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Influence of Recycled Coarse Aggregate on some Properties of Fresh and Hardened Concrete

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Abstract

Sustainable development in the construction industry has become a major concern over the years mainly driven by the waste produced during construction, but more particularly, during demolition and/or destruction of concrete structures. Due to this ever increasing amount of concrete waste, the idea of recycling such waste to produce aggregate for use in construction has been increasingly encouraged, thereby promoting the use of a substitute for natural aggregate. In the present study, experimental investigations were based on recycled coarse aggregate (RCA) obtained from crushing waste concrete (broken kerb stones) found at the University of Botswana Academic Hospital construction site. The focus of the research was ascertaining the workability of the fresh concrete as well as the 28-day compressive strength for concrete with varying RCA content of 0%, 25%, 50%, 75%, and 100%. Five mixes with water-cement ratio of 0.45, and another five with a water-cement ratio of 0.5 were utilized for this purpose. It was found that for both water-cement ratios, the slumps of the fresh concrete progressively reduced with increase in the level of RCA replacement. There was broadly a decrease in the 28th day compressive strength with increase in the RCA content. However, the 50% RCA concrete mixes of both water-cement ratios produced very similar compressive strengths to those of the controls.

Keywords: *Sustainability, recycling, coarse, aggregate, slump, concrete, strength.*

1. Introduction

Wastes from construction and demolition works have increased tremendously over the last few decades. Lack of waste management is problematic to environmental sustainability, and mitigation measures are recommended to reduce the adverse effects of this neglect on climate change [1]. Adoption of sustainable concrete construction is one of the mitigation measures required to deal with this issue. At present, concrete waste disposal continues to pose a serious problem in the construction industry. In Japan for example, according to Tomosawa and Noguchi [2], concrete waste is said to be largely dumped into landfills while a smaller proportion is used in the construction of roads, raising concerns with regards to environmental waste disposal. Increasing unavailability of space for landfills, the cost of dumping waste in landfills and the attendant environmental issues are factors that promote the recycling of concrete [3]. Most of this material would be from demolition works, or to some extent, from construction sites containing discarded or unused concrete. According to Ajdukiewicz and Kliszczewicz [4], the re-use of aggregate from demolished concrete structures has been viewed in the context of environmental conservation as the resolution of the escalating waste storage crisis and the preservation of dwindling or inadequate natural sources of aggregate. Sérifou et al [5] opined that in Aquitaine, France, production of natural aggregate became a considerable problem such that recycling of concrete to produce aggregates had to come into play. However, they also state that the use of fresh concrete wastes is more preferable than employing demolition waste because the former has far more likelihood of containing relatively less impurities. In Botswana, Kgosiesele and Zhaohui [6] have noted the environmental problems posed in recent years by the careless dumping of wastes. A similar trend had earlier been observed by Macozoma [7] in the Republic of South Africa in respect of construction and demolition (CD) wastes.

It was on account of the previous reasons that Franklin and Gumede [8] undertook a comprehensive review on the strength of concrete utilizing recycled coarse aggregates (RCA) sourced from CD wastes. They noted that there was a lack of studies in the South African sub-continent on the subject. Subsequently in Botswana, Gumede and Franklin [9] initiated a programme of study on the compressive and flexural strengths of RCA concrete collected from a major landfill site in Gaborone the capital city. They found that with increasing RCA replacement of natural coarse aggregate, the densities as well as the compressive and flexural strengths of concrete are progressively reduced in relation to the control concrete. The focus of the present study however is on RCA sourced from building debris and fresh concrete wastes. A primary aim of the investigation is to assess the effect of the level of RCA replacement on the workability, density and strength of the concrete.

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2. Experimental Details

Two types of aggregates were used to perform the study, namely natural aggregate (fine and coarse) as well as recycled coarse aggregate.

2.1 Recycled Coarse Aggregate (RCA)

The RCA used in the study was obtained from crushing broken and unused kerb stones collected from the University of Botswana Academic Hospital construction site. The kerb stones were cleaned and broken down into sizes small enough to fit into the jaw crusher. For further size reduction the jaws of the crusher were opened to a width of 19mm to produce aggregate of desired nominal size. A large percentage of the aggregates obtained from the jaw crusher were angular-shaped with sharp edges, while some aggregate were elongated; the observed texture of all the recycled aggregates was rough. It was also observed that after crushing, some of the aggregates were found to have the desirable width along a single dimension, that is to say, the largest available aggregate size in the crushed sample measured 19mm or less along one direction and greater than 19mm along the other directions. Consequently during the sieve analysis testing, most of such aggregates were retained on the 19mm sieve. To account for this, the aggregate were fed into the jaw crusher at least twice to increase the chances of having most of the material at nominal measurements. In the present study, it was observed that for recycled aggregate obtained from the jaw crusher (termed as combined recycled aggregate, comprising fine and coarse particles), the percentage of fines increased with the number of times the aggregates were crushed. It was also observed that the resulting shape and texture of the aggregates during crushing were greatly dependent on the amount of cement paste adhered to individual parent aggregate found in the combined recycled aggregate. More cement paste adhered to a parent aggregate particle meant a more angular-shaped and sharp-edged recycled particle and a rougher texture, while less cement paste gave a less angular shape with a smaller degree of roughness. The RCA was obtained through separating the fines portion (most of the material passing through sieve size 4.75mm) from a sample of combined recycled aggregate. The sieve analysis test was carried out in accordance with the ASTM C136 standard [10]. The results are shown in Figure 1. This coupled with further analysis, confirmed that the sieved sample had a single-sized gradation without fines.

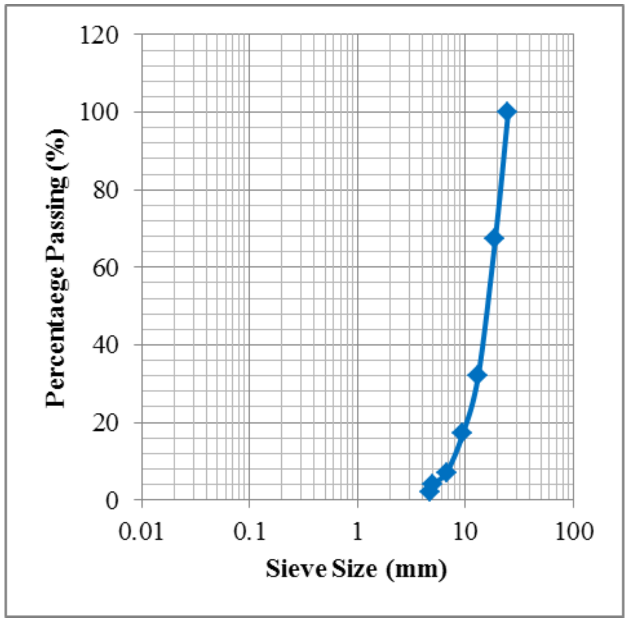

Fig. 1 Particle size distribution of RCA sample

2.2 Natural Aggregate

Two types of natural aggregate were used in this study: fine aggregate and coarse aggregate. The natural coarse aggregate (NCA) had a fairly rounded shape and a medium texture (intermediate of smooth and rough) in comparison to the RCA. The natural fine aggregate (NFA) was synthesized from crushed rock with fairly angular shape and a rough texture. Crushed stone has a general tendency to produce more angular and elongated aggregates [11]. Such aggregates have a higher surface to volume ratio and superior bonding characteristics, although as a consequence, the workability of concrete is reduced.

2.3 Specific Gravity and Water Absorption

The adhered cement paste of RCA affects the absorption potential of the aggregate. According to Tsujino et al [12], the presence of the adhered cement paste has been reported to increase the absorption capacity of aggregate and adversely affect the properties of concrete such as the workability of fresh concrete, and the density and possibly the compressive strength, of hardened concrete. This is on account of the adhered mortar being more porous than the natural aggregate. The specific gravity and water absorption of the RCA were determined in accordance with the ASTM C127 standard [13] to predict the amount of water to adequately hydrate all dry ingredients as well

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as to further adequately moisten all RCA in the fresh concrete mix. The bulk specific gravity, G_{sb} is given by Equation (1) as follows:

$$G_{sb} = \frac{W_{od}}{W_{ssd} + W_{pycno,water} - W_{pycno,ssd,water}} \quad (1)$$

where W_{od} is the weight of aggregate in an oven dry state, W_{ssd} is the weight of aggregate in a saturated surface dry state, $W_{pycno,water}$ is the weight of pycnometer and water, and $W_{pycno,ssd,water}$ is the weight of aggregate in a saturated surface dry state, pycnometer and water.

The bulk specific gravity of natural coarse aggregate was found to be 3.028 in contrast to the slightly lesser value for RCA of 2.973. The closeness of the estimates might be due to loss of a large amount of adhered cement paste from the RCA during crushing. However, the presence of adhered cement paste makes the aggregate become less dense because the ratio of the volume to mass of the RCA is comparatively less than what it would have been without the adhered cement paste. Hence in general, concrete with more natural coarse aggregate content is expected to be denser than concrete with more RCA.

The moisture content, m_c and the absorption, a_m of the RCA were used to alter the batch weight of water to cater for the actual moisture condition of the aggregate. The absorbed moisture for the RCA is given by Equation (2) as follows:

$$a_m = 100[(W_{ssd} - W_{od}/W_{od})] \quad (2)$$

The absorbed moisture and moisture content for the RCA were found to be 2.668% and 1.051% respectively. Consequently the aggregate will absorb water from the concrete mix, leading to a reduction in the workability of the concrete, unless its absorption value is incorporated in the mix proportion design. For comparison purposes, the preceding exercise was also carried out on the natural coarse aggregate (NCA). The absorbed moisture and the moisture content of the NCA were found to be 0.272% and 0.193% respectively. Hence the NCA should absorb water from the concrete mix. However due to the relatively small difference between the two value in this case (less than 0.1%), the water absorbed will be somewhat insignificant. With respect to the RCA therefore, the altered weights of batched water for all the different concrete mixes was computed using Equation (3) as follows:

$$W_{bw} = W_{dw} - [W_{dc}\,(m_c - a_m)/100] \quad (3)$$

where W_{bw} is the adjusted weight of water to be batched in the mix, W_{dw} is the weight of water in the mix design, and W_{dc} is the weight of RCA in the mix design. The changes in the amount of water for the mix designs before and after adjustment are illustrated in Figure 2.

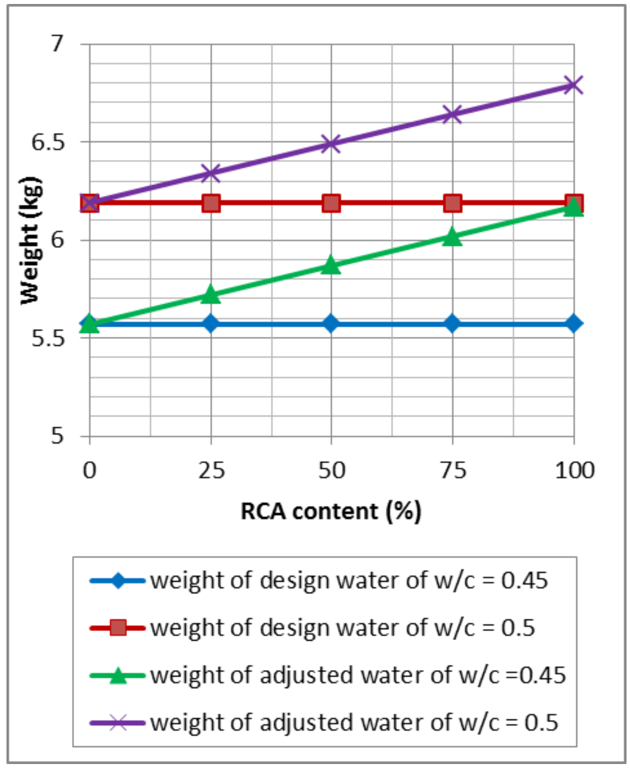

Fig. 2 Water used per 150 mm cube versus corresponding RCA content

2.4 Portland Cement

The type of cement used in this study was BOTCEM characterized by the strength class of 32.5R. According to the Pretoria Portland Cement Company Limited, PPC [14], BOTCEM is manufactured in accordance to the SANS 50197-1 standard, and it is identified as Cement CEM II/B-W 32.5R.

2.5 Water

Potable water, in compliance with the ASTM C1602 standard [15], was used in making the fresh concrete mixes in the study. The reason for using potable water was because it had no deleterious substances that might affect the strength gain in the concrete mixes. According to Kosmatka et al [16], excessive impurities affect setting time and concrete strength. Additionally, efflorescence, staining, corrosion of reinforcement, volume instability, and reduced durability may also be caused due to impurities in mixing water.

2.6 Mix Proportion

The typical mix design proportions used in this study was 1:2:3 of cement to fine aggregate to coarse aggregate respectively. In order to carry out the study effectively, different design mixes incorporating the RCAs were adopted. For improved accuracy, two water-cement ratios of 0.5 and 0.45 were also adopted. The design mixes are tabulated in Table 1. The masses indicated are per 150 mm concrete cubes.

Table 1: Masses of dry materials required

Mix no.	1	2	3	4	5
RCA (kg)	0%	25%	50%	75%	100%
	0.00	1.03	2.06	3.10	4.13
NCA (kg)	100%	75%	50%	25%	0%
	4.13	3.10	2.06	1.03	0.00
NFA (kg)	2.75				
Cement (kg)	1.38				

2.7 Mixing and Casting

Fresh concrete was cast into 150mm cube moulds after mixing in a concrete mixer. Addition of concrete ingredients into the mixer was performed strategically by firstly adding dry ingredients and thereafter, adding water. The dry ingredients were added according to the following sequence – coarse aggregate, then cement and finally, fine aggregate. This sequence was adopted for the purpose of preventing cement particles from escaping in the form of dust by weighing it down with the fine aggregate. After the addition of water, all ingredients were mixed until the fresh concrete had an even appearance as well as an even distribution of particles throughout the entire mix. Mixing for extended periods of time was avoided to prevent segregation of aggregate from the cement paste. Immediately after casting, cubes containing fresh concrete were placed on a vibrating table to compact the concrete and to eliminate any honey-comb structure that would likely manifest in the concrete. Vibration was carried out with great care to prevent segregation of cement paste from aggregate and subsequent cement paste bleeding.

2.8 Curing

The curing process was performed in compliance with the ASTM C192 standard [17]. Covering of the fresh concrete cubes for at least 24 hours with an impermeable membrane of plastic sheathing was carried out immediately after compaction on the vibrating table, to prevent excessive loss of moisture. This allowed the fresh concrete to reach its final setting time and ensured full normal hydration of the cement. After 24 hours, the concrete cubes were fully immersed in a water tank filled with potable water to help accelerate the rate of gain of strength of concrete. The curing periods adopted were 7, 14 and 28 days as required.

2.9 Compressive Strength Testing

All concrete cubes were crushed using a 3,000 kN compression testing machine. According to Rahman et al [18], the strength generally gives an overall picture of the quality of concrete that is directly related to the structure of the hydrated cement paste. The mass of each concrete cube was determined and recorded. For each curing period, three concrete cubes were tested and their mean crushing strength was taken to be the average compressive strength.

3. Results and Discussion

3.1 Workability and Slump

Workability of a concrete mix is highly dependent on its measured slump. However, the water-cement ratio is a variable that governs the consistency, slump and workability of the mix. The slump test was performed in accordance with the ASTM C143 standard [19]. It was observed that even with the largest re-adjustment of water content in each mix, as a way of catering for absorbed moisture and moisture content of the RCAs, the slumps were not affected by increment of water by mass. Figure 3 suggests that there was a decrease in the slumps of the concrete mixes with respect to increment of RCA content; the concrete mixes of 0% and 25% RCA content recorded the highest slumps while those of 75% and 100% gave the lowest slumps. These findings are in agreement with the observations of Gumede and Franklin [9] in their studies based on CD wastes. A possible explanation here can be attributed to the increased inter-particle friction between angular-shaped particles with increment in RCA content. This, coupled with the greater surface area for angular particles, would lead to the production of concrete with lower workability, according to Patil et al [20].

3.2 Compressive Strength

The compressive strength of the various concrete mixes can be influenced by several factors. These factors include properties of aggregate used in the concrete mixes, the water-cement ratio, the amount of adhered cement paste on the RCA, and the amount of RCA in the mixes. Figures 4 and 5 show the variation of strength development of concrete with different curing periods. It is observed that with increase in curing period, there is an apparent increase of compressive strength regardless of the percentage of RCA replacement. The results also indicate that there is an

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increase in compressive strength with reduction in water-cement ratio, as would normally be expected. Generally, concrete mixes with water-cement ratio of 0.45 exhibited more strength gain over the 28-day curing period than mixes with water-cement ratio of 0.5. However, there were instances where concrete mixes with water-cement ratio of 0.5 had a higher rate of strength development as compared to some of those with water-cement ratio of 0.45. Such instances were noticed in concrete mixes of 25% and 50% over the curing periods of 14 to 28 days.

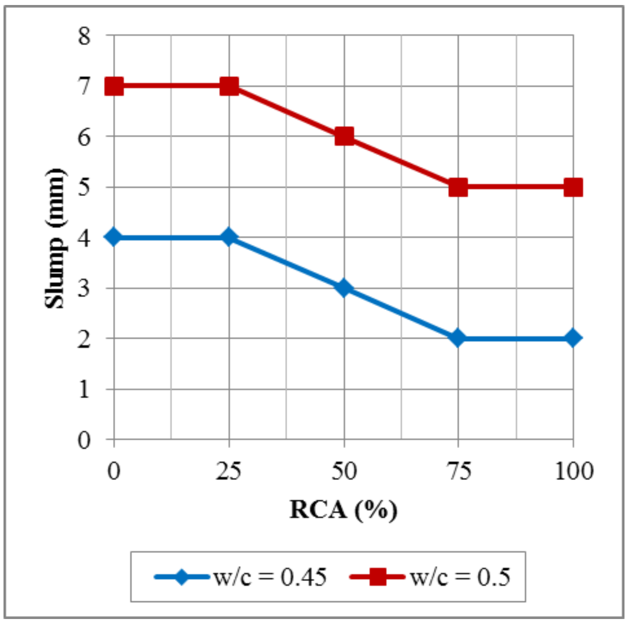

Fig. 3 RCA contents and corresponding slumps for both w/c ratios

It is obvious from Figure 6 that with increase in RCA content, there is in broad terms a decrease in compressive strength. At the water-cement ratio of 0.45, the reduction for the RCA content of 100% is about 13.7% relative to the control specimen with 0% RCA content. For the water-cement ratio of 0.5, the corresponding reduction is 15.3%. These results are in agreement with those of Gumede and Franklin [9]. Concrete specimens with 50% RCA content show strength gain characteristics at 28 days similar to those of 0% RCA. This is illustrated in Figure 4, where the mix with 50% RCA content with water- cement ratio of 0.45 exhibited 99.4% of the compressive strength recorded for that with 0% RCA content. A similar scenario is noticed in the mix with 50% RCA content and water-cement ratio of 0.5 which gained 103.5% of the compressive strength observed for that with 0% RCA content (Figure 5). These results are similar to those observed by both Yong and Teo [21] and Patil et al [20], where the compressive strengths of specimens with 50% RCA content were in close proximity to the results of the control.

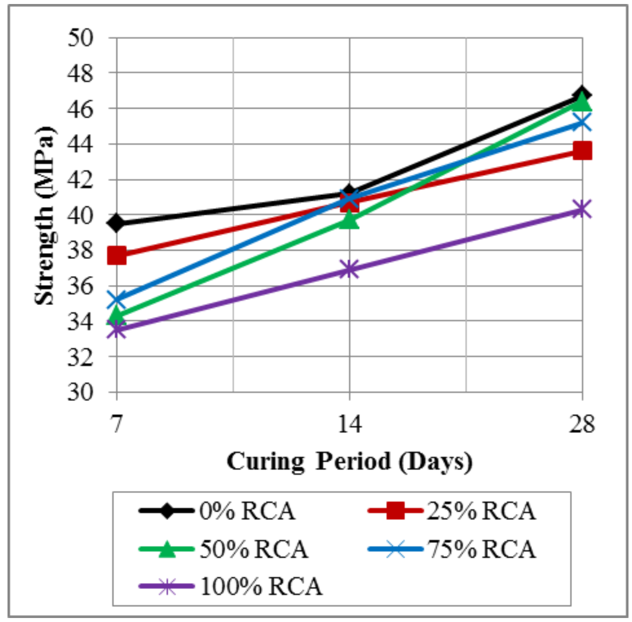

Fig. 4 Compressive strength of concrete cubes at w/c ratio of 0.45

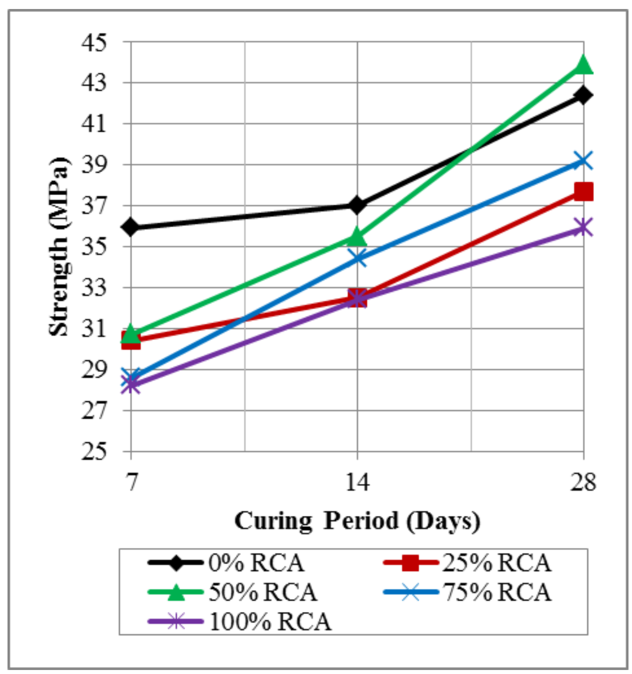

Fig. 5 Compressive strength of concrete cubes at w/c ratio of 0.5

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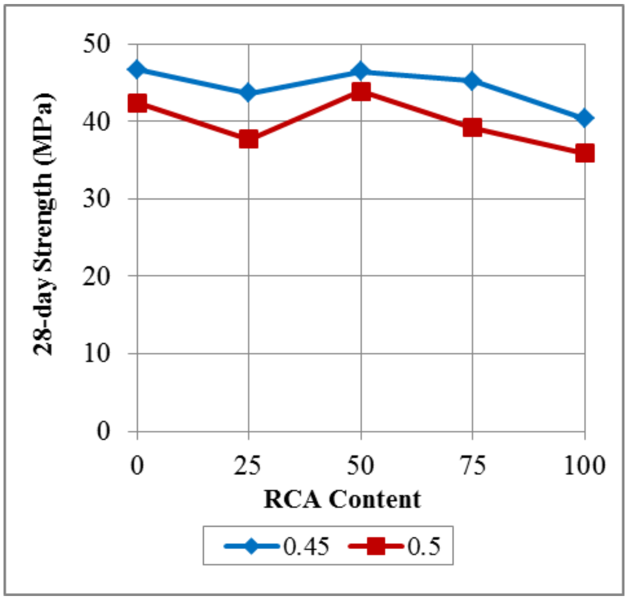

Fig. 6 Variation of compressive strength with RCA % replacement

The size of aggregate used in a concrete mix, however, also has an influence on the compressive strength values. Rahman et al [18] concluded that regardless of the size of aggregate used in a mix, the concrete cubes they tested had similar strength characteristics during the first 14 days of curing but this was not the case for the last 14 days. Concrete made from small-sized RCA revealed much higher compressive strength in the last 14 days of curing compared to concrete made with large-sized aggregate. An increase in size of RCA resulted in a consequent reduction in strength gain. With regards to the findings in the present study, these might have been affected by the lack of adequate distribution of aggregate particles to form homogenous mixes of fresh concrete. Shortage of an adequate amount of small size aggregate may lead to an increase of voids within the concrete mix. The voids then contribute to the porosity of the concrete and ultimately affect the compressive strength of the concrete.

The compressive strength of the concrete cubes may have been also affected by the shape and texture of the particles used in making the concrete mixes. The RCA employed in this study had angular shapes and sharp edges. Alexander and Mindess [22] have argued that the use of angular aggregates induces a higher degree of internal friction; hence higher concrete strengths may result, on condition that full compaction is achieved. Patil et al [20] have suggested that aggregate possessing more angularity and a rough surface texture tend to produce a higher mechanical bond between the fresh cement paste and the surface of the aggregate particle through interlocking, hence influencing the strength of the aggregate. However, the shape and texture of the aggregate particles also influence the workability and slump of fresh concrete as noted earlier.

Another factor that might have influenced the compression test results is the amount of old cement paste on the RCA. According to Etxeberria et al [23], the amount of cement paste adhered to the surface of the RCA contributed to the loss of 28-day strength gain with increase in recycled aggregate content. They mentioned that the loss of strength gain is due to the weak mechanical bond formed between the hardened cement paste and the fresh cement paste. Sérifou et al [5] have noted that during compression testing, cracks and fissures in concrete with RCA content are created on the transition zone between the old cement paste and the parent coarse aggregate sooner than in other areas. As a consequence, the old cement paste is the weak point in recycled aggregate concrete.

3.3 Bulk Density

According to Osei [24], the various concrete mixes that fall within the range of 2,200 – 2,600 kg/m^3 are regarded as concretes with normal weights. In the present study, the masses of all concrete cubes were weighed prior to crushing. Densities of concrete cubes were calculated from their corresponding masses. Figure 7 shows the variation of the average densities of the concrete with RCA replacement levels. The densities of the concrete mixes reduce gradually with increase in recycled aggregate content. Concretes of 0% RCA possess the highest densities while those with 100% RCA the lowest. In the concrete with a water-cement ratio of 0.45, the reduction in densities at the 50% and 100% RCA replacement levels is 2.8% and 5.1% respectively. For the water-cement ratio of 0.5, the corresponding reductions are 2.3% and 4.7%. A possible explanation for this phenomenon is due to the presence of adhered mortar. RCA contains adhered cement paste, and several investigators including Rao et al [25], Kumutha and Vijai [26] and Gumede and Franklin [9] have stated that RCA concrete is less dense compared to natural coarse aggregate concrete. The higher porosity of the RCA gives rise to higher air content for the recycled aggregate concrete

It is obvious from Figure 7 that densities of specimens with similar RCA content fall within specific ranges, irrespective of the water-cement ratio. The recorded low densities of concrete with increasing RCA content is due to shortage of an adequate amount of fine aggregate within an interlocking matrix of angular-shaped particles. With increase in RCA content, there is a consequent increase in angular-shaped particles which tend to not compact easily due to increased inter-particle friction.

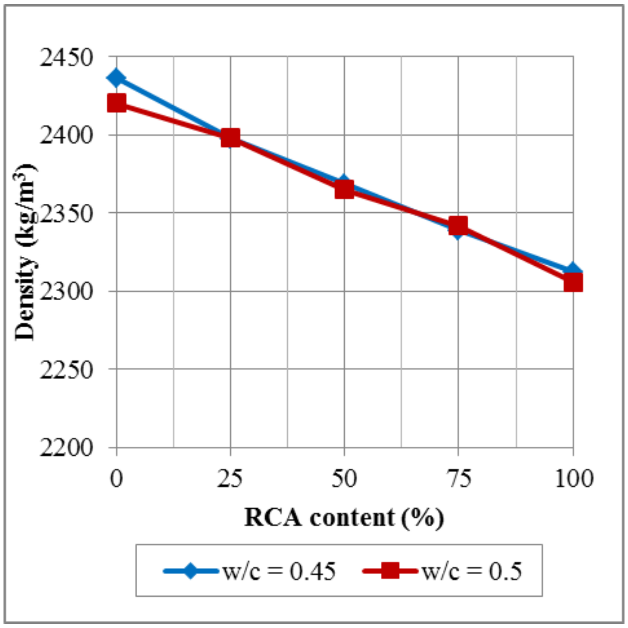

Fig. 7 Average densities of concrete cubes vs. RCA content

4. Conclusions

One main aim of the study reported herein was to assess the influence of varying levels of RCA content on the workability, density and strength of the concrete. Based on the work carried out, the following conclusions have been reached.

Firstly, with increase in RCA content, there is in broad terms a decrease in compressive strength. For the water-cement ratio of 0.45, the reduction for an RCA content of 100% is about 13.7% relative to the control; the corresponding value at a water-cement ratio of 0.5 is 15.3%. Additionally, the concrete specimens with 50% RCA contents give very similar compressive strengths at 28 days as those of the control specimens with 0% RCA, for both water-cement ratios utilized in the study. This demonstrates that concretes containing up to 50% RCA replacement content have potential as substitutes for natural coarse aggregate concrete. Thirdly, the compressive strength of concrete containing RCA increases with decrease in water-cement ratio. This is true for all levels of percentage RCA content. Furthermore, the use of RCA as replacement for natural concrete aggregate in concrete production can result in concrete whose density is 5% less, as compared to the control specimens. This throws open the possibility of attaining relatively lighter weight concrete for structural purposes. Finally, the presence of the old adhered cement paste in RCA contributes significantly to its higher water absorption capacity as compared to natural coarse aggregate concrete.

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