions of RCA. The outcome from this observation can be related to the fact that aggregates such as N100A and R15A have higher FI values and therefore provide improved aggregate interlocking.

The higher percentage RCA mixtures plane of failure passed through many of the aggregates as seen in Figure 7.18. The brick and mortar particles clearly show evidence of the failure plane. The mixtures containing higher proportions of NA had less failure through the aggregates and more failure around the aggregates.



Figure 7.18 Photograph shows the failure plane passing through the aggregate in the R100S mixture from August

Provided in Table 7.6 is the relationship between the tensile strength and compressive strength. From the Table 7.6 it can be seen that the tensile strength was about 10 to 11% of the compressive strength and as the percentage replacement increased, the relationship between the tensile strength and compressive strength decreased. The lower percentage between the tensile and compressive strength in the mixtures containing RCA shows that the aggregates had a greater influence on the tensile strength.

Table 7.6 Relationship between 28 day tensile and compressive strength

Sample	March (%)	June (%)	August (%)	Average (%)
N100C	10.4	11.3	14.3	12.0
R15C	10.8	11.1	11.7	11.2
R30C	10.9	10.9	11.5	11.1
R50C	10.2	10.4	10.8	10.5
R100C	9.9	10.0	10.9	10.2
N100S	11.2	11.0	11.4	11.2
R30S	10.4	10.3	11.5	10.7
R100S	9.6	9.4	11.0	10.0

Durability properties

The durability results are discussed separately for each month to determine the possible influence of aggregates used in the concrete for that month and combined to see the possible overall influence of RCA on the durability of hardened concrete. Included in Appendix E are the results from the individual specimens for each concrete mixture. The degree of variance between the samples was checked for the oxygen permeability and water sorptivity. The spreadsheets provided by the University of Cape Town for the OPI and water sorptivity tests describe the coefficient of variation as either: “Good”, “Caution” or “Invalid”. The descriptions are used to check whether a set of specimens may have not been tested properly or vary significantly, such that the results may be questionable.

The concern around the curing and conditioning of the specimens may be questionable as some specimens were not cured equally and some were not conditioned for the full 7 days. Table 7.7 shows the curing and conditioning periods for the different monthly samples used in the durability tests. The curing period should not have such a large impact in the results of the durability tests; however the conditioning period may influence the comparison between the monthly concrete batches. Reference/control mixtures are produced with each month and therefore accurate comparisons can be made between the individual mixtures. The durability property results are assessed for the influence of the following: percentage replacement, binder content and curing period.

Table 7.7 Curing and conditioning periods for durability tests

March 7 day		June & August 7 day	
Curing period		Curing period	
Set1 curing	7 days	Set1 curing	8 days
Set2 curing	6 days	Set2 curing	7 days
Conditioning period		Conditioning period	
OPI and Water Sorptivity	5 days	OPI and Water Sorptivity	6 days
Chloride Conductivity	7 days	Chloride Conductivity	7 days
March 28 day		June & August 28 day	
Curing period		Curing period	
Set1	31 days	Set1	29 days
Set2	30 days	Set2	28 days
Conditioning period		Conditioning period	
OPI and Water Sorptivity	7 days	OPI and Water Sorptivity	6 days
Chloride Conductivity	8 days	Chloride Conductivity	7 days

7.2.3 Oxygen permeability

The concrete mixtures from each month performed well according to the durability performance index in Table 3.33. Provided in Table 7.8 are the coefficients of permeability (k) and OPI value results for the respective mixtures from each month. No clear trend could be seen when replacing NA with RCA in the mixtures. The best and worst performing mixtures from March were the R50C and N100S mixtures respectively for both curing periods. The R30C mixture performed the best at 7 days and the R50C mixture at 28 days for the June concrete mixtures. The N100S mixture again performed the worst for both curing period in the June mixtures. The best performing mixtures in the August mixtures were the R30C and R50C mixtures at 7 days and the N100C mixture at 28 days. The N100S performed the worst for the August concrete mixtures for both curing periods.

Table 7.8 OPI results for the concrete mixtures from each month

March							
Curing		7 days			28 days		
Mixture	k (m/s)	OPI	DI Index	k (m/s)	OPI	DI Index	
N100C	9.53E-11	10	Excellent	1.09E-10	10	Excellent	
R15C	8.81E-11	10.1	Excellent	6.71E-11	10.2	Excellent	
R30C	8.73E-11	10.1	Excellent	8.77E-11	10.1	Excellent	
R50C	5.22E-11	10.3	Excellent	5.22E-11	10.3	Excellent	
R100C	7.35E-11	10.1	Excellent	6.30E-11	10.2	Excellent	
N100S	1.78E-10	9.8	Good	2.09E-10	9.7	Good	
R30S	1.39E-10	9.9	Good	9.87E-11	10	Good	
R100S	9.11E-11	10	Good	1.27E-10	9.9	Good	
June							
Curing		7 days			28 days		
Mixture	k (m/s)	OPI	DI Index	k (m/s)	OPI	DI Index	
N100C	2.50E-10	9.6	Good	1.83E-10	9.7	Good	
R15C	1.95E-10	9.7	Good	1.27E-10	9.9	Good	
R30C	1.34E-10	9.9	Good	1.51E-10	9.8	Good	
R50C	2.10E-10	9.7	Good	1.01E-10	10	Good	
R100C	2.08E-10	9.7	Good	2.31E-10	9.6	Good	
N100S	5.27E-10	9.3	Poor	3.67E-10	9.4	Poor	
R30S	3.67E-10	9.4	Poor	3.99E-10	9.4	Poor	
R100S	4.16E-10	9.4	Poor	1.63E-10	9.8	Good	
August							
Curing		7 days			28 days		
Mixture	k (m/s)	OPI	DI Index	k (m/s)	OPI	DI Index	
N100C	1.51E-10	9.8	Good	6.84E-11	10.2	Excellent	
R15C	1.14E-10	9.9	Good	8.65E-11	10.1	Excellent	
R30C	8.33E-11	10.1	Excellent	1.28E-10	9.9	Good	
R50C	8.82E-11	10.1	Excellent	1.11E-10	10	Good	
R100C	1.14E-10	9.9	Good	7.15E-11	10.1	Excellent	
N100S	1.14E-09	8.9	Invalid	1.01E-09	9	Good	
R30S	9.37E-10	9	Invalid	1.84E-10	9.7	Good	
R100S	1.67E-10	9.8	Good	1.42E-10	9.8	Good	

The influence of binder content is evident from the durability results. The k value was higher for the slag mixtures than the OPC mixtures. The higher k values will result in a lower OPI value and therefore a poor performance index. The slag mixtures obtained performed “Poor” to “Good”, while the OPC mixtures performed “Good” to “Excellent”. The slag mixtures should perform better than the OPC mixtures according to Section 3.3.2 due to the finer cement particles reducing the pore size distribution. Kutegeza (2004) and Heiyantuduwa & Alexander (2009) reported similar results for mixtures with a w:c ratio of 0.6. Kutegeza (2004) noted that the prolonged bleeding in fresh concrete may have created interconnected capillary pores, resulting in a higher permeability. The slag mixtures were more workable than the OPC mixtures and possibly required less water to achieve the correct workability, thus the above statement may be plausible.

The influence which curing had on the OPI results was varied and generally minimal. It must be noted that the June 7 day durability mixtures were not produced from the same batch of concrete. The coring machine broke on the day which the specimens were to be prepared. The specimens were therefore discarded and new specimens were produced, but from a smaller (volume) mixture. The effect of this may not be evident in the OPI results, but the influence in the porosity and water sorptivity results is apparent.

Figures 7.19 and 7.20 provide a graphical description of the 7 day and 28 day OPI results respectively for the individual concrete mixtures from each month. The March mixtures performed marginally better than the August mixtures and higher than the June mixtures. The “Invalid” results due to high coefficients of variability noted in Appendix E for the August N100S and R30S 7 day mixtures clearly show that the results could in fact be higher. The August N100S mixture at 28 days also had an OPI value lower than the observed trend due to a high coefficient of variation. The conclusion must be made then that the specimens were not tested correctly.

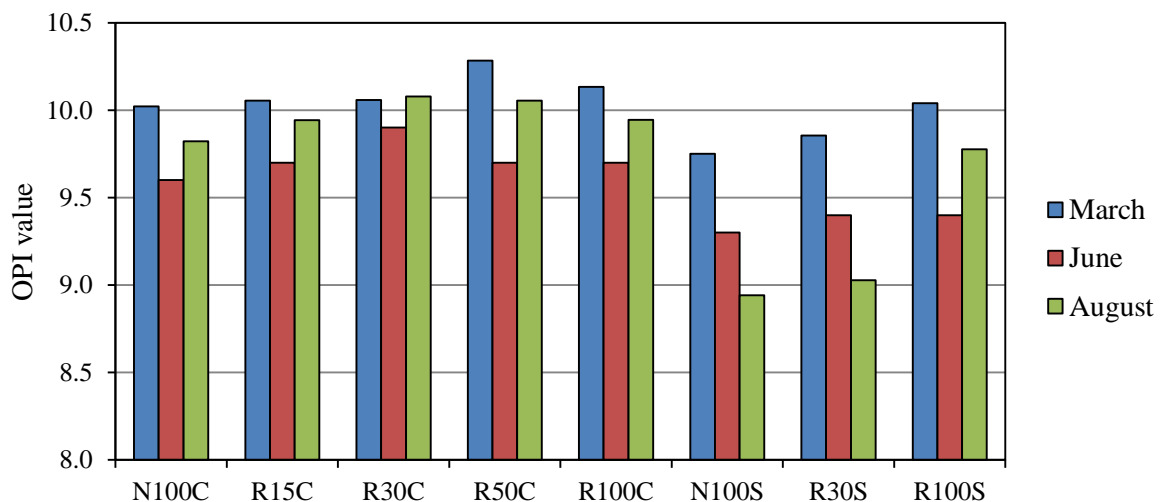


Figure 7.19 OPI values for the concrete mixtures from each month cured for 7 days

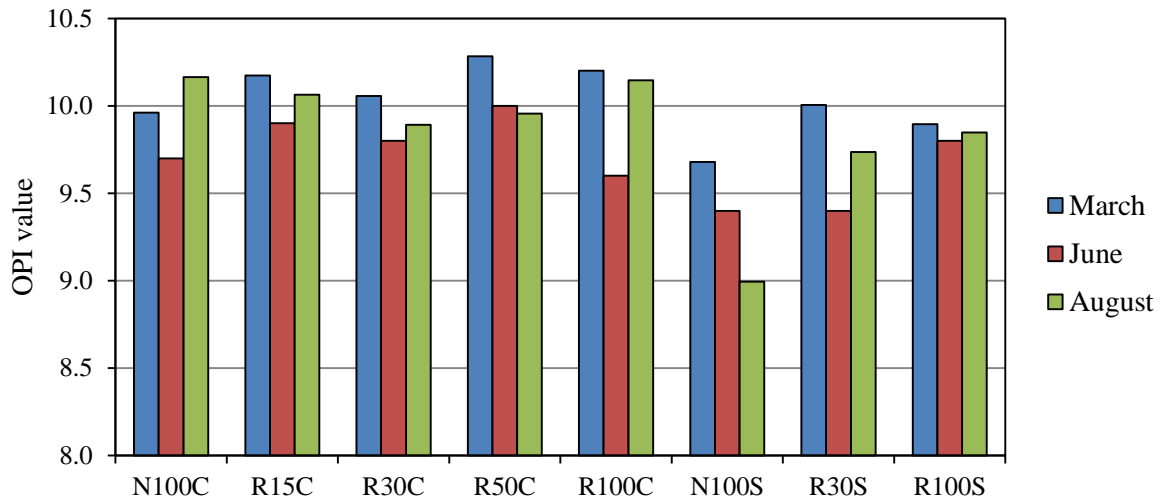


Figure 7.20 OPI values for the concrete mixtures from each month cured for 28 days

Interestingly, from the outcomes of the OPI tests the August mixtures, which could be considered the “worst” mixtures due to the aggregate properties and fresh concrete results, performed well. The amount of stone/mortar combination and brick was significantly higher in the August RCA samples and most researchers in Section 3.3.2 have associated poor OPI results to aggregates with similar constituents. The reason for the outcomes from the OPI results has to do with the consistency of the fresh concrete and constituents of the RCA.

Considering the OPC mixtures, the August concrete mixtures had high slump values indicating that the excess mixing water was available due to the coarser fine aggregate (Figure 7.21). The air content in the August mixtures was also the highest when compared to the other mixtures. The June concrete mixtures had the lower slump values and air content results. The June RCA mixtures had less stone/mortar combination particles. It can therefore be assumed that the RCA absorbed the excess mixing water due to the higher water absorption than the natural aggregate. This absorbed water may have reacted with old cement in the RCA to some degree and in doing so reduced the pores and microcracks inherent to the RCA.

Considering the other concrete mixtures based on the above statement, the new ITZ regions (Figure 7.22) and capillary pores in the RCA mixtures were then improved and generally the RCA replacement mixtures performed similar and even better than the control mixture. The water absorption for the August aggregate was higher than the March aggregate, and the latter higher than the June aggregate. The March mixtures performed better than the August mixtures because the consistency of the mixtures was better.

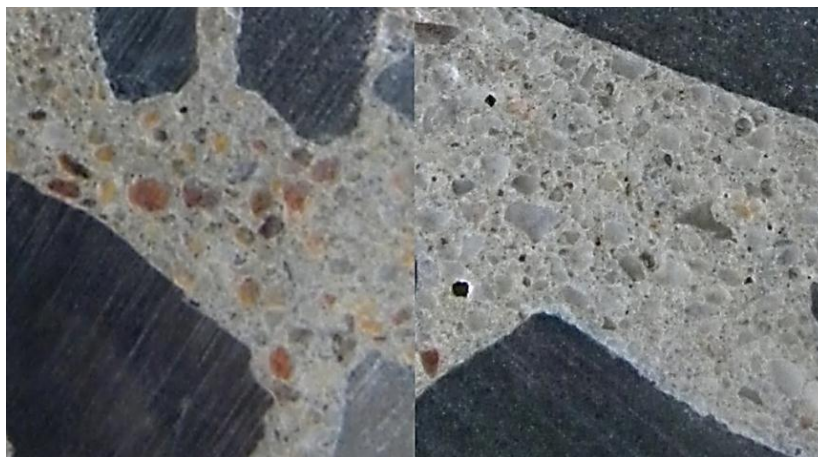


Figure 7.21 Coarser August sand (left) and finer June sand (right)

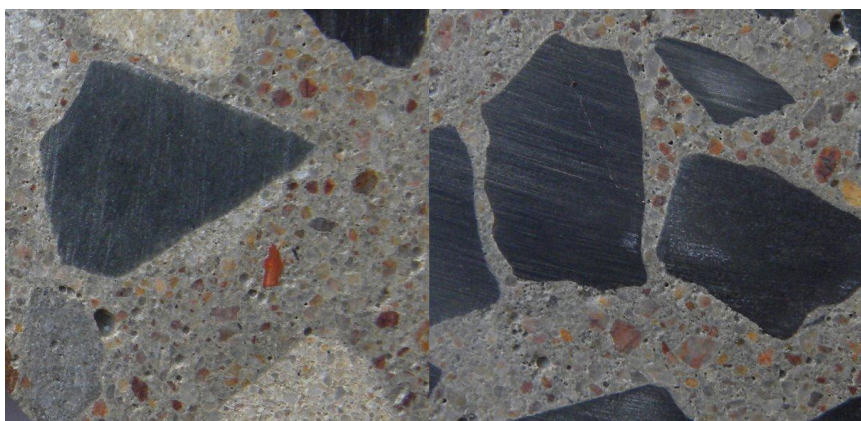


Figure 7.22 August R100C (left) with attached mortar and N100C (right)

7.2.4 Water sorptivity and porosity

The water sorptivity and porosity for the concrete mixtures from each month are presented in Table 7.9. The durability performance index for water sorptivity from Table 3.33 is included in Table 7.9 for the individual concrete mixtures from each month. The increase in percentage replacement had no clear overall trend. The lower porosity did not result in a decrease in water sorptivity. For the individual performance of mixtures from each month according to the porosity, the R100C mixture generally had the highest porosity for both curing periods and the R30S mixture had the lowest porosity at both 7 and 28 days curing. Considering the water sorptivity results, the influence and performance of individual mixtures was varied. The mixtures generally performed similar to one another for each month.

Table 7.9 Water sorptivity and porosity results for the concrete mixtures from each month

March						
Curing 7 days				28 days		
Mixture	Porosity (%)	Sorptivity (mm/√hr)	DI Index	Porosity (%)	Sorptivity (mm/√hr)	DI Index
N100C	11.5	6.9	Good	10.4	6.7	Good
R15C	11.9	6.6	Good	10.8	6.3	Good
R30C	11.5	6.3	Good	11.1	5.6	Excellent
R50C	11.6	6.8	Good	10.4	6.3	Good
R100C	12.3	6.7	Good	11.3	6	Good
N100S	10.8	7.1	Good	9.5	6.9	Good
R30S	10.7	7.1	Good	9.5	6.7	Good
R100S	11.5	5.4	Excellent	9.3	5.9	Excellent
June						
Curing 7 days				28 days		
Mixture	Porosity (%)	Sorptivity (mm/√hr)	DI Index	Porosity (%)	Sorptivity (mm/√hr)	DI Index
N100C	9.8	9.1	Good	10.9	7.6	Good
R15C	10.1	9.2	Good	11.3	6.7	Good
R30C	10.6	9.3	Good	11.5	7.2	Good
R50C	10.8	9	Good	10.7	7.2	Good
R100C	11.2	9	Good	11.3	7	Good
N100S	10	9.3	Good	9.6	7.3	Good
R30S	9.7	8.5	Good	10.7	8.2	Good
R100S	10.5	8.7	Good	10.8	7.3	Good
August						
Curing 7 days				28 days		
Mixture	Porosity (%)	Sorptivity (mm/√hr)	DI Index	Porosity (%)	Sorptivity (mm/√hr)	DI Index
N100C	9.7	6.2	Good	10.3	5.5	Excellent
R15C	10.4	5	Excellent	10.3	5.8	Excellent
R30C	10.7	5.5	Excellent	10.5	5.5	Excellent
R50C	10.8	6.2	Good	10.2	5.1	Excellent
R100C	12.7	7	Good	11.3	5.8	Excellent
N100S	8.7	5.2	Excellent	9.3	5	Excellent
R30S	8.2	5.2	Excellent	9.1	5.2	Excellent
R100S	10.6	5.7	Excellent	11	5.8	Excellent

Comparing the different binder contents showed lower porosities in the slag mixtures at lower RCA percentage replacements. The durability performance according to the water sorptivity showed that the OPC and slag mixtures performed similarly, with some individual mixtures performing better than others. Overall the concrete mixtures performed “Good” to “Excellent”.

Longer curing generally improved the porosity of the mixtures and water sorptivity but not significantly. The June mixtures had a significant improvement in water sorptivity and higher porosity with longer curing. The fact that the mixtures were not produced from the same batch is evident here with the porosity and water sorptivity more sensitive to the degree of compaction.

To examine the porosity between the concrete mixtures from each month, Figures 7.23 and 7.24 are provided. Considering that the June 7 day results are not consistent with the other two months, the 28 day results are examined for comparison. The overall porosity in the mixtures is generally the same, with the June mixtures having a higher porosity than the March and August concrete mixtures.

The porosity results reflect the outcomes from the OPI tests. From the OPI results the June mixtures should have had a higher porosity and the March mixture the lowest. The August mixtures have a slightly lower overall porosity than the March mixtures. This may be because the porosity results reflect the amount of pores in the bulk cement paste rather than the smaller pores where gases permeate more easily.

The slag mixtures however do not reflect the outcomes from the OPI results. The slag mixtures have the lowest overall porosity, but do not perform better in the OPI results. The reason for this outcome is not explained as it is not the focus of the investigation. The porosity in the bulk cement paste should reduce according to Section 3.3.2 due to the greater formation of hydration products with slag.

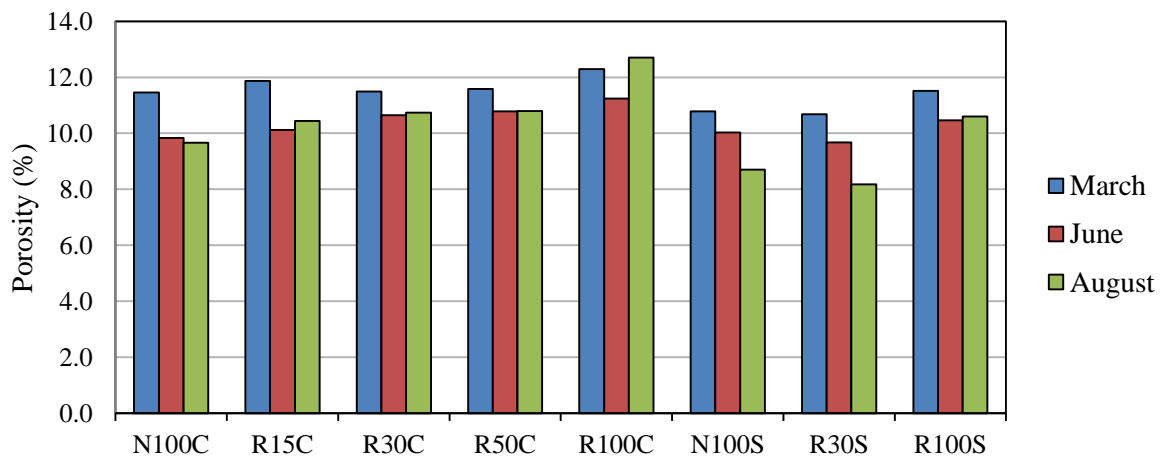


Figure 7.23 Porosity of the concrete mixtures from each month cured for 7 days

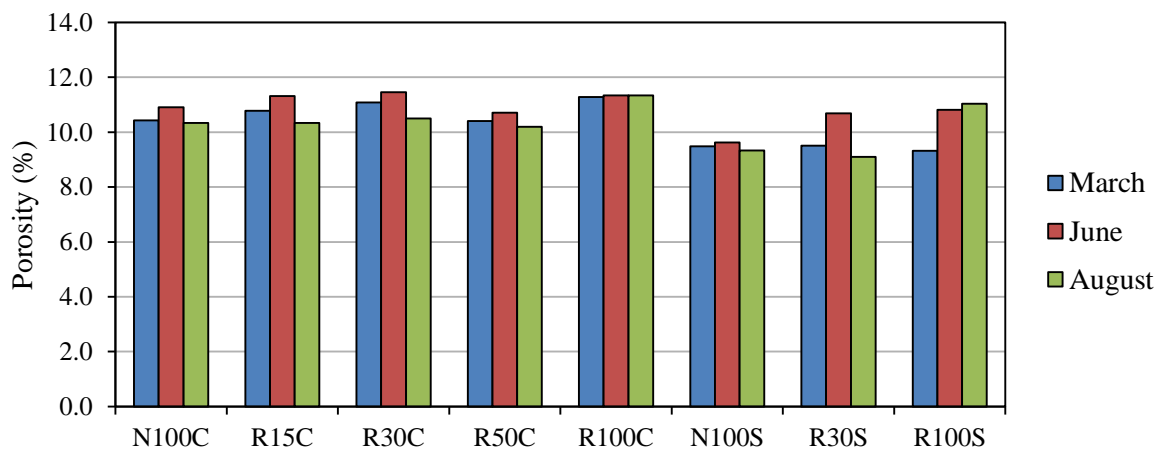


Figure 7.24 Porosity of the concrete mixtures from each month cured for 28 days

The water sorptivity results are presented in Figures 7.25 and 7.26 and a comparison is made with the 28 day curing results. The June mixtures performed the poorest and the August mixtures performed the best overall. The individual mixtures from each month as noted performed relatively similar to one another. A possible explanation for the performances of the mixtures containing RCA is due to the adhered mortar. Most researchers in Section 3.3.2 note that inclusion of materials such as brick and mortar which are highly water absorbent will reduce the performance with regard to the water sorptivity.

The August mixture had the highest presence of brick and stone/mortar combination. As stated in the OPI results the excess mixing water may have been absorbed by such materials thus reducing the w:c ratio and promoting higher strength. Taking this into consideration, as well as the possibility that the adhered mortar utilised the additional water for hydration of old cement, resulted in an improved water sorptivity. The porous nature of the adhered mortar was improved with the greater formation of hydration products in the concrete.

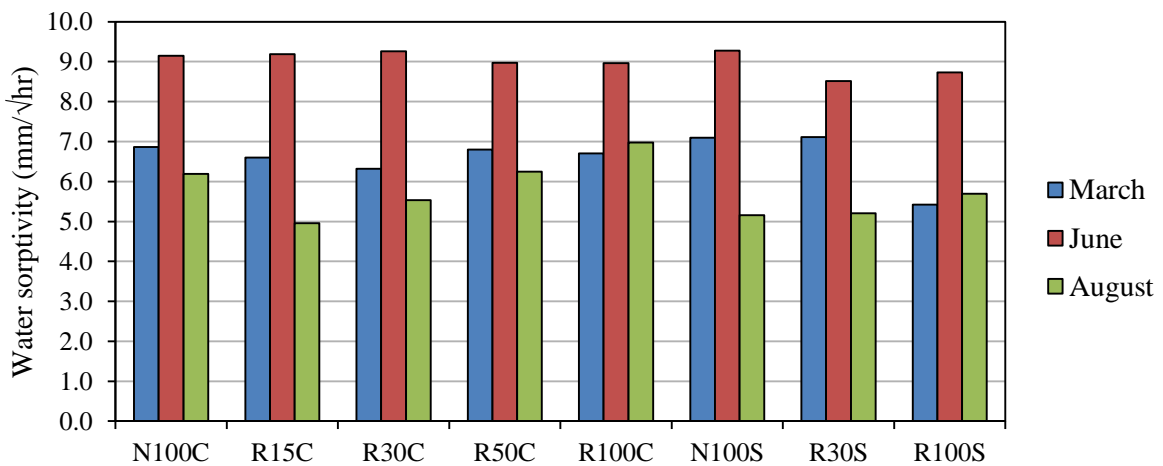


Figure 7.25 Water sorptivity of the concrete mixtures from each month cured for 7 days

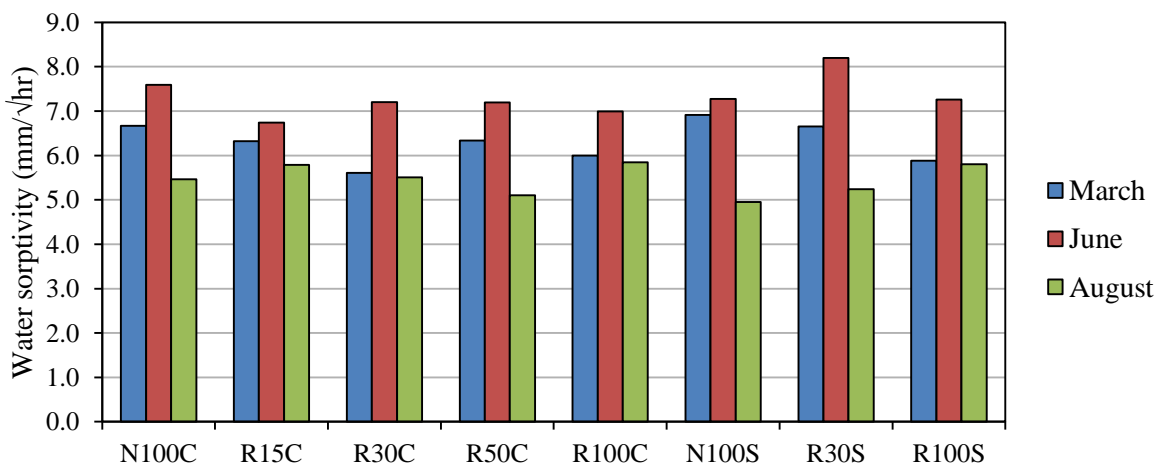


Figure 7.26 Water sorptivity of the concrete mixtures from each month cured for 28 days

7.2.5 Chloride conductivity

The chloride conductivity results reflect the amount of chloride ions found in the aggregate samples in Section 5.2.7. The chloride conductivity results for the concrete mixtures from each month are provided in Table 7.10. The durability performance index for chloride conductivity from Table 3.33 is included in Table 7.10 for the individual concrete mixtures from each month. Considering the OPC mixtures, the chloride conductivity increased with increasing percentage replacement in the concrete mixtures for 7 days curing. The chloride conductivity generally decreased with increasing percentage replacement at 28 days, except in the August mixtures. The chloride conductivity in the slag mixtures showed no clear overall trend with percentage replacement.

The influence of different binder content is clearly evident and showed expected results. The inclusion of slag reduced the chloride conductivity of the concrete mixtures when compared to the OPC mixtures. The reason for the reduction was noted in Section 3.3.2 as the increased chloride binding by the aluminate phases in the materials such as slag.

The longer period of curing significantly improved the results of mixtures containing higher presence of chloride ions. The June RCA had a higher amount of chloride ions than the March RCA. The August RCA had the lowest amount of chloride ions present. Considering the March and June mixtures, the mixtures containing 100% RCA had the highest chloride conductivity at 7 days, but showed the greatest improvement in the reduction of chloride conductivity at 28 days. The fact that the June 7 day mixtures were produced from different concrete batches will not significantly influence the chloride conductivity outcomes. The influence of binder type and curing conditions are greater than the degree of compaction. Although the pore structure allows for the movement of ions, the chloride content and the previously mentioned factors should have a greater influence. The August mixtures had lower chloride conductivity results compared to the other two months and with longer curing, some of the mixtures had higher conductivity values. The only mixtures which showed an improvement were the mixtures containing 50 and 100% RCA.

Considering the durability performance index for chloride conductivity, the March and June mixtures performed “Poor”, but improved with longer curing to achieve a “Good” performance index. The slag mixtures from these months also showed a clear improvement in performance with longer curing, improving from “Good” to “Excellent”. The August concrete mixtures did not improve in durability performance with longer curing. The OPC mixtures achieved a “Good” durability performance for both the 7 and 28 day results, while the slag mixtures achieved an “Excellent” durability performance for both curing periods.

Table 7.10 Chloride conductivity results for concrete mixtures from each month

March					
Mixture	7 days (mS/cm)	DI Index	28 days (mS/cm)	DI Index	Difference (mS/cm)
N100C	1.62	Poor	1.11	Good	-0.51
R15C	1.64	Poor	1.15	Good	-0.48
R30C	1.53	Poor	1.13	Good	-0.40
R50C	1.68	Poor	1.06	Good	-0.62
R100C	1.65	Poor	1.03	Good	-0.62
N100S	0.99	Good	0.47	Excellent	-0.53
R30S	0.95	Good	0.51	Excellent	-0.44
R100S	0.88	Good	0.39	Excellent	-0.48
June					
Mixture	7 days (mS/cm)	DI Index	28 days (mS/cm)	DI Index	Difference (mS/cm)
N100C	1.76	Poor	1.55	Good	-0.21
R15C	1.74	Poor	1.60	Good	-0.14
R30C	1.86	Poor	1.49	Good	-0.37
R50C	1.87	Poor	1.51	Good	-0.36
R100C	1.92	Poor	1.51	Good	-0.42
N100S	1.07	Good	0.60	Excellent	-0.47
R30S	0.97	Good	0.77	Good	-0.19
R100S	0.96	Good	0.59	Excellent	-0.37
August					
Mixture	7 days (mS/cm)	DI Index	28 days (mS/cm)	DI Index	Difference (mS/cm)
N100C	1.29	Good	1.37	Good	0.07
R15C	1.30	Good	1.37	Good	0.07
R30C	1.22	Good	1.43	Good	0.21
R50C	1.43	Good	1.42	Good	-0.01
R100C	1.49	Good	1.42	Good	-0.07
N100S	0.57	Excellent	0.68	Excellent	0.11
R30S	0.52	Excellent	0.60	Excellent	0.08
R100S	0.71	Excellent	0.71	Excellent	0.01

Figures 7.27 and 7.28 show the chloride conductivity results for the concrete mixtures at 7 and 28 days curing respectively. The results from the chloride conductivity analysis further emphasize the possible hydration of old cement in the adhered mortar. The 100% RCA mixtures showed the greatest improvement in chloride conductivity for all the monthly concrete batches. These mixtures would have had a higher percentage of stone/mortar particles and in the case of the August mixtures, the only mixtures which showed improvement in the lower presence of chloride ions were the 50% and 100% RCA mixtures. The presence of additional water resulted in a reduction of chloride ions through the formation of the hydration products which react with these chloride ions.

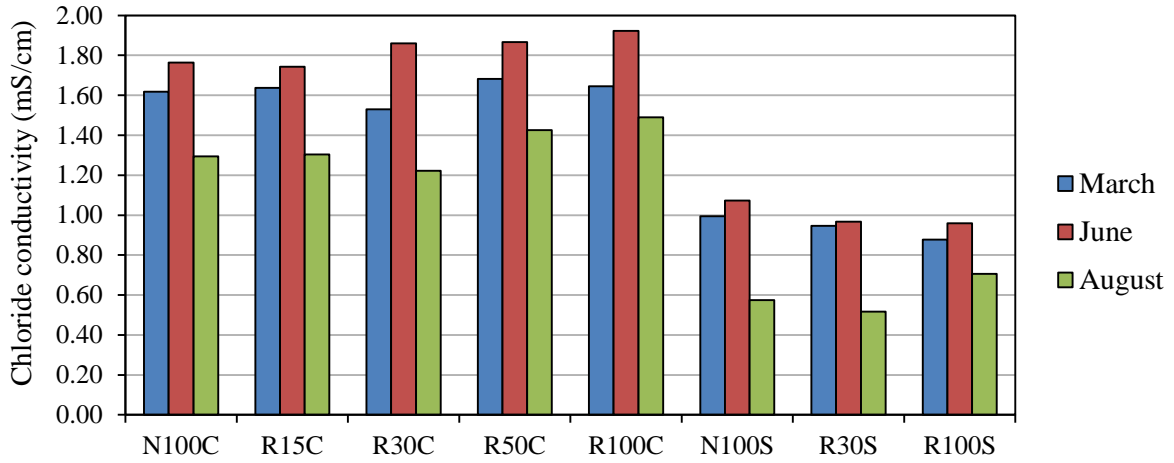


Figure 7.27 Chloride conductivity results for concrete mixtures from each month for 7 days curing

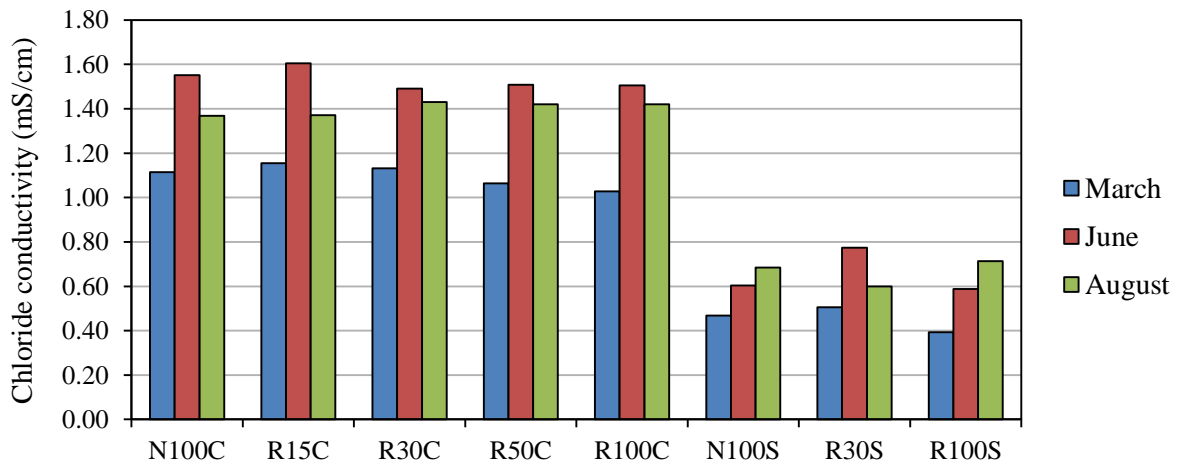


Figure 7.28 Chloride conductivity results for concrete mixtures from each month for 28 days curing

Dimensional properties

7.2.6 Modulus of elasticity

The modulus of elasticity at 28 days reflected some of outcomes from the compressive strength results in Section 7.2.1. The modulus of elasticity results for the individual concrete mixtures from each month are presented in Table 7.11. No clear trend can be seen from the results between the concrete mixtures from each month. The March and June concrete mixtures had similar a concrete stiffness as well as concrete strength. The August concrete mixtures had the lowest overall elastic modulus results due to the less consistent fresh concrete. The slag mixtures generally produced similar concrete stiffness results to the OPC mixtures.

Table 7.11 Modulus of elasticity results for 28 days curing

Month	March		June		August	
Sample	E-modulus (GPa)	COV (%)	E-modulus (GPa)	COV (%)	E-modulus (GPa)	COV (%)
N100C	34.3	8.6	37.7	1.1	27.7	3.5
R15C	35.0	1.4	37.0	4.7	33.1	4.8
R30C	36.7	5.2	36.7	1.2	30.1	3.3
R50C	35.7	2.1	37.5	1.2	31.8	4.4
R100C	37.2	5.0	35.1	6.0	28.6	0.7
N100S	38.9	1.9	35.6	0.6	32.5	0.0
R30S	33.6	9.2	35.3	7.7	32.8	4.6
R100S	40.7	1.0	34.5	4.7	30.6	0.7
Average	36.5	4.3	36.2	3.4	30.9	2.7

Seen in Figure 7.29 are the box and whisker plot for the overall variation between the concrete mixture results. The results for the individual mixtures are equally distributed in the upper and lower percentiles. The mixtures had no outliers with the maximum and minimum results falling within the whisker boundary. Overall the concrete mixtures produced similar modulus of elasticity results.

The stiffness of the concrete is affected by the individual constituent stiffness, volume of aggregate and degree of compaction. The effect of the fresh concrete consistency is evident in modulus of elasticity results. The inclusion of 100% RCA did not significantly affect the modulus of elasticity of the concrete in the March, June and August mixtures when compared to the control mixtures with the same binder content. Considering the OPC mixtures, the intermediate (15%, 30% and 50%) mixtures generally had the higher concrete stiffness. With the results presented in Table 7.11 the RCA should not affect the elastic modulus of the concrete.

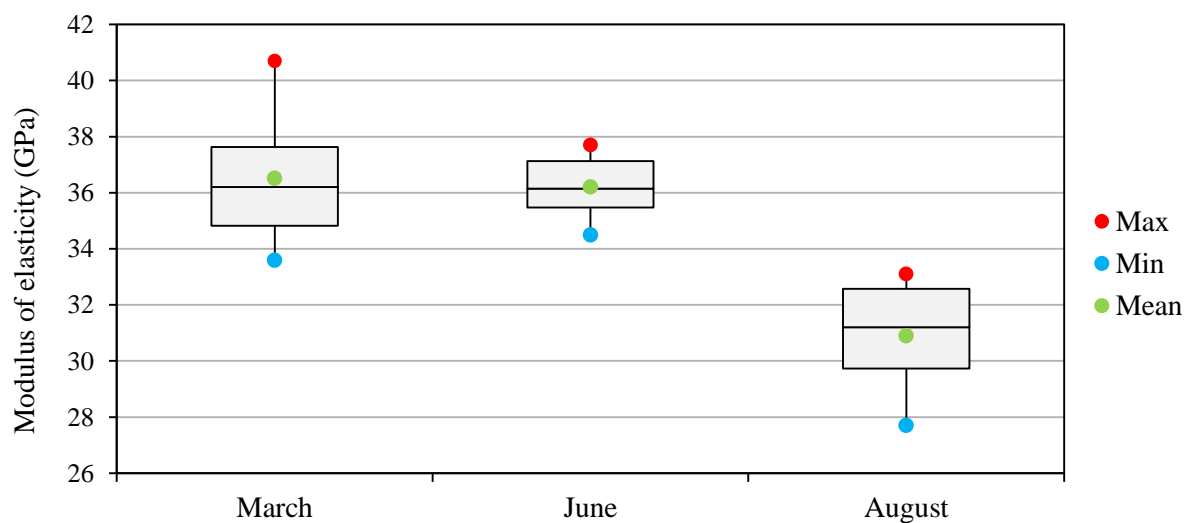


Figure 7.29 Box and whisker plot for the elastic modulus results from each month

7.2.7 Shrinkage

The difference between the shrinkage results of the specimens cured for 28 days from each month was marginal. Table 7.12 provides the shrinkage strains (ϵ_{sh}) measured at 90 days for the different mixtures from each month. The difference between the highest shrinkage strain and the lowest shrinkage strain was 17.8%, 14.7% and 15.6% for the March, June and August concrete mixtures, respectively. The N100C and R30C mixtures generally had higher shrinkage strains than the R50C and R100C mixtures. The August mixtures had lower shrinkage strains than both the other months, while the June mixtures had the highest shrinkage strains. The higher porosity measured in the June samples and lower porosity in the August samples from the durability results could have contributed to the outcomes from the shrinkage tests.

Table 7.12 Shrinkage strains at 90 days for the concrete mixtures from each month

Mixture	ϵ_{sh} ($\mu\text{m}/\text{m}$)	COV (%)	Mixture	ϵ_{sh} ($\mu\text{m}/\text{m}$)	COV (%)	Mixture	ϵ_{sh} ($\mu\text{m}/\text{m}$)	COV (%)
March			June			August		
N100C	510	10.7	N100C	551	20.4	N100C	392	15.2
R30C	492	17.4	R30C	470	19.3	R30C	410	16
R50C	430	15.8	R50C	529	7.8	R50C	351	21.2
R100C	419	13.1	R100C	494	18.5	R100C	346	28
Average	463	14.3	Average	511	16.5	Average	375	20.1
Std Dev.	39		Std Dev.	31		Std Dev.	27	

Figures E.12 to E.14 in Appendix E graphically show the shrinkage results from each month. The early age results varied significantly with the individual readings. The device which was used to measure the deformation was sensitive and use resulted in abnormal readings. This was noticed and corrected by using the device with care when readings were taken. The concrete remained moist at the sealed ends for a long period of time which could cause these varied results with loss of moisture prevented in specimens. There were definite changes in climate conditions around 40 days, 65 days and 75 days indicated by the changes in slope of the results is consistent with each month.

The shrinkage of concrete is generally dependent on the volume of bulk cement paste and external conditions. A possible reason for the lower shrinkage rates in the higher RCA percentage mixtures could be associated to the water absorption of the aggregates. The RCA may absorb available water during mixing and curing and retain this water once removed from moist conditions. The mixtures which had higher shrinkage strains at an early age were the N100C and R30C and would retain less water because of the lower water absorption percentages. The R50C and R100C retained more water at an early age and therefore reduced the rate of shrinkage with a slower rate of moisture loss. This was noted by Chandra Paul (2011) and Kutegeza (2004) as shown in Section 3.3.3.

7.2.8 Creep

The creep specimens were cured for 7 days and tested for 14 days under loading conditions. Presented in Table 7.13 are the results for average ultimate strength, 35% average strength, the measured total deformation strain (ϵ_d), measured shrinkage, the specific creep and the coefficient of variation between the different readings from each mixture.

To correctly interpret the results from the creep tests the measured total strain had to be normalised because of the difference in applied load and actual concrete strength (Figure 7.30). The specific creep (strain per unit stress) result had to be determined by dividing the measured creep strain ($\mu\text{m/m}$) by the applied load (MPa). To determine the creep strain the elastic strain and shrinkage strain had to be subtracted from the measured total strain. Unfortunately, due to time constraints, the 14 day shrinkage results from the 28 day cured shrinkage specimens were used and elastic strain could not be subtracted, as the modulus of elasticity results in Section 7.2.6 resulted from mixtures which used different fine aggregate. The specific creep should not include strains not resulting from loading conditions. For comparative reasons it was assumed that the elastic strain would be similar between the individual mixtures because of the compressive strengths and could be of negligible influence.

Table 7.13 Deformation strains and specific creep values for creep analysis

Mixture	Strength ^a (MPa)	35% Strength (MPa)	Measured ϵ_d ^b ($\mu\text{m/m}$)	COV ϵ_d (%)	Measured ϵ_{sh} ^c ($\mu\text{m/m}$)	Specific creep ($\mu\text{m/m}$)/MPa
March						
N100C	19.9	6.9	639	19.4	380	43
R30C	14.5	5.1	864	9.9	387	80
R50C	14.5	5.1	629	18.8	335	49
R100C	22.1	7.7	605	20.9	283	54
Average	17.7	6.2	684	17.3	346	56
Std Dev	3.4	1.2	105		42	14
June						
N100C	18	6.3	827	7.7	413	59
R30C	20.8	7.3	887	14.9	336	79
R50C	20.5	7.2	838	16.1	376	66
R100C	21.8	7.6	766	12.7	349	60
Average	20.3	7.1	830	12.9	369	66
Std Dev	1.4	0.5	43		29	8
August						
N100C	17.7	6.2	882	15.5	316	81
R30C	20.1	7.0	860	12.9	310	79
R50C	19.6	6.8	879	7.9	204	96
R100C	22.2	7.8	850	8.1	255	85
Average	19.9	7.0	868	11.1	271	85
Std Dev	1.6	0.6	13		46	7

^a Average strength of the 75% cube strength and actual cylinder strength (7days cured)

^b Measured total deformation strain after 14 days loading

^c Measured shrinkage strain at 14 days (28 days cured)

The specific creep results for all the concrete mixtures were not significantly different. The August mixtures which had the lowest shrinkage strains had higher creep strains than what was expected. This was due to the fact that at the start of the creep test the temperature was higher in the climate room, which resulted in a greater loss of moisture and therefore higher measured strains.

The measured total deformation strain includes elastic strain, creep strain, and drying shrinkage. The creep component consists of drying creep and basic creep. The creep measured in this investigation could represent the loading conditions experienced by most structural elements. In-situ members are cured for shorter periods and therefore loaded at an early age. From Figure 7.30 it can be seen that the creep strains for the different mixtures would continue to increase.

The creep of concrete is affected by the same factors as the shrinkage. Noted in Section 3.3.3 the creep of concrete will be reduced if before loading the moisture content is reduced. The August mixtures showed that once loaded the loss of moisture resulted in an increased creep strain due to pores in the bulk cement paste losing moisture due to drying and loading. The concrete mixtures containing higher percentages of RCA retained more water due to the water absorption at an early age, therefore delaying the creep of concrete relative to the mixtures with less RCA.

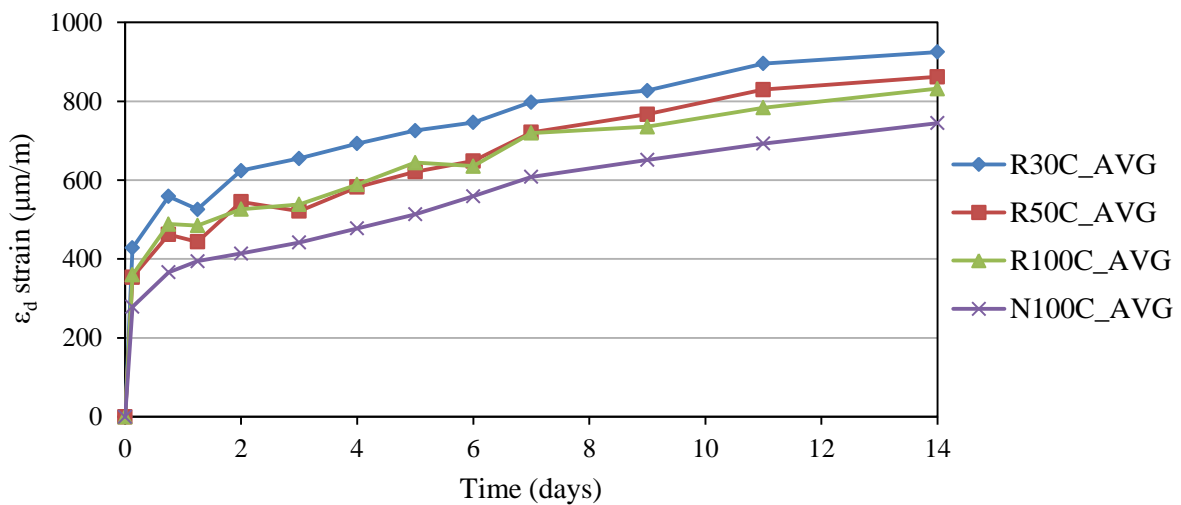


Figure 7.30 Measured total deformation strains for the concrete mixtures from June

7.3 Concluding Summary

The hardened concrete properties were assessed for the concrete mixtures containing RCA from three different samples. The NA was replaced by RCA at 0, 15, 30, 50 and 100% to determine the influence of percentage replacement on the hardened concrete properties. The hardened concrete properties were examined for three characteristics of concrete namely: mechanical strength, durability performance and dimensional stability. Most researchers conditioned the aggregates to an SSD condition prior to mixing to reduce the water absorption effects inherent to RCA. From these investigations the RCA generally produced poorer results when compared to mixtures containing only NA. The RCA in this investigation was mixed with the other constituents in an air dry state to produce concrete which resulted in hardened concrete properties which were in most cases similar to the control mixtures.

The compressive strength displayed no clear trend with increasing percentage replacement of RCA. The mixtures containing RCA produced strengths similar to and better than the control mixtures for both binder contents and curing periods. The slag mixtures produced low early age strength, but resulted in the highest overall strength with the mixtures containing 100% RCA. The water absorption and packing ability of the RCA were the reasons for the improved compressive strength results. The compressive strength tests also showed that mixture consistency is important in a fresh state. The RCA mixtures which had excess mixing water absorbed this water to produce higher strengths due to the w:c ratio being adjusted.

The hardened concrete density decreased with increasing percentage replacement due to the lower RD of the RCA. The slag mixtures produced the highest concrete densities for the respective RCA percentages. The RCA generally reduced the tensile splitting strength of hardened concrete due to the lower FI value with RCA. The more angular and flaky the aggregate particles, resulted in a better aggregate interlocking. The tensile strength was between 10 to 11% of the compressive strength. The weaker aggregate particles such as brick and old mortar had failure planes which passed through these particles.

The durability of the concrete containing RCA was not significantly affected. The possible hydration of old cement in the adhered mortar was the possible reason for the better performance in the RCA mixtures. The OPI resulted in no clear trend with increasing RCA replacement. The mixtures performed similar and in some cases better than the control mixtures for different binder contents. The OPC mixtures obtained “Good” to “Excellent” OPI performances according to the durability index for both curing periods. The slag mixtures performed poorer than the OPC mixtures with “Poor” to “Good” OPI performance indices.

The water sorptivity results also produced no clear trend with increasing RCA replacement. The mixtures for both binder contents produced similar durability performance indices which were “Good” to “Excellent”. Longer curing did not significantly improve the water sorptivity performance index in most mixtures. The chloride conductivity increased with increasing percentage replacement, especially in mixtures which had RCA with higher amounts of chloride ions. The mixtures containing 100% RCA had the highest chloride conductivity at 7 days curing, but improved the greatest with chloride conductivity results lower than the other mixtures. The OPC mixtures obtained “Poor” to “Good” durability performance indices for chloride conductivity. The slag mixtures had significantly lower chloride conductivity results with performance indices of “Good” to “Excellent”. The curing of concrete significantly improved the chloride conductivity.

The modulus of elasticity results were varied for the different mixtures. There was no clear difference in RCA percentage replacement or binder content. The concrete mixtures generally had elastic moduli which were similar. The lower RCA replacement percentages produced modulus of elasticity results which were marginally higher for each batch of concrete. The deformation change due to shrinkage and creep showed no clear difference between the mixtures containing RCA. The water absorption of the RCA retained the moisture within the concrete resulting in a lower deformation at an early age. This lower early age deformation resulted in a similar later age deformation to that of the control mixture.

The hardened concrete properties were not significantly affected by the inclusion of RCA. The results from most of the hardened concrete tests produced no clear trend with the increase of percentage replacement. Replacing NA with 100% RCA is possible based on the data presented in this investigation. Many engineers may be hesitant to include this amount of RCA in structural concrete for high grade applications. Most studies and specifications generally recommend that RCA used in concrete should be limited to $\pm 30\%$ and considering the percentage recommended for fresh concrete. Including 30 to 50% RCA in concrete mixtures in an air dry condition would not considerably influence the mechanical, durability and dimensional properties of hardened concrete and is therefore recommended. The recommendation is based on concrete which utilises RCA with similar or better properties established in this investigation. The effect of RCA in low strength concrete is mostly minimal, but may vary with increasing concrete strength. The inclusion of RCA at 30 to 50% from this investigation would be recommended for a concrete strength between 30 to 40 MPa.

Chapter 8

Conclusions and Recommendations

The aim of this research was to investigate the potential use of coarse recycled concrete aggregate (RCA) as a material in structural concrete. The lack of knowledge and specifications in South Africa was the main reason for this research of RCA. By increasing the database of research of RCA in South Africa, the possibility of guidelines and/or specifications for this alternative building material can be initiated. The implications of such specifications would lead to RCA acceptance in concrete design and therefore reducing the amount construction and demolition (C&D) waste accumulating at landfill sites and decreasing the extraction of depleting natural aggregates.

The following conclusions and recommendations can be made based on the data presented in this investigation:

- The physical properties of RCA are dependent on the geometrical properties, while taking into consideration that the geometrical properties are dependent on the source and method of recycling the original C&D waste. The chemical properties are dependent on the physical properties. The various properties assessed for the RCA batches examined in this investigation fall within the limits defined by the international standards and specifications. The RCA material from this study could be included in concrete with a maximum strength class of C40/50.
- The higher percentages of RCA negatively influenced the fresh concrete properties, although not significantly. The mixtures containing 15% RCA displayed the best fresh concrete results. However, the amount of NA replaced by this amount of RCA is minimal and it is recommended to use between 30 to 50% RCA replacement without considerably influencing the fresh concrete properties. The hardened concrete test specimens were moderately compacted in a fresh state without segregation of the constituents. The outcomes from the hardened concrete tests should produce results which reflect the fresh concrete consistency.
- The hardened concrete properties were not significantly affected by the inclusion of RCA. The results from most of the hardened concrete tests produced no clear trend with the increase of percentage replacement. Replacing NA with 100% RCA is possible based on the data presented in this investigation. Many engineers may be hesitant to include this amount of RCA in structural concrete for high grade applications. Most studies and specifications generally recommend that RCA used in concrete should be limited to $\pm 30\%$ and considering the percentage recommended for fresh concrete. Including 30 to 50% RCA in concrete mixtures in an air dry condition would not influence the mechanical, durability and dimensional properties of hardened concrete and is

therefore recommended. The recommendation is based on concrete which utilises RCA with similar or better properties established in this investigation. The inclusion of RCA at 30 to 50% from this investigation would be recommended for a concrete strength between 30 to 40 MPa.

For the inclusion of RCA in concrete the following is recommended to be reviewed and specified for possible guidelines for RCA in South Africa:

- The incoming material should be visually inspected for any indications of large scale contamination. To prevent this from occurring, the demolition of a project should be completed in such a way that the foreign items in the waste stream are reduced. This can be completed by manual or systematic removal of components known to produce foreign items such as partitioning walls and masonry non-structural elements. To assess the amount of foreign items or contaminants, a constituent composition analysis should be completed. The amount of constituents prescribed by the BS EN 12620:2008 and BS 8500-2:2006 should be used as limiting factors. The recommended amount of clay masonry items should be limited to 5% for structural concrete according to the BS 8500-2.
- The material should meet the requirements for coarse natural aggregate as specified by SANS 1083:2006. The material should be graded in such a way that higher percentages of smaller particles are included in the material to improve packing capacity. Reducing the amount of foreign or weaker materials such as mortar or brick will improve the overall aggregate strength. The dust content can be assessed at first and if the material has a higher dust content it should be washed to reduce this percentage. It is recommended that RCA should be washed and graded to produce a superior secondary material. The FI value is controlled by the method of crushing and RCA generally has a lower FI value than NA which should not exceed the limit as specified in the standard.
- Prior to examining the properties stated above, the following could be tested to assess the potential outcomes for the other aggregate properties. The RD will give a good indication to the amount of lower density materials in a sample of RCA. The RD according to this investigation should be limited to 2.6, but standards have allowed for lower RD values. The presence of lower density materials such as clay masonry items and adhered mortar will result in increased water absorption. The water absorption according to RILEM TC 121-DRG (1994) and JIS A 5021 Class H for high strength concrete should be limited to 3% which is above the water absorption found for aggregates in this study. It is therefore recommended that this limit be specified, as RCA with higher water absorption will possibly reduce the properties of fresh concrete and hardened concrete.

- To address the durability concerns, an analysis for the amount of water soluble ions should be conducted. RCA from C&D waste which was derived from coastal regions has the potential for higher chloride ion content. The amount of chloride ions permissible depends on the degree of steel reinforcing. The chloride conductivity tests showed that greater chloride conductivity results are possible with a higher amount of chloride ions. RCA with the possibility of high chloride ion content to be used in concrete should be either mixed with a high percentage of slag cement extender or cured for a longer period.
- All of the standards and specifications for RCA are concerned with the potential ASR when utilising this material. To assess the potential for ASR, an XRF analysis could be conducted to determine the chemical-mineralogical composition of the material. In practice this is not always possible and therefore simpler methods need to be proposed. Methods for determining the ASR potential are described in the ACI E1-09, JIS A 5021 and BS EN 12620. The alkali levels in the original concrete and new concrete should be inspected along with inclusion of aggregates which contribute to this reaction. The ASR potential should be designated and such material used should be limited or improved by the necessary methods.
- It is recommended that further research is conducted on RCA to accurately specify additional guidelines. Studies into the difference between RCA resulting from C&D waste processed on-site with less sophisticated recycling methods and large scale commercial recycling could produce different results. The effects of foreign items, both floating and non-floating, on the durability of large structural elements should be investigated. These items may cause localised failures which cannot be accurately represented by small scale tests. The improved durability performance of RCA, especially when containing higher percentages of stone/mortar combination is interesting. The reasoning according to this study is based on assumptions, but more conclusive evidence is needed to correctly define the reason for this result.
- Finally, based on the current standard for aggregates in concrete for South Africa, RCA cannot be correctly specified. It is therefore recommended that the international standards and specifications should be consulted to accurately designate a particular RCA batch for the intended concrete class. According to the aggregate and concrete properties examined in this investigation, the full replacement of NA in structural concrete is possible and will improve the sustainable development of the construction industry.

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Appendix A. SANS 1083:2006

SANS 1083:2006
Edition 1.2

Table 2 — Coarse aggregate for concrete

1 Property	2 Requirement										10 Test method subclause
	3	4	5	6	7	8	9	Nominal size of aggregate mm			
Grading ¹⁾ , mass percentage of material that passes sieves ²⁾ of nominal aperture size, mm 75,0 53,0 37,5 26,5 19,0 13,2 9,5 6,7 4,75 2,36 1,18	75,0	37,5	26,5	19,0	13,2	9,5	6,7				6.2
	100	100	100	100	100	100	100	100	100	100	
	0-50	85-100	100	100	100	100	100	100	100	100	
	0-25	0-50	85-100	100	100	100	100	100	100	100	
	0-5	0-25	85-100	100	100	100	100	100	100	100	
	0-5	0-25	85-100	100	100	100	100	100	100	100	
	0-5	0-25	85-100	100	100	100	100	100	100	100	
	0-5	0-25	85-100	100	100	100	100	100	100	100	
	0-5	0-25	85-100	100	100	100	100	100	100	100	
	0-5	0-25	85-100	100	100	100	100	100	100	100	
Dust content, material that passes a 75 µm sieve ²⁾ , mass percentage, max.	2										6.3
Aggregate crushing value (ACV) ³⁾ , of less than 13,2 mm and more than 9,5 mm fraction (dry), mass percentage, max.	29										6.11
10 % FACT value, of less than 13,2 mm and more than 9,5 mm fraction (dry), kN, min.	Coarse aggregate for use in concrete subject to surface abrasion, structural elements of reinforced or prestressed concrete (or both): 110 Coarse aggregate for use in concrete not subject to surface abrasion: 70										6.12
Flakiness index, max.	35										6.13
1) Other gradings are permitted if so required (see annex A). Such a grading shall be specified in terms of the appropriate nominal sizes specified in the table.											
2) Complying with SANS 3310-1 or SANS 3310-2.											
3) Optional alternative to the 10 % FACT value.											

Amdt 1

Appendix B. Mixture Proportions

Aggregate preparation



Figure B.1 Photographs showing how the RCA batches were washed by placing the bags of RCA over a raised sieve and washing the material under a jet of water



a) unwashed

b) washed

Figure B.2 The difference between the aggregate after washing by removing the layer of dust



Figure B.3 Large amount of RCA placed over plastic sheet and allowed to dry

Mixture proportions*Table B.1 June mix design for percentage replacements of RCA and binder*

JunR15C				JunR50C			
Constituents	kg/m ³	RD	litres	Constituents	kg/m ³	RD	litres
Water	175	1.00	175	Water	175	1.00	175
Cement	292	3.14	93	Cement	292	3.14	93
Cement Extender	0	2.90	0	Cement Extender	0	2.90	0
Natural Stone	855	2.73	313	Natural Stone	503	2.73	184
Recycled Stone	147	2.66	55	Recycled Stone	490	2.66	184
Sand (CHOICE)	960	2.64	364	Sand (CHOICE)	960	2.64	364
Total Stone	1002		1000	Total Stone	993		1000

JunR30C				JunR100C			
Constituents	kg/m ³	RD	litres	Constituents	kg/m ³	RD	litres
Water	175	1.00	175	Water	175	1.00	175
Cement	292	3.14	93	Cement	292	3.14	93
Cement Extender	0	2.90	0	Cement Extender	0	2.90	0
Natural Stone	704	2.73	258	Natural Stone	0	2.73	0
Recycled Stone	294	2.66	111	Recycled Stone	980	2.66	368
Sand (CHOICE)	960	2.64	364	Sand (CHOICE)	960	2.64	364
Total Stone	998		1000	Total Stone	980		1000

JunR30S				JunR100S			
Constituents	kg/m ³	RD	litres	Constituents	kg/m ³	RD	litres
Water	175	1.00	175	Water	175	1.00	175
Cement	146	3.14	46	Cement	146	3.14	46
Cement Extender	146	2.90	50	Cement Extender	146	2.90	50
Natural Stone	697	2.73	255	Natural Stone	0	2.73	0
Recycled Stone	291	2.66	109	Recycle Stone	970	2.66	365
Sand (CHOICE)	960	2.64	364	Sand (CHOICE)	960	2.64	364
Total Stone	988		1000	Total Stone	970		1000

JunN100C				JunN100S			
Constituents	kg/m ³	RD	litres	Constituents	kg/m ³	RD	litres
Water	175	1.00	175	Water	175	1.00	175
Cement	292	3.14	93	Cement	146	3.14	46
Cement Extender	0	2.90	0	Cement Extender	146	2.90	50
Natural Stone	1006	2.73	368	Natural Stone	995	2.73	365
Recycled Stone	0	2.66	0	Recycled Stone	0	2.66	0
Sand (CHOICE)	960	2.64	364	Sand (CHOICE)	960	2.64	364
Total Stone	1006		1000	Total Stone	995		1000

Table B.2 August mix design for percentage replacements of RCA and binder

AugR15C				AugR50C			
Constituents	kg/m ³	RD	litres	Constituents	kg/m ³	RD	litres
Water	175	1.00	175	Water	175	1.00	175
Cement	292	3.14	93	Cement	292	3.14	93
Cement Extender	0	2.90	0	Cement Extender	0	2.90	0
Natural Stone	845	2.73	310	Natural Stone	497	2.73	182
Recycled Stone	142	2.59	55	Recycled Stone	472	2.59	182
Sand (CHOICE)	960	2.61	368	Sand (CHOICE)	960	2.61	368
Total Stone	987		1000	Total Stone	969		1000

AugR30C				AugR100C			
Constituents	kg/m ³	RD	litres	Constituents	kg/m ³	RD	litres
Water	175	1.00	175	Water	175	1.00	175
Cement	292	3.14	93	Cement	292	3.14	93
Cement Extender	0	2.90	0	Cement Extender	0	2.90	0
Natural Stone	696	2.73	255	Natural Stone	0	2.73	0
Recycled Stone	283	2.59	109	Recycled Stone	944	2.59	364
Sand (CHOICE)	960	2.61	368	Sand (CHOICE)	960	2.61	368
Total Stone	979		1000	Total Stone	944		1000

AugR30S				AugR100S			
Constituents	kg/m ³	RD	litres	Constituents	kg/m ³	RD	litres
Water	175	1.00	175	Water	175	1.00	175
Cement	146	3.14	46	Cement	146	3.14	46
Cement Extender	146	2.90	50	Cement Extender	146	2.90	50
Natural Stone	689	2.73	252	Natural Stone	0	2.73	0
Recycled Stone	280	2.59	108	Recycle Stone	934	2.59	360
Sand (CHOICE)	960	2.61	368	Sand (CHOICE)	960	2.61	368
Total Stone	969		1000	Total Stone	934		1000

AugN100C				AugN100S			
Constituents	kg/m ³	RD	litres	Constituents	kg/m ³	RD	litres
Water	175	1.00	175	Water	175	1.00	175
Cement	292	3.14	93	Cement	146	3.14	46
Cement Extender	0	2.90	0	Cement Extender	146	2.90	50
Natural Stone	995	2.73	364	Natural Stone	984	2.73	360
Recycled Stone	0	2.59	0	Recycled Stone	0	2.59	0
Sand (CHOICE)	960	2.61	368	Sand (CHOICE)	960	2.61	368
Total Stone	995		1000	Total Stone	984		1000

Table B.3 Mixture proportions for the shrinkage and creep concrete mixtures

Mixtures		MarR30C			JunR30C			AugR30C		
Constituents	kg/m ³	RD	litres	kg/m ³	RD	litres	kg/m ³	RD	litres	
Water	175	1.00	175	175	1.00	175	175	1.00	175	
Cement	292	3.14	93	292	3.14	93	292	3.14	93	
Cement Extender	0	2.90	0	0	2.90	0	0	2.90	0	
Natural Stone	696	2.73	255	696	2.73	255	696	2.73	255	
Recycled Stone	290	2.65	109	291	2.66	109	283	2.59	109	
Sand (CHOICE)	960	2.61	368	960	2.61	368	960	2.61	368	
Total Stone	986		1000	987		1000	979		1000	
Mixtures		MarR50C			JunR50C			AugR50C		
Constituents	kg/m ³	RD	litres	kg/m ³	RD	litres	kg/m ³	RD	litres	
Water	175	1.00	175	175	1.00	175	175	1.00	175	
Cement	292	3.14	93	292	3.14	93	292	3.14	93	
Cement Extender	0	2.90	0	0	2.90	0	0	2.90	0	
Natural Stone	497	2.73	182	497	2.73	182	497	2.73	182	
Recycled Stone	483	2.65	182	485	2.66	182	472	2.59	182	
Sand (CHOICE)	960	2.61	368	960	2.61	368	960	2.61	368	
Total Stone	980		1000	982		1000	969		1000	
Mixtures		MarR100C			JunR100C			AugR100C		
Constituents	kg/m ³	RD	litres	kg/m ³	RD	litres	kg/m ³	RD	litres	
Water	175	1.00	175	175	1.00	175	175	1.00	175	
Cement	292	3.14	93	292	3.14	93	292	3.14	93	
Cement Extender	0	2.90	0	0	2.90	0	0	2.90	0	
Natural Stone	0	2.73	0	0	2.73	0	0	2.73	0	
Recycled Stone	965	2.65	364	969	2.66	364	944	2.59	364	
Sand (CHOICE)	960	2.61	368	960	2.61	368	960	2.61	368	
Total Stone	965		1000	969		1000	944		1000	
Mixtures		MarN100C			JunN100C			AugN100C		
Constituents	kg/m ³	RD	litres	kg/m ³	RD	litres	kg/m ³	RD	litres	
Water	175	1.00	175	175	1.00	175	175	1.00	175	
Cement	292	3.14	93	292	3.14	93	292	3.14	93	
Cement Extender	0	2.90	0	0	2.90	0	0	2.90	0	
Natural Stone	995	2.73	364	995	2.73	364	995	2.73	364	
Recycled Stone	0	2.65	0	0	2.66	0	0	2.59	0	
Sand (CHOICE)	960	2.61	368	960	2.61	368	960	2.61	368	
Total Stone	995		1000	995		1000	995		1000	

Appendix C. Aggregate Properties

Grading

Fine aggregate grading analysis example

Aggregate Type: August Malmesbury sand

Mass a =	524.7	g	Dry mass before washing
Mass b =	491.5	g	Dry mass after washing
Total =	490.9	g	Total mass after sieving
% Original	99.9%		
% Difference	0.12%	< 1.0%	OK

Sieve unit	Sieve mass	Sieve + mass retained	Individual mass retained R	Individual percentage retained (R/total x 100)	Cumulative percentage (4750 µm to 150 µm sieves)	Percentage of material that passed
(µm)	(g)	(g)	(g)	(%)	(%)	(%)
4750	592.8	593.9	1.1	0.2%	0.2%	99.8%
2360	518.5	520.7	2.2	0.4%	0.7%	99.3%
1180	481	604.2	123.2	25.1%	25.8%	74.2%
600	467.3	635.8	168.5	34.3%	60.1%	39.9%
300	409	485.3	76.3	15.5%	75.6%	24.4%
150	390.8	451.6	60.8	12.4%	88.0%	12.0%
Subtotal 1			432.1	88.0%	250.4%	-
75	433.2	484.1	50.9	10%	-	8%

Pan

Mass c	565.7	573.6	7.9	2%
Mass a - b			33.2	7%
Subtotal 2			41.1	8%
Total =			490.9	100%

$$\text{Dust content} = [(a - b) + c]/M_{Ff} \times 100$$

a =	524.7
b =	491.5
c =	7.9
M_{Ff} =	524.1

$$\text{Dust content} = \mathbf{7.8\%}$$

$$\text{FM} = \mathbf{2.5} \quad \sum \text{Cumulative percentage retained}/100 \text{ (4750 } \mu\text{m to 150 } \mu\text{m sieves)}$$

Coarse aggregate grading analysis example

Aggregate Type: JunR50C

Mass d =	5006.5	g	Dry mass before washing
Mass e =	4983.5	g	Dry mass after washing
Total =	4984.1	g	Total mass after sieving
% Original	99.6%		
% Difference	0.45%	< 1.0%	OK
Bag	5	g	

Sieve unit (mm)	Material plus bag (g)	Material retained (g)	Individual percentage retained (R/total x 100) (%)	Cumulative percentage (26.5mm to 4.75mm) (%)	Percentage of material that passed (%)
26.5	0.0	0.0	0.0	0.0	100.0
19	395.9	390.9	7.8	7.8	92.2
13.2	3464.4	3459.4	69.4	77.3	22.7
9.5	839.3	834.3	16.7	94.0	6.0
6.7	302.6	297.6	6.0	100.0	0.0
4.75	6	1	0.0	100.0	0.0
Pan	5.9	0.9	0.0		0.0
75 (µm)	Material plus sieve		100.0	379.0	
75 Sieve mass	455.7	1	= Material retained on 75µm sieve (f)		
	454.7				

$$\text{Dust content} = [d - (e + f)]/M_{Fc} \times 100$$

$$M_{Fc} = \boxed{5007.1} \text{ g}$$

$$\text{Dust content} = \boxed{0.4\%}$$

$$FM = \boxed{3.79} \sum \text{Cumulative percentage retained}/100 \text{ (26.5mm - 4.75mm sieves)}$$

Flakiness Index				
Sieve Size (mm)	Percentage Retained (%)	Amount Passing (g)	% Passing slot (%)	FI
26.5	0.0	0.0	0.0	0.0
19.0	7.8	137.1	35.1	2.8
13.2	69.4	564.2	16.3	11.3
9.5	16.7	88.3	10.6	1.8
6.7	6.0	13.2	4.4	0.3
4.8	0.0	0.0	0.0	0.0
			FI =	16

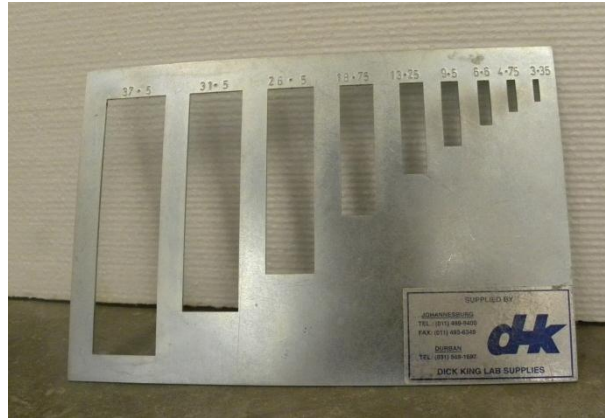


Figure C.1 Apparatus used for Flakiness Index evaluation

Constituents and foreign materials in RCA



a) 15%

b) 30%

c) 50%

Figure C.2 Particle distribution for the 15%, 30% and 50% aggregate replacements with RCA



a) Clay masonry items

b) Bituminous materials

c) Glass

Figure C.3 Photographs of the constituents found in RCA



a) Apparatus



b) Floating materials measured

Figure C.4 Apparatus used to measure the volume of floating materials



a) March RCA



b) August RCA

Figure C.5 Total foreign items found in the March and August RCA batches

Physical properties

Table C.1 Relative density calculation example (June R50A)

Sample	Sample mass (m_a) (g)	Water mass (m_b) (g)	Water & Sample mass (m_c) (g)	RD
JunR50A.1	504.5	1293.3	1608.8	2.67
JunR50A.2	503.8	1293.3	1608.2	2.67
JunR50A.3	504.3	1293.2	1610.1	2.69
JunR50A.4	541.6	1293.3	1633.9	2.69
JunR50A.5	559	1293.3	1645.5	2.70
JunR50A.6	494.8	1293.2	1604.9	2.70
			Average	2.69

Table C.2 LBD and CBD calculation example (June R100A)

Sample	LBD mass (kg)	CBD mass (kg)	Container vol. (l)	LBD (kg/m ³)	CBD (kg/m ³)
JunR100A.1	21.29	23.58	14.68	1450	1606
JunR100A.2	21.38	23.46	14.68	1456	1598
JunR100A.3	21.28	23.44	14.68	1450	1597
Average				1452	1600



a) Relative density apparatus



b) Bulk density apparatus

Figure C.6 Apparatus used to measure the respective aggregate densities

Table C.3 Water absorption calculation example (August R100A)

Sample	SSD mass (ma)	OD mass (mb)	WA (%)
AugR100A.1	2052.4g	2003.1g	2.46
AugR100A.2	2033.2g	1980.9g	2.64
AugR100A.3	2013.3g	1960.7g	2.68
Average			2.59

Table C.4 ACV calculation example (Reference material N100A)

Sample	Mass before crushing (9.5mm)	Mass after crushing (9.5mm)	Mass after crushing (2.32mm)	ACV	% Material loss
RefN100A.1	2878g	2562.4g	312.3g	10.9	0.11
RefN100A.2	2862.1g	2544.2g	315.2g	11.0	0.09
RefN100A.3	2856.7g	2536.8g	317.2g	11.1	0.09
Average				11	



Figure C.7 Apparatus used to test the ACV of the aggregates

Chemical Properties



a) Test sample prepared for XRF analysis



b) Test sample for soluble ion analysis



c) XRF analysis



d) Atomic absorption spectrometer

Figure C.8 Sample and testing equipment used in the chemical properties analysis

Appendix D. Fresh Concrete Properties

Slump Values

Main concrete mixtures (40 litres)

Table D.1 Measured slump values (mm) for 40l March concrete mixtures

Mixture\Time	0 min	15 min	30 min	45 min	60 min	% loss
N100C	90	70	60	50	45	50
R15C	100	95	90	75	60	40
R30C	105	90	70	80	70	33
R50C	100	100	90	80	70	30
R100C	100	85	65	60	50	50
N100S	120	100	100	85	70	42
R30S	145	120	90	90	80	45
R100S	125	105	90	80	65	48

Table D.2 Measured slump values (mm) for 40l June concrete mixtures

Mixture\Time	0 min	15 min	30 min	45 min	60 min	% loss
N100C	70	55	45	40	45	36
R15C	60	60	55	55	40	33
R30C	80	60	50	45	35	56
R50C	70	65	55	50	45	36
R100C	90	60	55	50	50	44
N100S	100	85	75	65	65	35
R30S	80	65	60	60	65	19
R100S	85	65	55	50	45	47

Table B.3 Measured slump values (mm) for 40l August concrete mixtures

Mixture\Time	0 min	15 min	30 min	45 min	60 min	(%) loss
N100C	200	150	140	140	160	20
R15C	125	130	125	130	120	4
R30C	160	125	135	135	150	6
R50C	155	115	120	130	155	0
R100C	150	90	90	90	85	43
N100S	140	135	140	130	120	14
R30S	160	100	105	105	110	31
R100S	100	75	75	60	65	35

Durability concrete mixtures (20 litres)*Table D.4 Measured slump values (mm) for durability mixtures for March concrete*

Mixture\Time	0 min	15 min	30 min	% loss
N100C	75	70	70	7
R15C	115	85	75	35
R30C	85	65	60	29
R50C	60	55	45	25
R100C	120	90	70	42
N100S	110	85	70	36
R30S	90	75	60	33
R100S	155	90	70	55

Table D.5 Measured slump values (mm) for durability mixtures for June concrete

Mixture\Time	0 min	15 min	30 min	% loss
N100C	55	35	45	18
R15C	45	45	35	22
R30C	55	55	45	18
R50C	55	50	35	36
R100C	60	40	35	42
N100S	55	45	45	18
R30S	70	45	45	36
R100S	60	50	45	25

Table D.6 Measured slump values (mm) for durability mixtures for August concrete

Mixture\Time	0 min	15 min	30 min	% loss
N100C	125	125	110	12
R15C	140	120	90	36
R30C	160	140	120	25
R50C	145	90	80	45
R100C	75	60	50	33
N100S	130	115	100	23
R30S	125	100	75	40
R100S	65	55	45	31

Shrinkage and creep concrete mixtures (12 litres)*Table D.7 Measured slump values (mm) for shrinkage and creep mixture from each month*

Mixture\Test	12l March		March		June		August	
	Shrinkage	Creep	Shrinkage	Creep	Shrinkage	Creep	Shrinkage	Creep
N100C	155	150	140	105	150	160		
R30C	145	75	155	110	145	60		
R50C	150	150	120	105	90	70		
R100C	160	150	165	125	40	50		



a) March concrete mixture

b) June concrete mixture

Figure D.1 Typical slump results for mixtures which are cohesive and robust

Fresh density



Figure D.2 Mould used to measure fresh compacted density

Air content



Figure D.3 Type B measurement device used to measure air content

Appendix E. Hardened Concrete Properties

Mechanical properties

Table E.1 Strength results for 14 days curing

Month	March		June		August	
Sample	Strength (MPa)	COV (%)	Strength (MPa)	COV (%)	Strength (MPa)	COV (%)
N100C	31.4	4.8	29.8	3.9	23.1	2.3
R15C	30.4	3.7	28.1	4.4	26.5	3.1
R30C	29.6	3.1	30.6	2.2	24.6	3.4
R50C	24.8	6.0	30.6	4.4	25.7	3.5
R100C	25.7	3.3	30.8	0.9	27.6	2.5
N100S	22.2	1.2	29.4	3.2	27.5	3.4
R30S	28.7	2.4	29.3	2.6	28.5	6.0
R100S	25.1	5.5	31.0	1.9	31.3	3.0
Average	27.2	3.7	29.9	2.9	26.9	3.4



a) *Contest compression machine*



b) *Curing conditions*

Figure E.1 Compression testing machine and curing of specimens

Tensile splitting test



Figure E.2 Failure plane in tensile splitting test for AugN100C specimen



Figure E.3 Failure plane in tensile splitting test for AugR100C specimen



Figure E.4 Failure plane in tensile splitting test for AugN100S specimen



Figure E.5 Failure plane in tensile splitting test for AugR100S specimen

Durability results**OPI and water sorptivity results**

MarR15C 7 days					
Disk #:	1	2	3	4	Mean
k (m/s):	6.30E-11	1.06E-10	5.87E-11	1.25E-10	8.81E-11
OPI:	10.20	9.98	10.23	9.90	10.06
COV % (Mean k):	36.8				
Variability Check:	Good				

Disk #:	1	2	3	4	Mean
Sorptivity (mm/√hr):	6.58	5.89	7.26	6.67	6.60
Porosity (%):	12.20	12.34	11.17	11.77	11.9
Mean Sorptivity:	6.6	COV:	8.5	Variability	Good
Mean Porosity:	11.9	COV:	4.4	Variability	Good

MarR30S 7 days					
Disk #:	1	2	3	4	Mean
k (m/s):	1.05E-10	2.49E-10	8.96E-11	1.14E-10	1.39E-10
OPI:	9.98	9.60	10.05	9.94	9.86
COV % (Mean k):	53.1				
Variability Check:	Good				

Disk #:	1	2	3	4	Mean
Sorptivity (mm/√hr):	6.78	8.11	6.49	7.06	7.11
Porosity (%):	10.42	10.04	10.93	11.34	10.7
Mean Sorptivity:	7.1	COV:	9.9	Variability	Good
Mean Porosity:	10.7	COV:	5.3	Variability	Good

MarR50C 7 days					
Disk #:	1	2	3	4	Mean
k (m/s):	5.43E-11	5.04E-11	5.31E-11	5.08E-11	5.22E-11
OPI:	10.27	10.30	10.28	10.29	10.28
COV % (Mean k):	3.6				
Variability Check:	Good				

Disk #:	1	2	3	4	Mean
Sorptivity (mm/√hr):	6.62	7.08	6.68	6.81	6.80
Porosity (%):	11.71	11.84	11.57	11.21	11.6
Mean Sorptivity:	6.8	COV:	3.0	Variability	Good
Mean Porosity:	11.6	COV:	2.3	Variability	Good

MarR100S 7 days					
Disk #:	1	2	3	4	Mean
k (m/s):	1.16E-10	9.43E-11	8.01E-11	7.46E-11	9.11E-11
OPI:	9.94	10.03	10.10	10.13	10.04
COV % (Mean k):	20.1				
Variability Check:	Good				

Disk #:	1	2	3	4	Mean
Sorptivity (mm/√hr):	6.21	5.18	5.13	5.16	5.42
Porosity (%):	11.47	11.37	11.88	11.35	11.5
Mean Sorptivity:	5.4	COV:	9.7	Variability	Good
Mean Porosity:	11.5	COV:	2.1	Variability	Good

MarR30C 7 days

Disk #:	1	2	3	4	Mean
k (m/s):	7.42E-11	6.89E-11	9.72E-11	1.09E-10	8.73E-11
OPI:	10.13	10.16	10.01	9.96	10.06
COV % (Mean k):	21.7				
Variability Check:	Good				

Disk #:	1	2	3	4	Mean
Sorptivity (mm/ $\sqrt{\text{hr}}$):	7.02	6.26	6.42	5.57	6.32
Porosity (%):	11.38	11.37	11.24	11.99	11.5
Mean Sorptivity:	6.3	COV:	9.4	Variability	Good
Mean Porosity:	11.5	COV:	2.9	Variability	Good

MarN100C 7 days

Disk #:	1	2	3	4	Mean
k (m/s):	8.62E-11	1.41E-10	7.31E-11	8.15E-11	9.53E-11
OPI:	10.06	9.85	10.14	10.09	10.02
COV % (Mean k):	32.1				
Variability Check:	Good				

Disk #:	1	2	3	4	Mean
Sorptivity (mm/ $\sqrt{\text{hr}}$):	6.78	7.47	5.90	7.29	6.86
Porosity (%):	10.88	11.56	11.61	11.80	11.5
Mean Sorptivity:	6.9	COV:	10.3	Variability	Good
Mean Porosity:	11.5	COV:	3.5	Variability	Good

MarR100C 7 days

Disk #:	1	2	3	4	Mean
k (m/s):	6.91E-11	8.03E-11	7.18E-11	7.27E-11	7.35E-11
OPI:	10.16	10.10	10.14	10.14	10.13
COV % (Mean k):	6.5				
Variability Check:	Good				

Disk #:	1	2	3	4	Mean
Sorptivity (mm/ $\sqrt{\text{hr}}$):	6.88	6.09	6.68	7.17	6.71
Porosity (%):	13.03	12.76	11.50	11.89	12.3
Mean Sorptivity:	6.7	COV:	6.8	Variability	Good
Mean Porosity:	12.3	COV:	5.8	Variability	Good

MarN100S 7 days

Disk #:	1	2	3	4	Mean
k (m/s):	1.68E-10	1.03E-10	7.62E-11	3.65E-10	1.78E-10
OPI:	9.78	9.99	10.12	9.44	9.75
COV % (Mean k):	73.3				
Variability Check:	Caution				

Disk #:	1	2	3	4	Mean
Sorptivity (mm/ $\sqrt{\text{hr}}$):	6.79	7.14	7.19	7.25	7.09
Porosity (%):	10.94	10.44	10.26	11.49	10.8
Mean Sorptivity:	7.1	COV:	2.9	Variability	Good
Mean Porosity:	10.8	COV:	5.1	Variability	Good

MarR15C 28 days

Disk #:	1	2	3	4	Mean
k (m/s):	6.25E-11	6.99E-11	6.97E-11	6.60E-11	6.71E-11
OPI:	10.20	10.16	10.16	10.18	10.17
COV % (Mean k):	5.3				
Variability Check:	Good				

Disk #:	1	2	3	4	Mean
Sorptivity (mm/√hr):	6.53	6.63	6.33	5.80	6.32
Porosity (%):	9.97	10.80	10.81	11.51	10.77
Mean Sorptivity:	6.3	COV:	5.8	Variability	Good
Mean Porosity:	10.8	COV:	5.9	Variability	Good

MarR30S 28 days

Disk #:	1	2	3	4	Mean
k (m/s):	1.17E-10	8.89E-11	1.23E-10	6.62E-11	9.87E-11
OPI:	9.93	10.05	9.91	10.18	10.01
COV % (Mean k):	26.6				
Variability Check:	Good				

Disk #:	1	2	3	4	Mean
Sorptivity (mm/√hr):	5.76	6.44	7.51	6.90	6.65
Porosity (%):	8.55	9.97	9.71	9.79	9.51
Mean Sorptivity:	6.7	COV:	11.1	Variability	Good
Mean Porosity:	9.5	COV:	6.8	Variability	Good

MarR50C 28 days

Disk #:	1	2	3	4	Mean
k (m/s):	5.19E-11	6.08E-11	5.44E-11	4.16E-11	5.22E-11
OPI:	10.28	10.22	10.26	10.38	10.28
COV % (Mean k):	15.3				
Variability Check:	Good				

Disk #:	1	2	3	4	Mean
Sorptivity (mm/√hr):	6.25	6.10	6.59	6.41	6.34
Porosity (%):	10.40	10.51	10.56	10.16	10.41
Mean Sorptivity:	6.3	COV:	3.3	Variability	Good
Mean Porosity:	10.4	COV:	1.7	Variability	Good

MarR100S 28 days

Disk #:	1	2	3	4	Mean
k (m/s):	7.47E-11	1.79E-10	8.28E-11	1.73E-10	1.27E-10
OPI:	10.13	9.75	10.08	9.76	9.90
COV % (Mean k):	44.2				
Variability Check:	Good				

Disk #:	1	2	3	4	Mean
Sorptivity (mm/√hr):	5.23	5.78	6.04	6.48	5.88
Porosity (%):	9.70	8.36	9.19	10.03	9.32
Mean Sorptivity:	5.9	COV:	8.9	Variability	Good
Mean Porosity:	9.3	COV:	7.8	Variability	Caution

MarR30C 28 days

Disk #:	1	2	3	4	Mean
k (m/s):	1.04E-10	1.10E-10	5.50E-11	8.20E-11	8.77E-11
OPI:	9.98	9.96	10.26	10.09	10.06
COV % (Mean k):	28.3				
Variability Check:	Good				

Disk #:	1	2	3	4	Mean
Sorptivity (mm/√hr):	6.00	5.39	5.27	5.77	5.61
Porosity (%):	10.80	10.47	12.42	10.64	11.08
Mean Sorptivity:	5.6	COV:	6.0	Variability	Good
Mean Porosity:	11.1	COV:	8.1	Variability	Caution

MarN100C 28 days

Disk #:	1	2	3	4	Mean
k (m/s):	1.05E-10	8.49E-11	1.53E-10	9.49E-11	1.09E-10
OPI:	9.98	10.07	9.82	10.02	9.96
COV % (Mean k):	27.6				
Variability Check:	Good				

Disk #:	1	2	3	4	Mean
Sorptivity (mm/√hr):	6.65	5.85	6.34	7.85	6.67
Porosity (%):	10.58	10.30	10.64	10.19	10.43
Mean Sorptivity:	6.7	COV:	12.8	Variability	Good
Mean Porosity:	10.4	COV:	2.1	Variability	Good

MarR100C 28 days

Disk #:	1	2	3	4	Mean
k (m/s):	6.18E-11	5.37E-11	7.33E-11	6.32E-11	6.30E-11
OPI:	10.21	10.27	10.13	10.20	10.20
COV % (Mean k):	12.8				
Variability Check:	Good				

Disk #:	1	2	3	4	Mean
Sorptivity (mm/√hr):	6.82	6.17	5.06	5.93	5.99
Porosity (%):	10.81	11.28	12.39	10.62	11.28
Mean Sorptivity:	6.0	COV:	12.2	Variability	Good
Mean Porosity:	11.3	COV:	7.0	Variability	Good

MarN100S 28 days

Disk #:	1	2	3	4	Mean
k (m/s):	1.67E-10	2.84E-10	1.38E-10	2.46E-10	2.09E-10
OPI:	9.78	9.55	9.86	9.61	9.68
COV % (Mean k):	32.4				
Variability Check:	Good				

Disk #:	1	2	3	4	Mean
Sorptivity (mm/√hr):	6.93	6.44	7.27	7.00	6.91
Porosity (%):	10.15	9.52	9.50	8.76	9.48
Mean Sorptivity:	6.9	COV:	5.0	Variability	Good
Mean Porosity:	9.5	COV:	6.0	Variability	Good

JunR15C 7 days					
Disk #:	1	2	3	4	Mean
k (m/s):	1.67E-10	Invalid	2.25E-10	1.94E-10	1.95E-10
OPI:	9.78	Invalid	9.65	9.71	9.71
COV % (Mean k):	14.9				
Variability Check:	Good				

Disk #:	1	2	3	4	Mean
Sorptivity (mm/ $\sqrt{\text{hr}}$):	9.44	9.40	9.04	8.87	9.19
Porosity (%):	10.30	9.92	9.86	10.39	10.1
Mean Sorptivity:	9.2	COV:	3.0	Variability	Good
Mean Porosity:	10.1	COV:	2.7	Variability	Good

JunR30S 7 days					
Disk #:	1	2	3	4	Mean
k (m/s):	4.12E-10	3.96E-10	3.61E-10	3.00E-10	3.67E-10
OPI:	9.39	9.40	9.44	9.52	9.43
COV % (Mean k):	13.5				
Variability Check:	Good				

Disk #:	1	2	3	4	Mean
Sorptivity (mm/ $\sqrt{\text{hr}}$):	7.32	8.57	8.31	9.85	8.51
Porosity (%):	9.91	9.23	9.93	9.59	9.7
Mean Sorptivity:	8.5	COV:	12.2	Variability	Good
Mean Porosity:	9.7	COV:	3.4	Variability	Good

JunR50C 7 days					
Disk #:	1	2	3	4	Mean
k (m/s):	1.79E-10	1.75E-10	2.35E-10	2.51E-10	2.10E-10
OPI:	9.75	9.76	9.63	9.60	9.68
COV % (Mean k):	18.4				
Variability Check:	Good				

Disk #:	1	2	3	4	Mean
Sorptivity (mm/ $\sqrt{\text{hr}}$):	8.98	9.13	8.48	9.30	8.97
Porosity (%):	10.61	11.51	11.08	9.92	10.8
Mean Sorptivity:	9.0	COV:	4.0	Variability	Good
Mean Porosity:	10.8	COV:	6.3	Variability	Good

JunR100S 7 days					
Disk #:	1	2	3	4	Mean
k (m/s):	4.08E-10	3.15E-10	5.08E-10	4.32E-10	4.16E-10
OPI:	9.39	9.50	9.29	9.36	9.38
COV % (Mean k):	19.2				
Variability Check:	Good				

Disk #:	1	2	3	4	Mean
Sorptivity (mm/ $\sqrt{\text{hr}}$):	8.82	8.80	8.04	9.26	8.73
Porosity (%):	11.07	9.95	10.66	10.18	10.5
Mean Sorptivity:	8.7	COV:	5.8	Variability	Good
Mean Porosity:	10.5	COV:	4.8	Variability	Good

JunR30C 7 days

Disk #:	1	2	3	4	Mean
k (m/s):	1.49E-10	1.57E-10	1.21E-10	1.08E-10	1.34E-10
OPI:	9.83	9.81	9.92	9.96	9.87
COV % (Mean k):	17.0				
Variability Check:	Good				

Disk #:	1	2	3	4	Mean
Sorptivity (mm/ $\sqrt{\text{hr}}$):	9.63	9.01	8.83	9.56	9.26
Porosity (%):	9.68	10.11	11.60	11.18	10.6
Mean Sorptivity:	9.3	COV:	4.3	Variability	Good
Mean Porosity:	10.6	COV:	8.5	Variability	Caution

JunN100C 7 days

Disk #:	1	2	3	4	Mean
k (m/s):	2.29E-10	1.62E-10	3.59E-10	2.49E-10	2.50E-10
OPI:	9.64	9.79	9.44	9.60	9.60
COV % (Mean k):	32.9				
Variability Check:	Good				

Disk #:	1	2	3	4	Mean
Sorptivity (mm/ $\sqrt{\text{hr}}$):	8.76	9.02	9.64	9.15	9.14
Porosity (%):	10.40	9.65	9.49	9.78	9.8
Mean Sorptivity:	9.1	COV:	4.1	Variability	Good
Mean Porosity:	9.8	COV:	4.0	Variability	Good

JunR100C 7 days

Disk #:	1	2	3	4	Mean
k (m/s):	2.20E-10	1.74E-10	1.97E-10	2.40E-10	2.08E-10
OPI:	9.66	9.76	9.70	9.62	9.68
COV % (Mean k):	13.7				
Variability Check:	Good				

Disk #:	1	2	3	4	Mean
Sorptivity (mm/ $\sqrt{\text{hr}}$):	8.38	8.71	9.76	9.00	8.96
Porosity (%):	10.85	12.91	10.82	10.36	11.2
Mean Sorptivity:	9.0	COV:	6.6	Variability	Good
Mean Porosity:	11.2	COV:	10.2	Variability	Caution

JunN100S 7 days

Disk #:	1	2	3	4	Mean
k (m/s):	5.26E-10	8.58E-10	4.23E-10	3.00E-10	5.27E-10
OPI:	9.28	9.07	9.37	9.52	9.28
COV % (Mean k):	45.4				
Variability Check:	Good				

Disk #:	1	2	3	4	Mean
Sorptivity (mm/ $\sqrt{\text{hr}}$):	8.83	10.49	7.96	9.81	9.27
Porosity (%):	10.33	10.17	9.88	9.75	10.0
Mean Sorptivity:	9.3	COV:	11.9	Variability	Good
Mean Porosity:	10.0	COV:	2.6	Variability	Good

JunR15C 28 days

Disk #:	1	2	3	4	Mean
k (m/s):	1.15E-10	1.12E-10	1.27E-10	1.52E-10	1.27E-10
OPI:	9.94	9.95	9.89	9.82	9.90
COV % (Mean k):	14.6				
Variability Check:	Good				

Disk #:	1	2	3	4	Mean
Sorptivity (mm/√hr):	6.74	7.09	6.80	6.34	6.74
Porosity (%):	11.37	11.46	11.36	11.07	11.32
Mean Sorptivity:	6.7	COV:	4.6	Variability	Good
Mean Porosity:	11.3	COV:	1.5	Variability	Good

JunR30S 28 days

Disk #:	1	2	3	4	Mean
k (m/s):	3.83E-10	3.17E-10	2.26E-10	6.71E-10	3.99E-10
OPI:	9.42	9.50	9.65	9.17	9.40
COV % (Mean k):	48.2				
Variability Check:	Good				

Disk #:	1	2	3	4	Mean
Sorptivity (mm/√hr):	8.25	7.73	9.12	7.68	8.20
Porosity (%):	11.26	10.65	10.24	10.60	10.69
Mean Sorptivity:	8.2	COV:	8.1	Variability	Good
Mean Porosity:	10.7	COV:	3.9	Variability	Good

JunR50C 28 days

Disk #:	1	2	3	4	Mean
k (m/s):	8.83E-11	1.01E-10	1.29E-10	8.51E-11	1.01E-10
OPI:	10.05	10.00	9.89	10.07	10.00
COV % (Mean k):	19.9				
Variability Check:	Good				

Disk #:	1	2	3	4	Mean
Sorptivity (mm/√hr):	7.24	7.30	7.77	6.48	7.19
Porosity (%):	11.50	10.54	10.59	10.18	10.70
Mean Sorptivity:	7.2	COV:	7.4	Variability	Good
Mean Porosity:	10.7	COV:	5.2	Variability	Good

JunR100S 28 days

Disk #:	1	2	3	4	Mean
k (m/s):	1.20E-10	1.51E-10	2.11E-10	1.69E-10	1.63E-10
OPI:	9.92	9.82	9.68	9.77	9.79
COV % (Mean k):	23.3				
Variability Check:	Good				

Disk #:	1	2	3	4	Mean
Sorptivity (mm/√hr):	6.89	8.06	7.20	6.89	7.26
Porosity (%):	11.50	11.09	9.65	11.01	10.81
Mean Sorptivity:	7.3	COV:	7.6	Variability	Good
Mean Porosity:	10.8	COV:	7.4	Variability	Caution

JunR30C 28 days					
Disk #:	1	2	3	4	Mean
k (m/s):	1.40E-10	1.08E-10	1.37E-10	2.17E-10	1.51E-10
OPI:	9.85	9.97	9.86	9.66	9.82
COV % (Mean k):	31.1				
Variability Check:	Good				

Disk #:	1	2	3	4	Mean
Sorptivity (mm/ $\sqrt{\text{hr}}$):	6.54	7.66	7.05	7.56	7.20
Porosity (%):	12.08	12.17	11.19	10.38	11.46
Mean Sorptivity:	7.2	COV:	7.2	Variability	Good
Mean Porosity:	11.5	COV:	7.4	Variability	Good

JunN100C 28 days					
Disk #:	1	2	3	4	Mean
k (m/s):	1.24E-10	1.83E-10	2.53E-10	1.73E-10	1.83E-10
OPI:	9.91	9.74	9.60	9.76	9.74
COV % (Mean k):	29.0				
Variability Check:	Good				

Disk #:	1	2	3	4	Mean
Sorptivity (mm/ $\sqrt{\text{hr}}$):	7.60	8.96	6.41	7.39	7.59
Porosity (%):	11.18	11.37	10.64	10.43	10.90
Mean Sorptivity:	7.6	COV:	13.8	Variability	Caution
Mean Porosity:	10.9	COV:	4.1	Variability	Good

JunR100C 28 days					
Disk #:	1	2	3	4	Mean
k (m/s):	1.47E-10	2.46E-10	2.16E-10	3.14E-10	2.31E-10
OPI:	9.83	9.61	9.67	9.50	9.64
COV % (Mean k):	30.1				
Variability Check:	Good				

Disk #:	1	2	3	4	Mean
Sorptivity (mm/ $\sqrt{\text{hr}}$):	6.47	7.54	6.66	7.30	6.99
Porosity (%):	11.82	11.52	11.14	10.88	11.34
Mean Sorptivity:	7.0	COV:	7.3	Variability	Good
Mean Porosity:	11.3	COV:	3.7	Variability	Good

JunN100S 28 days					
Disk #:	1	2	3	4	Mean
k (m/s):	2.91E-10	3.04E-10	6.26E-10	2.47E-10	3.67E-10
OPI:	9.54	9.52	9.20	9.61	9.44
COV % (Mean k):	47.6				
Variability Check:	Good				

Disk #:	1	2	3	4	Mean
Sorptivity (mm/ $\sqrt{\text{hr}}$):	7.13	8.52	7.74	5.72	7.28
Porosity (%):	9.19	10.04	9.78	9.49	9.63
Mean Sorptivity:	7.3	COV:	16.3	Variability	Caution
Mean Porosity:	9.6	COV:	3.8	Variability	Good

AugR15C 7 days

Disk #:	1	2	3	4	Mean
k (m/s):	7.02E-11	7.69E-11	1.24E-10	1.84E-10	1.14E-10
OPI:	10.15	10.11	9.91	9.73	9.94
COV % (Mean k):	46.3				
Variability Check:	Good				

Disk #:	1	2	3	4	Mean
Sorptivity (mm/ $\sqrt{\text{hr}}$):	5.07	4.41	4.92	5.45	4.96
Porosity (%):	10.36	10.57	10.38	10.44	10.44
Mean Sorptivity:	5.0	COV:	8.6	Variability	Good
Mean Porosity:	10.4	COV:	0.9	Variability	Good

AugR30S 7 days

Disk #:	1	2	3	4	Mean
k (m/s):	1.45E-10	1.88E-09	3.99E-10	1.33E-09	9.37E-10
OPI:	9.84	8.73	9.40	8.88	9.03
COV % (Mean k):	86.1				
Variability Check:	Invalid				

Disk #:	1	2	3	4	Mean
Sorptivity (mm/ $\sqrt{\text{hr}}$):	5.44	5.53	4.99	4.86	5.21
Porosity (%):	8.14	7.99	8.68	7.88	8.17
Mean Sorptivity:	5.2	COV:	6.3	Variability	Good
Mean Porosity:	8.2	COV:	4.4	Variability	Good

AugR50C 7 days

Disk #:	1	2	3	4	Mean
k (m/s):	1.07E-10	7.88E-11	8.12E-11	8.57E-11	8.82E-11
OPI:	9.97	10.10	10.09	10.07	10.05
COV % (Mean k):	14.6				
Variability Check:	Good				

Disk #:	1	2	3	4	Mean
Sorptivity (mm/ $\sqrt{\text{hr}}$):	6.99	5.64	5.65	6.70	6.24
Porosity (%):	10.14	11.01	10.93	11.10	10.80
Mean Sorptivity:	6.2	COV:	11.2	Variability	Good
Mean Porosity:	10.8	COV:	4.1	Variability	Good

AugR100S 7 days

Disk #:	1	2	3	4	Mean
k (m/s):	2.16E-10	2.33E-10	6.97E-11	1.51E-10	1.67E-10
OPI:	9.67	9.63	10.16	9.82	9.78
COV % (Mean k):	44.3				
Variability Check:	Good				

Disk #:	1	2	3	4	Mean
Sorptivity (mm/ $\sqrt{\text{hr}}$):	Invalid	5.98	5.70	5.40	5.70
Porosity (%):	Invalid	10.16	11.96	9.66	10.59
Mean Sorptivity:	5.7	COV:	5.1	Variability	Good
Mean Porosity:	10.6	COV:	11.4	Variability	Caution

AugR30C 7 days

Disk #:	1	2	3	4	Mean
k (m/s):	7.21E-11	7.79E-11	9.43E-11	8.91E-11	8.33E-11
OPI:	10.14	10.11	10.03	10.05	10.08
COV % (Mean k):	12.2				
Variability Check:	Good				

Disk #:	1	2	3	4	Mean
Sorptivity (mm/√hr):	5.04	5.55	5.70	5.85	5.54
Porosity (%):	11.26	11.20	9.89	10.61	10.74
Mean Sorptivity:	5.5	COV:	6.3	Variability	Good
Mean Porosity:	10.7	COV:	5.9	Variability	Good

AugN100C 7 days

Disk #:	1	2	3	4	Mean
k (m/s):	1.57E-10	1.79E-10	1.21E-10	1.47E-10	1.51E-10
OPI:	9.81	9.75	9.92	9.83	9.82
COV % (Mean k):	16.1				
Variability Check:	Good				

Disk #:	1	2	3	4	Mean
Sorptivity (mm/√hr):	5.80	6.38	6.78	5.79	6.19
Porosity (%):	10.15	8.90	8.91	10.68	9.66
Mean Sorptivity:	6.2	COV:	7.8	Variability	Good
Mean Porosity:	9.7	COV:	9.3	Variability	Caution

AugR100C 7 days

Disk #:	1	2	3	4	Mean
k (m/s):	8.23E-11	9.36E-11	1.63E-10	1.15E-10	1.14E-10
OPI:	10.08	10.03	9.79	9.94	9.94
COV % (Mean k):	31.6				
Variability Check:	Good				

Disk #:	1	2	3	4	Mean
Sorptivity (mm/√hr):	6.51	8.47	6.30	6.63	6.98
Porosity (%):	12.99	12.43	12.42	13.00	12.71
Mean Sorptivity:	7.0	COV:	14.4	Variability	Caution
Mean Porosity:	12.7	COV:	2.6	Variability	Good

AugN100S 7 days

Disk #:	1	2	3	4	Mean
k (m/s):	2.79E-09	2.14E-10	2.16E-10	1.35E-09	1.14E-09
OPI:	8.55	9.67	9.67	8.87	8.94
COV % (Mean k):	106.9				
Variability Check:	Invalid				

Disk #:	1	2	3	4	Mean
Sorptivity (mm/√hr):	4.66	Invalid	5.47	5.34	5.16
Porosity (%):	8.50	Invalid	9.43	8.16	8.70
Mean Sorptivity:	5.2	COV:	8.5	Variability	Good
Mean Porosity:	8.7	COV:	7.6	Variability	Good

AugR15C 28 days

Disk #:	1	2	3	4	Mean
k (m/s):	1.62E-10	5.11E-11	7.36E-11	5.95E-11	8.65E-11
OPI:	9.79	10.29	10.13	10.23	10.06
COV % (Mean k):	59.0				
Variability Check:	Good				

Disk #:	1	2	3	4	Mean
Sorptivity (mm/√hr):	6.93	5.48	5.72	5.04	5.79
Porosity (%):	10.53	10.73	10.68	9.41	10.34
Mean Sorptivity:	5.8	COV:	14.0	Variability	Caution
Mean Porosity:	10.3	COV:	6.0	Variability	Good

AugR30S 28 days

Disk #:	1	2	3	4	Mean
k (m/s):	2.15E-10	1.66E-10	2.45E-10	1.10E-10	1.84E-10
OPI:	9.67	9.78	9.61	9.96	9.74
COV % (Mean k):	32.0				
Variability Check:	Good				

Disk #:	1	2	3	4	Mean
Sorptivity (mm/√hr):	4.63	5.35	5.77	5.21	5.24
Porosity (%):	9.27	8.99	9.64	8.49	9.10
Mean Sorptivity:	5.2	COV:	9.0	Variability	Good
Mean Porosity:	9.1	COV:	5.3	Variability	Good

AugR50C 28 days

Disk #:	1	2	3	4	Mean
k (m/s):	8.94E-11	9.44E-11	1.48E-10	Invalid	1.11E-10
OPI:	10.05	10.03	9.83	Invalid	9.96
COV % (Mean k):	29.4				
Variability Check:	Good				

Disk #:	1	2	3	4	Mean
Sorptivity (mm/√hr):	5.05	5.02	5.76	4.58	5.10
Porosity (%):	10.40	10.75	9.92	9.71	10.20
Mean Sorptivity:	5.1	COV:	9.6	Variability	Good
Mean Porosity:	10.2	COV:	4.6	Variability	Good

AugR100S 28 days

Disk #:	1	2	3	4	Mean
k (m/s):	9.44E-11	1.90E-10	1.09E-10	1.74E-10	1.42E-10
OPI:	10.03	9.72	9.96	9.76	9.85
COV % (Mean k):	33.3				
Variability Check:	Good				

Disk #:	1	2	3	4	Mean
Sorptivity (mm/√hr):	5.76	6.81	5.87	4.76	5.80
Porosity (%):	10.72	10.74	11.77	10.90	11.03
Mean Sorptivity:	5.8	COV:	14.5	Variability	Caution
Mean Porosity:	11.0	COV:	4.5	Variability	Good

AugR30C 28 days					
Disk #:	1	2	3	4	Mean
k (m/s):	1.00E-10	6.56E-11	1.07E-10	2.40E-10	1.28E-10
OPI:	10.00	10.18	9.97	9.62	9.89
COV % (Mean k):	59.9				
Variability Check:	Caution				

Disk #:	1	2	3	4	Mean
Sorptivity (mm/ $\sqrt{\text{hr}}$):	5.18	4.66	6.31	5.89	5.51
Porosity (%):	9.83	10.73	10.52	10.89	10.49
Mean Sorptivity:	5.5	COV:	13.4	Variability	Caution
Mean Porosity:	10.5	COV:	4.5	Variability	Good

AugN100C 28 days					
Disk #:	1	2	3	4	Mean
k (m/s):	7.66E-11	6.77E-11	6.36E-11	6.59E-11	6.84E-11
OPI:	10.12	10.17	10.20	10.18	10.16
COV % (Mean k):	8.3				
Variability Check:	Good				

Disk #:	1	2	3	4	Mean
Sorptivity (mm/ $\sqrt{\text{hr}}$):	4.94	6.39	5.32	5.19	5.46
Porosity (%):	10.38	11.22	9.91	9.83	10.34
Mean Sorptivity:	5.5	COV:	11.7	Variability	Good
Mean Porosity:	10.3	COV:	6.2	Variability	Good

AugR100C 28 days					
Disk #:	1	2	3	4	Mean
k (m/s):	7.48E-11	7.64E-11	5.96E-11	7.53E-11	7.15E-11
OPI:	10.13	10.12	10.22	10.12	10.15
COV % (Mean k):	11.2				
Variability Check:	Good				

Disk #:	1	2	3	4	Mean
Sorptivity (mm/ $\sqrt{\text{hr}}$):	5.63	5.78	5.69	6.28	5.84
Porosity (%):	11.83	10.66	11.01	11.83	11.33
Mean Sorptivity:	5.8	COV:	5.0	Variability	Good
Mean Porosity:	11.3	COV:	5.2	Variability	Good

AugN100S 28 days					
Disk #:	1	2	3	4	Mean
k (m/s):	3.06E-10	1.03E-09	1.69E-09	Invalid	1.01E-09
OPI:	9.51	8.99	8.77	Invalid	9.00
COV % (Mean k):	68.6				
Variability Check:	Caution				

Disk #:	1	2	3	4	Mean
Sorptivity (mm/ $\sqrt{\text{hr}}$):	5.23	5.17	4.45	4.96	4.95
Porosity (%):	8.78	10.50	8.87	9.16	9.33
Mean Sorptivity:	5.0	COV:	7.1	Variability	Good
Mean Porosity:	9.3	COV:	8.6	Variability	Caution

Chloride Conductivity

Table E.2 Chloride conductivity results for 7 days curing

Sample	March			June			August		
	σ (mS/cm)	Avg. (mS/cm)	COV (%)	σ (mS/cm)	Avg. (mS/cm)	COV (%)	σ (mS/cm)	Avg. (mS/cm)	COV (%)
R15C 1	1.77	MarR15C		1.79	JunR15C		1.41	JunR15C	
R15C 2	1.51	1.64	5.67	1.71	1.74	1.79	1.42	1.30	8.82
R15C 3	1.64			1.74			1.20		
R15C 4	1.63			1.73			1.17		
R30C 1	1.54			MarR30C			1.96		
R30C 2	1.45	1.53	4.71	1.71	1.86	5.11	1.29	1.22	10.53
R30C 2	1.49			1.91			1.01		
R30C 4	1.64			1.87			1.22		
R30S 1	0.93			MarR30S			1.05		
R30S 2	0.90	0.95	3.80	0.94	0.97	4.77	0.53	0.52	8.99
R30S 3	0.98			0.93			0.59		
R30S 4	0.98			0.95			0.47		
N100C 1	1.62			MarN100C			1.66		
N100C 2	1.68	1.62	2.27	1.83	1.76	3.68	1.10	1.29	10.63
N100C 3	1.58			1.76			1.22		
N100C 4	1.60			1.80			1.44		
R50C 1	1.70			MarR50C			1.94		
R50C 2	1.68	1.68	0.65	1.79	1.87	5.76	1.46	1.43	2.50
R50C 3	1.69			2.00			1.37		
R50C 4	1.67			1.73			1.45		
R100C 1	1.65			MarR100C			1.99		
R100C 2	1.54	1.65	5.61	1.91	1.92	3.38	1.67	1.49	14.75
R100C 3	1.79			1.82			1.56		
R100C 4	1.61			1.97			1.61		
R100S 1	1.01			MarR100S			1.07		
R100S 2	0.91	0.88	11.61	0.87	0.96	7.91	0.77	0.71	11.96
R100S 3	0.73			0.98			0.65		
R100S 4	0.86			0.92			0.81		
N100S 1	0.95			MarN100S			1.00		
N100S 2	0.90	0.99	8.88	0.96	1.07	8.69	0.57	0.57	2.19
N100S 3	1.00			1.18			0.58		
N100S 4	1.13			1.15			0.56		

Table E.3 Chloride conductivity results for 28 days curing

Sample	March			June			August		
	σ (mS/cm)	Avg. (mS/cm)	COV (%)	σ (mS/cm)	Avg. (mS/cm)	COV (%)	σ (mS/cm)	Avg. (mS/cm)	COV (%)
R15C 1	1.18	MarR15C		1.67	JunR15C		1.23	AugR15C	
R15C 2	1.09	1.15	5.53	1.65	1.60	3.43	1.29	1.37	8.20
R15C 3	1.10			1.54			1.48		
R15C 4	1.25			1.56			1.48		
R30C 1	1.02	MarR30C		1.43	JunR30C		1.54	AugR30C	
R30C 2	1.17	1.13	9.00	1.66	1.49	6.64	1.25	1.43	7.57
R30C 2	1.28			1.44			1.46		
R30C 4	1.06			1.43			1.46		
R30S 1	0.50	MarR30S		0.66	JunR30S		0.54	AugR30S	
R30S 2	0.52	0.51	2.22	0.89	0.77	12.71	0.67	0.60	8.20
R30S 3	0.50			0.85			0.58		
R30S 4	0.50			0.70			0.61		
N100C 1	1.22	MarN100C		1.50	JunN100C		1.45	AugN100C	
N100C 2	1.17	1.11	7.70	1.62	1.55	3.38	1.44	1.37	7.87
N100C 3	1.00			1.50			1.18		
N100C 4	1.07			1.58			1.40		
R50C 1	1.05	MarR50C		1.58	JunR50C		1.47	AugR50C	
R50C 2	1.02	1.06	3.07	1.47	1.51	2.78	1.31	1.42	4.42
R50C 3	1.07			1.50			1.45		
R50C 4	1.11			1.49			1.44		
R100C 1	1.08	MarR100C		1.49	JunR100C		1.55	AugR100C	
R100C 2	1.18	1.03	10.57	1.53	1.51	2.56	1.43	1.42	7.09
R100C 3	0.96			1.45			1.43		
R100C 4	0.89			1.55			1.27		
R100S 1	0.36	MarR100S		0.58	JunR100S		0.77	AugR100S	
R100S 2	0.44	0.39	7.68	0.58	0.59	3.53	0.81	0.71	11.77
R100S 3	0.38			0.57			0.61		
R100S 4	0.40			0.62			0.66		
N100S 1	0.43	MarN100S		0.67	JunN100S		0.74	AugN100S	
N100S 2	0.52	0.47	6.87	0.64	0.60	9.34	0.64	0.68	7.90
N100S 3	0.46			0.52			0.62		
N100S 4	0.47			0.59			0.73		

Durability specimen preparation and conditioning



Figure E.6 Machinery used to prepare durability test samples, diamond tipped core barrel drill (left) and wet saw concrete cutter (right)



Figure E.7 Durability specimens after coring and cutting (left) and specimens in oven (right)

Durability specimens



Figure E.8 Durability specimens, MarR100C (left), JunR100C (middle) and AugR100C (right)



Figure E.9 Durability specimens, MarR100S (left), JunR100S (middle) and AugR100S (right)



Figure E.10 Durability specimens, MarN100C (left), JunN100C (middle) and AugN100C (right)

Dimensional properties

Figure E.11 Machine used to grind the casting surfaces of the modulus of elasticity, shrinkage and creep specimens

Table E.4 Measured shrinkage strain readings at 90 days (with measurement errors)

Mixture	Strain ($\mu\text{m/m}$)	COV (%)	Mixture	Strain ($\mu\text{m/m}$)	COV (%)	Mixture	Strain ($\mu\text{m/m}$)	COV (%)
March			June			August		
N100C	483	21.9	N100C	665	30	N100C	457	25.2
R30C	541	22.3	R30C	558	28.2	R30C	450	28.7
R50C	485	23.2	R50C	618	19.1	R50C	462	41.3
R100C	425	24.4	R100C	540	19.1	R100C	557	62.1
Average	484	23.0	Average	595	24.1	Average	482	39.3
Std Dev.	41		Std Dev.	50		Std Dev.	44	

Table E.5 Measured shrinkage strain readings at 90 days (without measurement errors)

Mixture	Strain ($\mu\text{m/m}$)	COV (%)	Mixture	Strain ($\mu\text{m/m}$)	COV (%)	Mixture	Strain ($\mu\text{m/m}$)	COV (%)
March			June			August		
N100C	510	10.7	N100C	551	20.4	N100C	392	15.2
R30C	492	17.4	R30C	470	19.3	R30C	410	16
R50C	430	15.8	R50C	529	7.8	R50C	351	21.2
R100C	419	13.1	R100C	494	18.5	R100C	346	28
Average	463	14.3	Average	511	16.5	Average	375	20.1
Std Dev.	39		Std Dev.	31		Std Dev.	27	

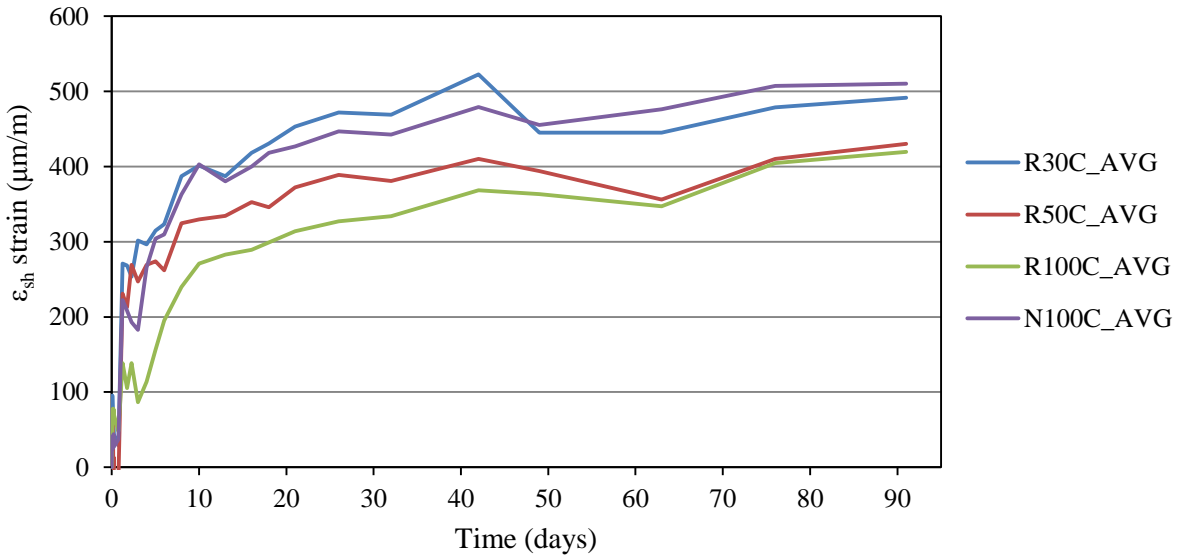


Figure E.12 Measured shrinkage readings for testing period with March mixtures (without errors)

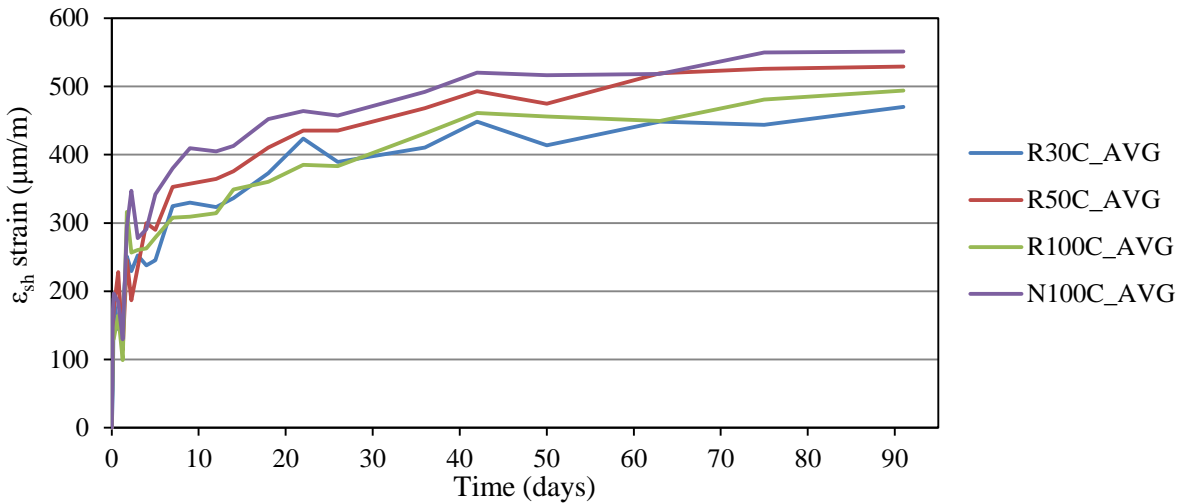


Figure E.13 Measured shrinkage readings for testing period with June mixtures (without errors)

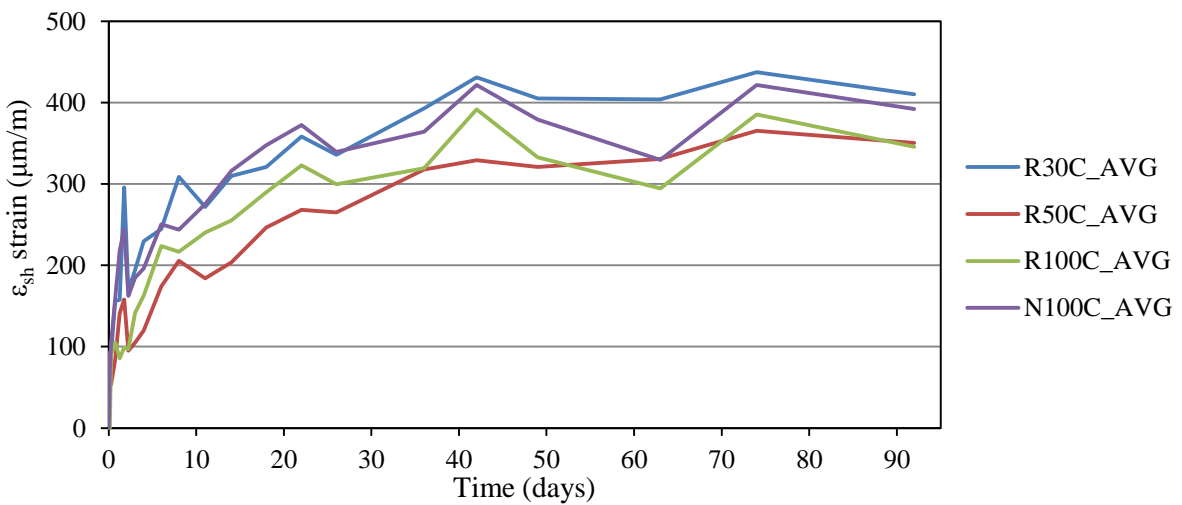


Figure E.14 Measured shrinkage readings for testing period with August mixtures (without errors)



Figure E.15 Shrinkage specimens (left) and targets used to measured deformation of shrinkage specimens (right)

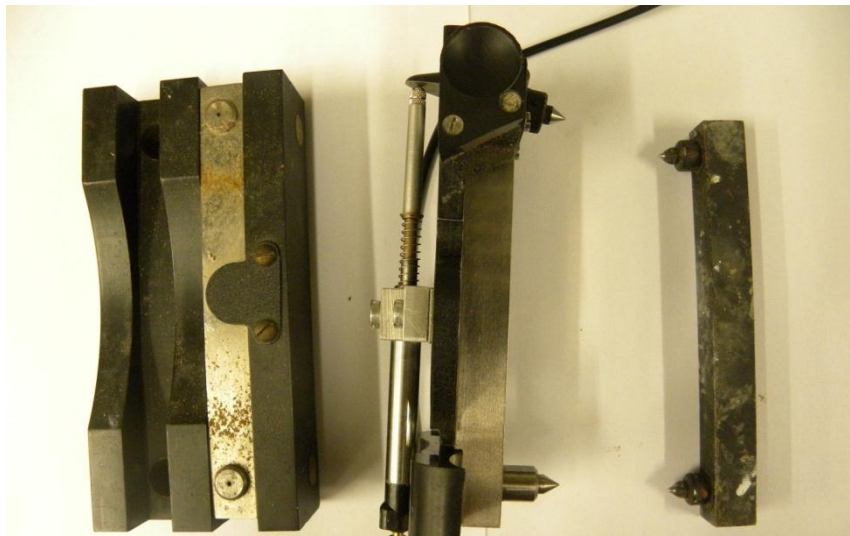


Figure E.16 Device used to measure deformation of shrinkage and creep specimens (middle), steel reference bar for calibrating each reading (left) and 101mm gauge used to position targets (right)

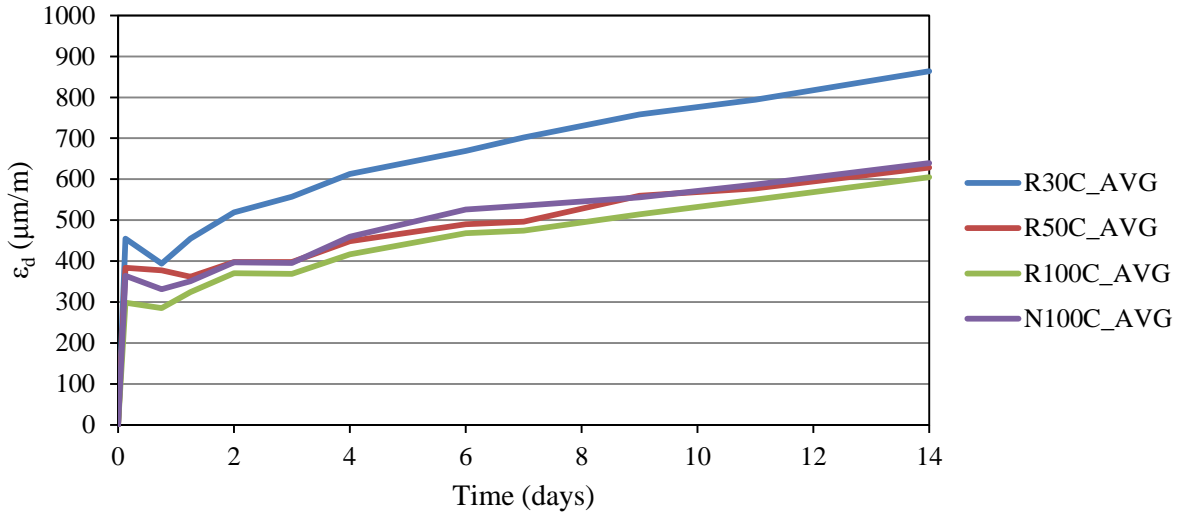


Figure E.17 Measured total deformation of creep specimens from March mixtures

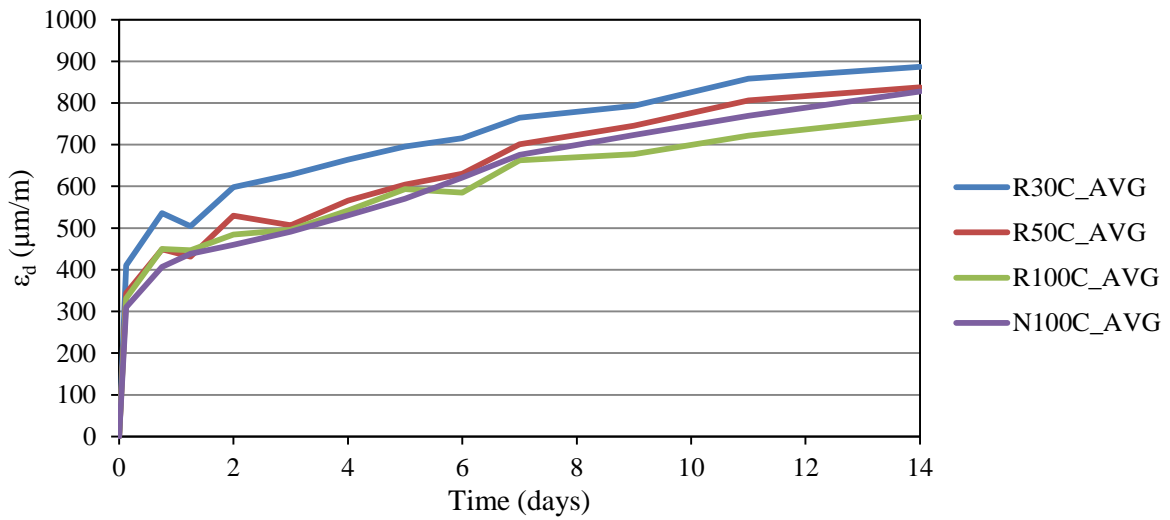


Figure E.18 Measured total deformation of creep specimens from June mixtures

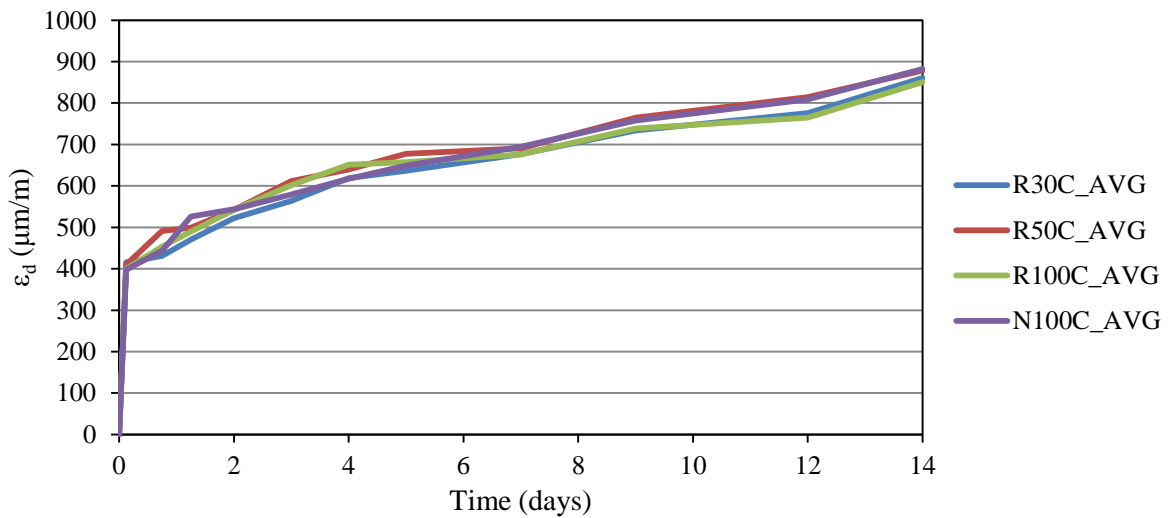


Figure E.19 Measured total deformation of creep specimens from August mixtures



Figure E.20 Photographs which show the failure which occurred during the testing of the creep specimens. The failure mechanism was corrected



Figure E.21 Final creep testing apparatus used in this investigation