**MECHANICAL AND DURABILITY PROPERTIES OF RECYCLED CONCRETE AGGREGATE FOR NORMAL STRENGTH STRUCTURAL CONCRETE**

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Received 20 March 2013; Revised 01 July 2013; Accepted 01 July 2013

**Abstract**

The purpose of this study was to determine the suitability of using Recycled Concrete Aggregate (RCA) in structural concrete based on a better understanding of its strength, stiffness and durability. RCA was collected from three different sources: a local landfill site, a local aggregate supplier and from the demolition of two old cooling towers in Cape Town, South Africa (RSA). All RCA was prepared by crushing the demolished concrete in a laboratory crusher at University of Stellenbosch. Their physical properties were determined for comparison of different sources of RCA. RCA replacement percentages of 0%, 30% and 100% to partially replace natural aggregate (NA) in concrete were tested at different ages. Cube strength classes 30-40 MPa concrete were made to investigate the mechanical properties of RCA. Creep, shrinkage and durability properties were also tested for concrete with 0% and 30% RCA replacement of NA. It was found that RCA replacement by 30% (RCA30%) of NA does not lead to any significant difference in strength and stiffness compared to concrete containing 100% NA in concrete. RCA100% replacement does show reduced strength and stiffness, but this is not significant and can be compensated for in standard ways. Durability index tests indicated similar durability performance of concrete with reasonable quality RCA30% compared with NA100%. Increased creep was however observed for RCA30% which must be considered in structural design. Little information is available about both the mechanical and durability properties of local RCA in RSA, where this research has been performed. The authors believe this report will assist to increase the confidence of engineers to consider using RCA in structural concrete in RSA as well as abroad.

***Keywords:*** *Recycled Concrete Aggregate (RCA), physical, mechanical and durability properties of RCA.*

# 1.0 Introduction

Concrete, one of the most dominant construction materials due to its availability, relatively lower cost and the possibility to be cast into desired shapes, has contributed strongly internationally in terms of infrastructure development. The successes are however accompanied by large volumes of construction and demolition waste (C&DW). Recycling of concrete by crushing C&DW and using it as aggregate in especially road base layers, but also in structural concrete, has become possible in several countries, where national standards provide for appropriate use of recycled concrete aggregate (RCA).

The use of RCA in construction work started almost 70 years ago just after the Second World War [1], when many structures were demolished by bombing. During rebuilding, the demolished concrete was used as aggregate especially in the base or sub-base layers in new road construction. Today, RCA is used successfully in many countries in many fields such as road construction, protection against erosion, parking areas as well as structural concrete. A number of structures in Germany, Norway, United Kingdom, Finland, and Netherlands have been built with RCA as partial or full replacement of natural aggregate (NA) [2]. Sustainability drivers in the use of RCA include reduced landfill and natural resource requirement, and potentially lower energy requirement to produce than NA. Several countries face the challenge of extending their landfill site areas, with C&DW forming a major portion [3,4]. Through price structuring, governments are encouraging sustainable solutions to such waste problems. Sound re-uses in concrete presents a solution.

Although RCA has been used as a construction material internationally for decades, the use in the Republic of South Africa (RSA) is still limited. Land fill space and resources of NA in RSA have until now been readily available at relatively low cost making it less important to consider the use of RCA [5]. From information gathered from local landfill sites, RCA in RSA is mostly used in road construction and some foundation work, although there are no specifications or guidelines available on the use of RCA in new construction. Reports show that 2-3 billion (thousand million) tons of construction and demolition waste (C&DW) [6] is produced yearly world-wide of which RSA produces 5-8 million ton [7]. These quantities are increasing with continued growth in population and economies. Many landfill sites have reached their capacity and need to be extended, or new sites are to be claimed within reasonable distance for viable waste delivery and management. In many cases landfill sites are surrounded by agricultural land on the fringes of cities. Extending them further is in direct competition with the farmers who do not want to lose their land and threaten with legal action. This is also a problem in RSA where many of the landfill areas are full and need to be extended. A way to mitigate this problem is to re-use the non-decomposing or non-combustible waste, of which C&DW currently forms a dominating part.

The use of RCA in concrete has to be controlled, and the composite behaviour understood to ensure that required performance is achieved. Required measures include screening for contaminants and testing to ensure compliance with physical and durability requirements. As RCA has already been used in the construction industry internationally for number of decades, a large pool of information towards good practice and of mechanical and durability behaviour is available. By applying good practice, it turns out that the mechanical properties of RCA are not that inferior, and meet the requirements of strength for certain applications [9,10]. There appears to be no or insignificant effect on concrete strength at the replacement level of up to 30% of coarse aggregate by RCA [11], while a gradual reduction in strength may be found at increasing replacement percentages [12,13]. Less information is available on dimensional stability and durability, and indications are that the potential exists for increased shrinkage and creep, and reduced durability in terms of rates of ingress of deleterious matter into concrete containing RCA in comparison with conventional concrete [14,15]. The results vary from country to country and also for different sources of RCA. Therefore there is a need for more and systematic research on the use of local RCA in concrete subjected to mechanical and environmental actions.

From these points of view, and inspired by an overfull local land fill site in Stellenbosch, a research project was performed on the use of RCA in concrete at Stellenbosch University in RSA. While full details are reported in an MScEng-thesis [16], this paper serves to summarise the research objectives, method, results and main findings. An experimental program was designed and executed to study mechanical performance of concrete containing RCA from three different sources, of clearly different physical properties. Concrete mixes were designed to have properties of a standard concrete strength class of 30-40 MPa cube strength, and containing coarse aggregate with 0% RCA (thus 100% NA), 30% RCA and 100% RCA. Compressive strength and elastic modulus, as well as splitting and flexural strengths were determined by standard tests. A selection of mixes was subjected to shrinkage and creep, as well as water permeability, oxygen and chloride penetration tests. These tests on mechanical and durability properties of RCA have been designed based on the pool of published international research results and practise, with the intent of deriving suitable categories of RCA quality for local structural use, and bridging between local and international results. The authors believe that the process followed and results hold international value, notably for regions where RCA may be considered to be implemented.

**2.0 Experimental Program**

**2.1 Experimental setup**

Four types of coarse aggregates were used in this research work namely three RCAs and one NA, as well as natural fine aggregate. The C&DW was collected from the local land fill site in Stellenbosch, a local aggregate supplier in the Durbanville region 50 km from Stellenbosch, and from the cooling towers near Cape Town, demolished in 2010 at the time of starting up this research project – see Figure 1. The waste concrete was collected at these sites and mechanically reduced to sizes of roughly 150 mm diameter, and subsequently crushed in a small crusher at Stellenbosch University to a nominal particle size of 19 mm. Local Greywacke coarse aggregate was used throughout as NA in this research project. Their physical properties and the mix designs are shown in Tables 1 and 2. Tests were carried out on all aggregates to determine their relative density, water absorption, 10% FACT (10% fines crushing) value, flakiness index and particle size distribution. After testing, a mix design was prepared in accordance with the properties obtained from the test results. Concrete was then produced with the replacement of 0%, 30% and 100% of NA with RCA. All aggregates were saturated surface dry (SSD) before mixing of the new concrete except in step 1. Tests were conducted on these concretes in the fresh state to determine the workability (standard slump test) and air content. For the hardened concrete, the 28-days compressive strength, E-modulus and 28-days splitting tensile strength, flexural strength, shrinkage, creep and durability index were determined.



**Figure.1:** (Left) Stellenbosch land fill site and (right) demolished Cape Town cooling towers (2010) from where waste concrete was collected for RCA.

**Table 1:** Physical properties of NA and RCA

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Type | Used in step | Aggregate  size (mm) | Relative density | Absorption (%) | 10% Fact value (kN) | Flakiness index |
| NA | 1-4 | 9.5 - 19 | 2.74 | 0.65 | 370 | 25 |
| RCA-1 | 1 | 9.5 - 19 | 2.48 | 5.24 | 88 | 18 |
| RCA-2 | 2 | 9.5 - 19 | 2.52 | 4.40 | 125 | 19 |
| RCA-3 | 3-4 | 9.5 - 19 | 2.54 | 3.49 | 135 | 21 |

**2.2 Concrete compressive strength**

The 28-days compressive strength tests were performed in accordance with ASTM C 39 and SANS 5863:1994. The compressive strength of hardened concrete was determined on 150 mm x 250 mm cylinders and 150 mm concrete cubes which were cast and water-cured at 23 ± 1 0C before being tested at ages of 28-days. Note that, the 50 mm reduction in cylinder height was because of limited spacing in Contest Materials Testing Machine (CMTM). There was not enough free space for placing a 300 mm high cylinder specimen and a load cell in the CMTM. A 350 ton CMTM was used in this experimental work for applying pressure on the specimen and load cell was used for collecting data directly to the computer.

Table 2: Concrete mix designs: materials used kg/m3 of concrete.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Materials | Used in step | NA mixes | | RCA mixes | |
| 70% | 100% | 30% | 100% |
| CEM II 32.5 | 1 | 333 | | 333 | |
| CEM I 42.5 | 2-3 | 350 | | 350 | |
| 4 | 175 | | 175 | |
| GGCS | 4 | 175 | | 175 | |
| Water | 1 | 183 | | 183 | |
| 2-4 | 175 | | 175 | |
| \*Sand | 1 | 575 | 821 | 246 | 821 |
| 2-4 | 469 | 670 | 201 | 640 |
| 19 mm stone | 1 | 753.50 | 1076 | 322.50 | 968.50 |
| 2-4 | 868 | 1240 | 372 | 1185 |

\*Note that small correcting adjustments to the sand content were made to accommodate the different densities of NA and RCA in the different mixes.

**2.3 E-modulus of concrete**

The E-modulus of concrete is related to the E-modulus of cement mortar and to that of the coarse aggregate. The aggregate generally has a higher E-modulus than the concrete. Hence, the higher the E-modulus of coarse aggregate or the higher the coarse aggregate content is, the higher the E-modulus of the concrete typically will be. Crushed coarse aggregate which has a rough texture will produce better bond and will also result in a higher E-modulus of the concrete. In recycled aggregate concrete (RAC) the number of weakly-bonded areas is significantly more than in natural aggregate concrete (NAC), i.e. within the RCA between remaining mortar and original aggregate as well as the bonding with the new mortar paste. The number of micro-cracked regions in the RCA may be aggravated by the re-crushing. Therefore, RCA containing roughly the same amount of the original aggregate from the same base rock may lead to a lower E-modulus of the concrete composite. However, this remains to be determined from case to case, and can in fact be considered and perhaps compensated for in the design of concrete with particularly required mechanical properties.

The E-modulus was determined according to ASTM C 469 and was computed for water cured cylinders at the age of 28 days. For accurate determination of the E-modulus, an HBM 2000 kN load cell was placed over the specimen and two HBM 50 mm linear variable differential transformers (LVDTs) were used to measure deformation over a central gauge length of 120 mm. The setup also consisted of a Spider8 data collector and a computer to download the data from the test. The loading rate used was the same as that for the compressive strength test (3 ± 1 kN/s). In order to calculate E-modulus the 30-40% of the ultimate compressive strength was used. In total five cylinders from each concrete mix were tested to determine their ultimate compressive strength and E-modulus. Each specimen was preloaded with 3 loading cycles to 30-40% of the estimated peak load before the actual loading to failure took place, in order to lessen the impacts of non-structural deformation in the loading system.

**2.4 Flexural and splitting strength of concrete**

As a part of concrete design it may be necessary to determine the flexural strength of concrete mixtures, to examine compliance with the specifications and to provide the necessary information for designing an engineering structure. A Zwick Z250 materials testing machine was used to perform flexural (three point bending) and splitting tests of concretes studied in this research. For the flexural test, three prismatic specimens were used from each concrete mix, with dimensions 150 mm x 150 mm x 700 mm and supported over a span of 450 mm. One 200 kN load cell and two HBM 10 mm LVDT’s were connected with a Spider8 to plot a load versus deflection graph for the beam. By using the formula suggested by SANS 5864:1994, the flexural strength of each beam was calculated and the average value was taken for each of the concrete types.

The splitting tensile strength is easier to determine accurately than direct tensile strength. It is generally greater than direct tensile strength and lower than flexural strength. For the splitting test five 150 mm cubes were tested for each type of concrete at the age of 28 days. All the specimens were prepared in the same manner as for the compression test as discussed earlier. The standard test procedure as described in SABS Method 1253: 1994 was followed. In the test, a cube is subjected to compressive forces applied along two diametrically-opposed lines, of which the results are summarised in experimental results section.

## 2.5 Shrinkage and creep of concrete

Cylindrical specimens with diameter 100 mm and length 300 mm were used for shrinkage and creep testing. Note that only one type of RCA (RCA-3) at 30% replacement of NA was used for the shrinkage and creep tests, and compared to reference measurements on NA100% specimens, due to the time and number of creep frame limitations.

Methods of shrinkage measurement described in ASTM C 157-80 and SANS 1085 (2001) were followed. Shrinkage strain was measured over a period of 90 days on plain concrete for NAC100% and RAC30% concrete cylinder specimens with 28 day compressive strength of 37MPa. A total of five specimens for NAC100% and five for RAC30% were tested. The specimens were demoulded after 24 hours and cured in water until the age of 26 days after casting and left to dry for one day under laboratory conditions where the average temperature was 23 ± 1 0C and average relative humidity was 55 ± 5%. The specimens were capped to ensure parallel ends, and gauge targets were glued on. After one day the specimens were again put in water for another day until the testing started. Each shrinkage specimen was covered on both ends with plastic and aluminium foil paper to minimize axial drying, and to enforce only radial drying. Before taking any readings, the strain gauge was calibrated. Shrinkage strains of the specimen were measured within 1 minute after being removed from the water. The data was collected subsequently after 5, 10, 30, 100, 220 and 380 minutes during the first day. After that day strain measurements were taken daily for one week and the weekly until the end of the test.

For the creep test a total of five specimens of NAC100% and five of RAC30% were tested. All samples were cast and compacted by using a vibrating table and were water-cured similar to the shrinkage specimens. Creep cylinders had their ends capped in the same manner as for the compression test before loading to ensure smooth bearing surfaces. A sustained load of roughly 40% of the cylinder compressive strength was used. This load was determined by the cylinder compressive strength at the age of 28 days, 40% of which is 12 MPa which is 94 kN of load on the cylinder. This 94kN load was applied gradually at a loading rate approximately 160 N/s until the final load was reached. In order to minimize the effect of creep on the result, the initial elastic strains were measured as quickly as possible (within 10 minutes).

## 2.6 Durability index tests

Hostile agents entering concrete may lead to rapid deterioration of the concrete or steel it contains. Ingress of gas and water, which may also contain deleterious ions into concrete may be rapid in harsh conditions and concrete of low resistance to permeation, capillary suction and other transport mechanisms. The ingress of oxygen, carbon, water and chlorides are associated with various deterioration processes in reinforced concrete, including corrosion of reinforcement, freezing and thawing, alkali-aggregate reaction, sulphate attack and others. In this research, three durability index tests were performed in order to characterize fluid and ion transport mechanisms in RAC30% and compared with NAC100%. These are oxygen permeability index (OPI) for oxygen permeation, chloride diffusion and sorptivity for water absorption. Test procedures followed the University of Cape Town (UCT) durability index testing procedure manual, 2009, version 1 [17,18].

For all three tests, the samples used were concrete disks of 30 ± 2 mm thickness and 70 ± 2 mm diameter, tested at the age of 23 days. The samples were obtained by coring into the exposed surface of 100 mm concrete cubes, and then by cutting the cores into above mentioned disks sizes. The samples were thereafter placed in an oven kept at 50 ± 20 C and relative humidity of less than 20% for 7 days ± 4 hrs prior to testing. Four samples were prepared for each set of test results.

## 2.6.1 Chloride conductivity test

Chloride conductivity (CC) testing is done to monitor the diffusion characteristics of chloride in concrete. Diffusion is defined as the process by which liquid, gas or ions move through a porous material under the action of a gradient. It may occur in partially- or fully-saturated concrete and is an important transport mechanism for most concrete structures that are exposed to salts [17,18]. Chloride conductivity of the specimen was calculated as follows:

 (1)

where *i* is the electric current, *V* is the voltage difference, *d* is the average thickness and *A* is the cross-sectional area of the specimen.

## 2.6.2 Oxygen permeability test

Permeation is defined as the process of movement of fluids through a porous structure under an externally-applied pressure. Therefore, permeability refers to the capacity of concrete to transport gasses or fluids by permeation and is dependent on the concrete microstructure, the moisture condition of the material and the characteristics of the permeating gas or fluid. The oxygen permeability is presented as a permeability coefficient obtained from the measured flow of oxygen at different pressures through the specimen, expressed in terms of the D’arcy coefficient of permeability as follows:

 (2)

where *k* is the coefficient of permeability of test specimen (in length per unit time), ω is the molecular mass of oxygen (32 g/mol), *v* is the volume of oxygen under pressure in the permeameter, *g* is the acceleration due to gravity (9.81 m/s2), *R* is the universal gas constant (8.313 *Nm/K* mol), *θ*  is the absolute temperature (K) and *z* is the slope of the linear regression line is given by:

 (3)

where *P0* is the initial pressure at time *t0*, the start of the test, and *Pi* are the subsequent readings in pressure at times *ti*, measured from *t0*.

The oxygen permeability index (OPI) is given as the negative log of the average of the coefficients of permeability of the specimens. For *n* specimens this is:

 (4)

## 2.6.3 Water sorptivity test

Water sorptivity testing is performed to measure the rate of water movement into the concrete specimens under the action of capillary forces. It can be determined from weight gain of the specimen with time of exposure of the lower surface to water. The water sorptivity of the specimen (*S*) is then calculated as follows:

 (5)

where *m* is the slope of the best fit line to the graph of measured mass gain versus square root of time which the specimen is exposed to capillary suction, *M*sv is the vacuum saturated mass and *M*so is the mass of the specimen at the initial time (*t*0).

The porosity of each specimen was determined as follows:

 (6)

with  the density of water, and A is the specimen surface area exposed to the water.

## 3.0 Experimental results

## 3.1 Slump of concrete

The slump test values are summarised in Figure 2. In step1, for which all coarse aggregate was dried before mixing, the measured concrete slump was 80 mm for NAC100% and 30 mm for RAC100% - refer to Figure 2. The reason for this difference is the high absorption capacity of RCA used in step 1. This indicates that, unless aggregate is saturated beforehand, RCA concrete may have a lower workability than conventional concrete, which may lead to difficulty in placing, compacting and finishing the concrete. By limiting the amount of RCA to 30%, it is clear from Figure 2 that the workability reduction affect is limited. Alternatively, the aggregate can be prepared to be saturated surface dry (SSD) before mixing, which was done in steps 2 to 4 for both RCA and NA. This was successful in step 2, but inconsistent slump results were found for steps 3 and 4. Note that steps 3 and 4 used RCA from a different source than steps 1 and 2. The slump value can also be changed for the same mix design if the batch of the mix is changed and if the volume of concrete differs from one mix to another. More test data is required to come to a final conclusion on the relative workability of RAC and NAC.

## 3.2 Air in concrete

Figure 3 shows the air content, ranging from 1.3% to a maximum of 2.4%. It is judged that the actual air content of RAC will not be significantly different from the ordinary concrete if sound concrete mix design and practice is followed. It is however required that more tests should be conducted on RAC to increase the statistical base.





**Figure.3:** % Air in concrete

**Figure.2:** Slump of concrete





**Figure.5:** 28 days E-modulus of concrete

**Figure.4:** 28 days cylinder strength of concrete

## 3.3 28 days Compressive strength and E-modulus of NAC and RAC

The measured minimum, average and maximum cylinder compressive strengths for all steps are shown in Figure 4. It is worth mentioning that the average 28 day strength of all three types of concrete from the different steps indicate no significant influence of RCA replacement. A maximum of 2% and 3.5% lower values have been found for RAC30% and RAC100% respectively. Note that this cylinder strength is equivalent to a concrete class of cube strength of 40MPa.

The average E-modulus values of NAC and RAC are shown in Figure 5. There is negligible difference at all ages between the E-modulus values of RAC30% and NAC100%, while those of RAC100% are consistently lower. This is ascribed to the mortar adhered to original aggregate particles in RCA, and the associated lower stiffness by theory of mixtures. RAC30% has a slightly higher (1%) average E-modulus values than NAC100%, but the E-modulus of RAC100% is more than 21% lower value than the NAC100%.

## 3.4 Probability density function (PDF) of NAC and RAC

A total number of 55 cylinders (15 for NAC100%, 20 for RAC30% and 20 for RAC100%) were prepared and tested from the three different types of concrete of NAC and RAC of steps 1 to 4. The PDF of 28 day cylinder strength of these concrete are shown in Figure 6. With the PDF value, the variation of strength of concrete at a particular age can be determined. In the case of NAC100%, the strength varies between 27MPa and 37MPa, RAC30% varies between 27.5MPa and 40.5MPa and RAC100% varies between 27MPa and 36MPa. Therefore the variation of strength of RAC100% is lower than that of both NAC100% and RAC30%.

## 3.5 Cumulative distribution function (CDF) of NAC and RAC

The CDF in the probability speculation depicts the probability that a real value random variable X with a given probability distribution will be found at a value less than or equal to X. Figure 6 shows the CDF of cylinder strength for both NAC and RAC at 28 days. From the presented experimental results, the CDF value for RAC30% is higher than for NAC100% over a significant range in strength.

## 3.6 Flexural and Splitting strength of NAC and RAC

A comparison of the average 28 day flexural and splitting strength results in Figure 7 shows a trend of slight reduction in strength with increased RCA content. It is evident from these results that unlike the compressive strength, RCA cannot contribute directly to making the splitting and flexural strength equal to that of NAC. The average flexural strength of RAC30% is maximally 1% lower than that of NAC100% but up to 18% lower in the case of RAC100% while the splitting strengths of RAC30% and RAC100% are respectively 10% and 17% lower than that of NAC100%.





**Figure.6:** 28 days PDF & CDF of concrete

**Figure.7:** 28 days Splitting & Flexural strength of concrete

28 days PDF & CDF of concrete

## 3.7 Shrinkage of NAC and RAC

Figures 8 and 9 show the average value of the shrinkage strains (included drying + cooling) obtained from the five cylinder specimens of NAC100% and RAC30% respectively over time. After 90 days the average value of ultimate shrinkage strain (ϵsh,u) was 936µm/m for NAC100% and 839µm/m for RAC30%. In the case of NAC100%, two specimens, 1 and especially 2 in Figure 8, show higher values in comparison to the other three specimens. The actual reasons for these higher values are unknown. Specimen nr 2 is considered to be an outlier, with shrinkage values beyond twice the standard deviation of the average, so this specimen was not considered for the determination of creep shown in Figure 10. If specimen nr 2 is ignored, NAC100% shows an average ultimate strain of 822µm/m, which is 2% less than the average RAC30% drying shrinkage strain value. In the first four days a maximum coefficient of variation (CoV) of 58.92% was observed for the five NAC100% specimens and the same value (58.99%) was also found for the four specimens excluding specimen nr 2. At 90 days the maximum CoV of NAC100% was 33.41% for five specimens and 25.17% for four specimens but a maximum of 29.13% in the first four days and 7.79% at 90 days were observed for RAC30%. Therefore a higher variation of shrinkage strain was observed during the early stages of the test both for NAC100% and RAC30%. Later in the test period, the variation was small especially for the RAC30%.

It is interesting to see that in the first 6 hours of testing, almost 30% of the total 90 day shrinkage occurred for both concrete types (235µm/m for NAC100% and 244µm/m for RAC30%). Note that the first readings were taken 1 minute after taking the specimens out of the curing water, in order to get the zero shrinkage reading. This reading is crucial to the accurate determination of later shrinkage strain values. The strain difference between the two types of concrete is very small, which indicates that RCA30% replacement of this particular quality, in this concrete class does not have a great influence on the shrinkage properties. The slightly higher shrinkage strain of RAC30% could be attributed to its higher water content due to the extra mortar on the RCA surfaces.





**Figure.9:** Shrinkage of RAC30%

**Figure.8:** Shrinkage value of NAC100%





**Figure.11:** Creep strain of RAC30%

**Figure.10:** Creep strain of NAC100%

## 3.8 Creep of NAC and RAC

Creep strain was calculated by deducting the free drying shrinkage and elastic strain from the total strain of specimens under constant load. This result is shown in Figures 10 and 11. It can be seen that at 90 days maximum 571µm/m and 954µm/m creep strain values were found for NAC100% and RAC30% respectively. So the 90 days of creep strain of RAC30% is about 67% higher than that of NAC100%.

Higher values of total strain, i.e. before deduction of elastic and shrinkage strain, were found for RAC30% than NAC100%. Maximum values of total strain from the averaged responses are 1771µm/m and 2140µm/m for NAC100% and RAC30% respectively, representing a 21% higher total strain for RAC30%. Drying creep was not defined in this experiment since it involves sealed and un-sealed specimens of concrete subjected to creep loads. This research included only un-sealed specimens for the creep tests.

It is worth mentioning that specimens nr 3 and 4 of NAC100% were three days older (load applied on 31 days) than all the other specimens. These two specimens show lower strain values, as is expected for older concrete, compared to the other specimens, and contributed to the lower average creep strain for NAC100%.





**Figure.13:** Observed RH and temperature

**Figure.12:** Specific creep of NAC100% and RAC30%

## 3.9 Specific creep of NAC and RAC

Specific creep for NAC100% and RAC30% is shown in Figure 12. The specific creep was calculated by dividing the creep strain by the stress (12MPa) caused by constant load (94.25kN). The experimental specific creep (E-NAC100% and E-RAC30%) is shown together with the calculated specific creep (BS-NAC100% and BS-RAC30%) according to EC2 (2004)-BS EN 1992-1-1:2004.

Experimentally, specific creep strain development during day one is about 31% for NAC100% and 24% for RAC30%. According to BS EN 1992-1-1:2004, predicted strain development in one day for NAC100% and RAC30% is 28% and 29% respectively (the difference due to slightly different compressive strengths). Experimentally a 67% (RCA30% 80 µm/m/MPa and NAC100% 48 µm/m/MPa) larger strain value was found for RAC30% in comparison with NAC100% after 90 days while predicted values show only a 4% (RAC30% 49 µm/m/MPa and NAC100% 47 µm/m/MPa) strain increment. It must be noted that the values calculated from standardized equations are nominal values. Significantly different creep values may occur in practice, for instance due to particular aggregates used in concrete.

## 3.10 Relative humidity (RH) and temperature

In order to appraise the influence on the creep and shrinkage results, the RH and the temperature of the testing room were monitored during the testing period. Figure 13 shows the RH and temperature measurements. Fluctuations of results were found for both the RH and temperature. Especially after 49 days, a marked reduced temperature realized, due to a faulty thermal control system. This means that the shrinkage strains reported before include thermal shrinkage values in the period 49-90 days. However, the creep strains were found by subtracting the elastic strain and the total shrinkage strains (drying + cooling) measured on the free shrinkage specimens, which is correct. The creep strain was, however, not corrected for the fluctuating level of RH, due to uncertainty how this should in fact be done. Nevertheless, both types of concrete, RAC30% and NAC100%, were subjected to the same conditions, allowing comparison between the shrinkage and creep strains of these two concretes. All specimens were placed close together in the climate-controlled room, and there is no evidence that they did not all experience the same fluctuations in temperature and relative humidity.

## 3.11 Durability index results of NAC and RAC

## 3.11.1 Chloride conductivity

In a chloride conductivity test for both NAC100% and RAC30% and the average value of four specimens are shown in Table 3. A higher value was found for NAC100% and the reason for this higher value is unknown. Note that the four measurements do not represent a sufficient statistical base, so more tests are recommended to reduce uncertainty of this outcome. However, from these results it may be concluded that RAC30% shows good durability performance and fulfils the durability requirement for this ingress mechanism.

## 3.11.2 Oxygen permeability

In oxygen permeability tests for both NAC100% and RAC30%, the average value of four specimens of the same mix sample is shown in Table 3. It was found that, RAC30% does not have much of an influence on the OPI value in comparison with NAC100%.

## 3.11.3 Water sorptivity

Better sorptivity values were found (shown in Table 3) for NAC100%. RAC30% shows 14% higher sorptivity than NAC100%, but RAC30% still satisfies the same range requirements as NAC100%. It can be seen that three specimens from NAC100% show mass gains equal to or less than 2 gram. One specimen shows a slightly higher mass gain than 2.5 gram. On the other hand, only one specimen from RAC30% shows a mass gain less than 2 gm. Old mortar in RCA increases the sorptivity of the concrete as a results, sorptivity values increase with increases of RCA in new concrete. Nevertheless, similar durability index categories were found for both NAC100% and RAC30%.

Table 3: Durability Index (DI) results of NAC100% and RAC30%.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| DI tests | Four disks of NAC100% | | Four disks of RAC30% | |
| Avg value | CoV (%) | Avg value | CoV (%) |
| *OPI* (Eq.4) | 9.61 | 44.9 | 9.78 | 19 |
| *CC* (mS/cm) (Eq.1) | 1.65 | 3.28 | 1.34 | 6.58 |
| *S* (mm/hr1/2) (Eq.5) | 7.1 | 20.2 | 8.1 | 32.4 |
| *p* (%) (Eq.6) | 11 | 10 | 10.8 | 9.8 |

## 4.0 Summary of results

On the basis of the experimental tests carried out in this work, 30% of coarse RCA can be replaced with NAC as a major aggregate in structural concrete in South Africa. It is argued that every country should have a guideline for using RCA in its various allowed applications, based on research results on local materials. It will help the user to use RCA in concrete with confidence, and enable that performance specifications are met. Before RCA is used in a particular application, it is recommended that contaminant materials are screened for and removed, and the physical properties (absorption, density, flakiness, crushing strength) are measured. No major differences in the mechanical behaviour and durability performance were found when compared with NAC for the same strength class of concrete. The surface texture and relatively higher absorption characteristics of RCA result in an increase in creep and shrinkage strain but it may possible to get the same quality of characteristics in concrete with 30% replacement of NA by RCA as in NAC. Similar shrinkage strain and durability index results have been found for NAC100% and RAC30% but more than 60% higher creep strain was found for concrete with 30% RCA replacement of NA. Better OPI and CC values found for RAC30% than NAC100%. However no major difference in results found for both concrete. RAC30% shows 14% higher water sorptivity than NAC100% but all the durability results still satisfy the quality and durability requirements of concrete suggested by South African research [17,18].

Based on the fresh and hardened property data from this research project, physical property requirements for RCA for use in normal strength structural concrete are suggested in Table 4. Once a more extensive set of data is available from different local materials, these guidelines may be refined.

Table 4: Accepted range of physical properties of RCA when NA30% will be replaced by RCA in structural concrete (C30-40 MPa strength class).

|  |  |
| --- | --- |
| Property | RCA |
| Relative density | > 2.5 |
| Fact value (kN) | > 120 |
| Water absorption (%) | < 4.5 |
| Flakiness index | < 25 |

## 5.0 Conclusion and recommendations

The trend towards urbanization world-wide has provided, and probably will continue to provide, a strong demand for high-volume, low-cost aggregate material for the repair and development of additional infrastructure. The total demand for aggregates, driven by demographics, urbanization and the economy, is expected to remain strong. Potential sources for recycled material increase as replacement of infrastructure continues. Because of the finite life of infrastructure, this “urban deposit” may be considered a renewable resource. From the experimental results reported in this paper, the following conclusions can be drawn:

Generally RAC leads to a lower workability of fresh concrete than NAC, but it is possible to get similar workability for NAC and RAC by preparing the aggregates to be SSD before mixing.

It is possible to obtain concrete cube/cylinder strength of 40/32 MPa with RCA with a specific gravity of more than 2.5 and absorption of less than 4.5%, without changing the water/cement ratio. In this paper RCA with densities in the range 2.48 to 2.54, and absorption of 3.49% to 5.24% were used with w/c=0.5 and 0.55, with insignificant influence on compressive strength even with 100% replacement of NA of density 2.74 and absorption 0.65%.

For the same range in RCA properties as stated above, 100% replacement of NA led to a reduced average E-modulus from 36 GPa to 28 GPa. However for 30% replacement the E-modulus remained unchanged at 36 GPa.

There are indications that higher quality RCA (as used for instance in step 3 of this research) contributes towards higher E-modulus of concrete. However, a larger statistical base must be built to confirm this.

RCA in concrete leads to a reduction in the splitting and flexural strength, in this research to the value of 10% and 1% respectively for splitting and flexural strength at a level of 30% RCA, and 17% and 18% respectively at 100% replacement of NA with RCA.

30% replacement of NA with RCA of type 3 in this research led to a 2% increase in average 90 day shrinkage strain compared with concrete containing 100% NA.

Total strain under a sustained stress of 12 MPa, roughly 40% of the compressive strength, after 90 days of exposure to a laboratory controlled climate at roughly 23oC and 65 % RH was 20% higher for concrete where 30% of NA was replaced with RCA of type 3 in this research. By subtracting the elastic and shrinkage strains from the total strains to obtain the creep strains, a 67% higher creep strain is found for RAC30% than for NA100%. Such a difference in long term deformation under sustained load must be considered by designers.

Similar durability performance can be achieved by RAC30% as for NAC100%. RAC30% was found to have an average 14% higher sorptivity, 2% higher oxygen permeability, but 23% lower chloride conductivity than NAC100%. In terms of these durability indexes, the RAC30% is found to be within the same durability categories of good to excellent [17, 18] as NAC100% tested here. A larger statistical base should be used to confirm these results.

Finally in conclusion, structural concrete with target strength 30 - 40MPa cube strength, the RCA may comprise up to 30% of the total weight of coarse aggregate, without special mix adaption apart from saturated surface dry preparation of all aggregates to ensure good workability. However, the long term effects must be considered carefully in the particular application. Further studies are proceeding at Stellenbosch University to refine the characterisation of RCA in South Africa, with the intention of deriving sound guidelines for using local RCA in structural concrete.

**Acknowledgement**

The assistance and facilities sharing with Prof EP Kearsley of the University of Pretoria (creep frames), Prof MG Alexander and Dr H Beushausen of the University of Cape Town (durability testing) are gratefully acknowledged.

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