Short-Term Mechanical Properties Of Recycled Coarse Aggregate Concrete

Part B: Response To Impact Loading

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***Abstract*—This work forms part of a larger study into the effective usage of recycled coarse aggregates in building and environmental engineering. In the present investigation, coarse stones sourced from mortar bricks were utilized as replacement for natural aggregates in proportions of 0%, 20%, 40%, 60%, 80% and 100% for the production of concrete. Impact loading tests were conducted on manufactured beam specimens after 3, 7, 10, 14 and 21 days of curing. It was observed that the mean impact resistance over the range of curing days for both initial cracking as well as ultimate failure decreased with increase in the recycled coarse aggregate (RCA) fraction. In addition the difference in the mean number of blows required to cause ultimate failure and to initiate the first cracking reduced as the percentage of RCA fraction in the concrete mix increased. However the mean residual strength impact ratio over the range of curing days was approximately constant at 1.30, irrespective of the percentage RCA employed. It was concluded that additional impact tests would need to be carried out in order to provide a more complete evaluation of the response of RCA concrete beams to impact loading.**

Keywords—Recycled; coarse; aggregates; fractiion; impact; strength

I. INTRODUCTION

It can be argued with some justification that concrete has been the predominant construction material since the first quarter of the 20th century. The reasons for this are easily discernible. Concrete can be molded into a great variety of shapes, and in addition, it possesses good durability as well as erosion and fire resistance characteristics. Additionally, its constituent components can be sourced from almost every part of the globe. Finally, in recent decades, newer applications and developments such as high performance and self-compacting concretes, as well as fibre-reinforced concrete composites have arisen in concrete technology to enhance the already pre-eminent role of concrete in the built environment. However this ubiquitous nature of concrete coupled with the fact that its constituents make up a sizeable portion of the earth's raw materials has meant that far too numerous buildings and infrastructural facilities on completion of their service lives have become environmental concerns, both in terms of occupying useful spaces if left in place as well as presenting formidable challenges in respect of demolition and disposal. The latter is on account of the fact that the disposal of construction and demolition wastes in retrospect has not been handled as effectively and efficiently as possible. Construction and demolition wastes in the form of concrete products have all too often been disposed indiscriminately, leading to unwarranted environmental degradation [1].

Fortunately with reference to the above issues, there has been a growing awareness in recent decades of the potentials offered by the adoption of recycled aggregate concrete. Not only can the demolished concrete be broken to recover the crushed coarse aggregates, but also the latter can be utilized in the production of new concrete or more precisely, recycled coarse aggregate concrete (RCAC). It has been suggested that this RCAC could be usefully employed in a number of structural and non-structural applications such as road and pavement construction, bulk fills, embankment protection and noise barriers [2]. There are yet further potential applications for RCAC composites with the addition of materials such as fly ash, diverse forms of fibres, etc., all with the aim of modelling, improvement or enhancement of certain aspects of their mechanical characteristics [3]–[10].

The mechanical characteristics of RCAC have been the subject of considerable investigation; such studies have generally covered the compressive, flexural and tensile strengths. The impact strength of RCAC has not been researched to the same extent. One probable reason for this has been the observations that the results obtained from drop weight impact tests recommended by the ACI Committee 544 [11] exhibited poor correlation with the normal distribution, and as a consequence, proposals that such tests should be modified or completely discarded in preference for a more reliable alternative [12]. The foregoing notwithstanding, the need for additional impact strength testing of RCAC is still pressing. Such testing is required to provide valuable information on the failure of RCAC under impact loadings, the effects of variation of recycled coarse aggregates on the mechanical properties of RCAC, and the effects of gradation of aggregates on the mechanical performance of RCAC, amongst others.

With respect to the failure of concrete structures under high loading rates like debris impact and explosions, Weerheijm and van Doormaal [13, 14] stated that during the failure process, deformation and kinetic energy of the surrounding material at the point of application of the load is released into the fracture zone and cracks are formed. Rao et al. [15] subjected RCAC beams to low velocity drop weight impact loads. Recycled coarse aggregates (RCA) were utilized in lieu of natural coarse aggregates (NCA) in proportions of 0%, 25%, 50% and 100% RCA. It was observed that 25% RCA does not influence the strength of the concrete. Also the failure patterns of both normal and recycled aggregate concretes were closely related. Both concretes failed between 15 and 17 impact drops, and all beam specimens failed with the application of 1 to 2 extra drop loads after the first cracking. Vegt et al. [16] found that the failure of concrete was marked by the existence of a lot of micro-cracks that developed into macro-cracks. Their conclusions were in agreement with those of Rao et al. [15] in that failure was deemed to occur at the interface of the aggregates and the cement paste when specimens were subjected to impact loading.

Concerning the effects of variation of RCA on the mechanical properties of RCAC, Ismail and Ramli [7] conducted a study of three different categories of concrete, – natural, recycled aggregate, and recycled aggregate with fibres. They found that the impact value of the RCA was lower than that of the NCA, and that RCA contributed to the reduction of both the mechanical strength and the modulus of elasticity of the concrete. They also opined that the weak interfaces existing between the cement paste and aggregates contributed to the cracking of the concrete, in line with the findings of Rao et al. [15]. The results of Gao et al. [17] concurred with those of Ismail and Ramli [7] as they stated that comparison of natural aggregate concrete with RCAC containing 100% recycled aggregate for the same mix proportions caused the compressive strength to reduce by 9%, the tensile strength by 7% and the compressive and tensile elastic moduli reduced by 28% and 34% respectively. They suggested that the reduction of elastic modulus being significantly greater than the strength implied that the brittleness of recycled aggregate concrete was lowered and that its toughness was increased, despite the reduction of concrete strength caused by the addition of RCA. Furthermore they supported the notion that this replacement was positive to the impact resistance performance of RCAC in deference to natural concrete. However for them to improve this property even further, it was expedient to add steel and/or polypropylene fibres.

Kien et al. [18] found however that when natural aggregates were replaced by 100% RCA, the compressive strength at 28 days was decreased by 19%. Lu et al. [19] on the other hand contradicted Gao et al. [17] by stating that the efficiency of absorbing impact energy of natural aggregate concrete (NAC) was greater than that of recycled aggregate concrete (RAC); this was on account of the fact that the specific energy absorption and its increase velocity was greater for NAC specimens than for RAC specimens. Lu et al. [19] concluded that NAC absorbed impact energy relatively better, and consequently had the greater impact resistance when compared to RAC. Yehia et al. [20] as part of their investigations reviewed previous research on the physical and mechanical properties of fine and coarse recycled aggregate concretes. They suggested that 50% to 100% replacement of natural aggregates with recycled ones decreased the compressive strength by 5% to 25%. This broadly agreed with the findings of Gao et al. [17] and Ismail and Ramli [7]. Yehia et al. [20] furthermore stated in their review that up to 30% virgin aggregates could be replaced with RCA without compromising the concrete strength.

With regards to the effect of gradation on the mechanical properties of RCAC, Brown and Bassett [21] asserted that the presence of contents smaller than the number 200 sieve (or 0.075 mm) in the concrete mix was destructive and detrimental towards achieving desirable mechanical properties of concrete for construction. Brown and Cooper [22] conducted investigations on roadway bituminous base materials employing various gradations with maximum aggregate size up to 40 mm. They found that aggregate gradation had a significant effect on permanent deformation. Mixes with dense-graded and gap-graded aggregates were compared, and the gap-graded mix suffered far more permanent deformation. These results would suggest that impact strengths of RCAC could be reduced on account of gaps in the coarse aggregate gradation. Brown et al. [23] in their study supported this assertion by stating that their test results proved that both stability and impact strength decreased as voids in the RCAC increased. Kozul and Darwin [24] opined in their research report that as the size of aggregates increased, the fracture energy of high strength concrete decreased, while the fracture energy of normal strength concrete and the aggregate size were directly proportional. They further asserted that there was an increase in fracture toughness of concrete with increase in coarse aggregate size. Strange and Bryant [25] and Giaccio et al. [26] had earlier also concluded that the fracture energy increased with increase in coarse aggregate size.

The present investigation forms part of a wider based study into the mechanical properties of recycled coarse aggregate concrete being carried out at the University of Botswana [2]. In contrast however to a number of previous studies, it is the short-term impact loading response of RCAC that is of special interest. As a consequence of the widespread utilization and resultant proliferation of mortar bricks as construction wastes on numerous building sites, coarse aggregates were extracted from such bricks and utilized as recycled aggregates for the manufacture of concrete in the study detailed herein.

II. EXPERIMENTAL PROGRAMME

A. *Materials, mix proportioning and casting*

Ordinary Portland cement of specification 52.5 N, manufactured by PPC Ltd. was used for the study. It had initial and final setting times of 170 and 250 minutes respectively, a specific area (Blaine) of 400 m^2/kg, and compressive strengths at 2 and 28 days of 28 MPa and 58 MPa respectively. Also it had a relative density of 3.14 and soundness (Le Chatelier expansion) of 1.0 mm. Crushed fine aggregates passing a 4.75 mm sieve and possessing a fineness modulus of 3.12 and specific gravity of 2.34 was employed. This stone dust had a greyish black colour when dry, but appeared slightly reddish when wet. The natural coarse aggregates were obtained locally from Kgale Quarries. These were aggregates passing through a 19 mm aperture sieve and came from granite rock. They had a specific gravity of 2.64 and a fineness modulus of 2.59. Samples of the dry stone fine aggregate and natural granite coarse aggregate are shown in Figs. 1 and 2 respectively.

Fig. 1: Dry stone dust fine aggregate

Fig. 2: Natural granite coarse aggregate

For the recycled coarse aggregates, mortar bricks were acquired locally from Babirwa Bricks Industry and crushed using a hammer to reduce them to smaller sizes. Subsequently, a crushing machine was employed to reduce the materials sizes even further. The stones were all collected and sorted from the other mortar pieces by grading using sieves and a vibrating machine. Aggregates that passed through the 19 mm sieve but were retained by the 13.2 mm sieve were collected. These mortar stones served as the recycled coarse aggregates for the mix. They were used to replace the natural coarse aggregates in fractions of 20%, 40%, 60%, 80% and 100%. Samples of the recycled coarse aggregates are shown in Fig. 3.

Fig. 3: Graded recycled coarse aggregate

The mix design method adopted was that specified in the Department of Environment (DoE) revised procedure as described in [27]. Required information such as that from the sieve analysis of both coarse and fine aggregates was used in order to find the proportions of the concrete ingredients. Preliminary slump testing was also initiated in order to determine an acceptable mix for these proportions. The specification was for a characteristic compressive strength at 28 days of 50 MPa and a slump range of 30–60 mm. Due to the porous nature of mortar coarse aggregates, the water-cement ratio of every mix had to be adjusted in order to supplement the water that would be absorbed by the recycled coarse aggregates. From absorption tests carried out, the percentage absorption of water was found on average to be 7 % and the water-cement ratio was revised accordingly. Six different concrete mixes corresponding to the different RCA fractions were employed. For the control mix representing an RCA replacement fraction of 0%, a water-cement ratio of 0.47 was adopted. The cementitious materials, fine and natural coarse aggregates were kept constant at 447 kg/m^3, 662 kg/m^3 and 1081 kg/m^3 respectively representing a concrete mix ratio of 1:1.48:2.42 in proportions of cement, fine and coarse aggregates. However for the remaining five RCAC mixes, the water-cement ratios, the cement content and the fine aggregate content were kept constant at 0.5, 447 kg/m^3 and 662 kg/m^3 respectively. In the 20 % RCA replacement mix, the natural coarse aggregate (NCA) and the recycled coarse aggregate contents were 865 kg/m^3 and 216 kg/m^3 respectively. For the 40 % RCA replacement mix, the NCA and RCA contents were 649 kg/m^3 and 432 kg/m^3 respectively. These values were progressively adjusted for increasing RCA replacement fractions. For the 100 % RCA replacement mix, the NCA and RCA contents were 0 kg/m^3 and 1081 kg/m^3 respectively.

A total of seventy two (72) cubes of 100 mm sizes were cast for compressive strength tests, in addition to thirty-six (36) beams of dimensions 100 mm x 100 mm x 400 mm for the impact loading tests. The moulds for all specimens were provided by laboratory staff; all cast specimens were vibrated by means of a vibrating table and subsequently covered with wet hessian and translucent plastic sheets for 24 hours. They were then de-moulded and placed in a constant temperature curing bath for a total of 3, 7, 10, 14 or 21 days as required, prior to testing.

B. Testing methods

The tests on hardened concrete specimens were carried out at 3, 7, 10, 14, and 21 days after curing, for each recycled coarse aggregate replacement fraction. An Amsler compression test machine was utilized for the tests on the hardened cubes. The results of these tests had been reported earlier by the current investigators [28]. Hence no further details regarding the cube testing will presented hereafter. The impact loading tests were based on the principle of the free falling weight, and conducted on the hardened 100 mm x 100 mm x 400 mm concrete beams. In the absence of an international standard approved device, a representation of the free falling weight testing apparatus was fabricated. A rammer produced by ELE International and consisting of a guide sleeve and hammer was employed. Steel flat bars were welded to the bottom part of the guide sleeve in order to hold the specimens in place while the procedure was performed. The flat bars were connected in such a manner that they held both the long and short sides of the beam specimens. The hammer was the main component of this device as it represented a free falling weight which caused the impact load. The hammer had a constant mass of 2.5 kg and a diameter of 50.8 mm. The drop height was kept constant at 305 mm from the top surface of the beam. The guide sleeve was machined steel tubing with air pressure release vents at the bottom to allow the weight to drop freely without opposition by pressure in the tubing. The complete device, excluding the holding bars, had a mass of 4.1 kg. The device was fabricated in such a manner that the hammer made contact with the centre of the test beams with each drop, and the holding bars ensured that the eccentricity of the hammer was kept at zero to avoid any secondary effects.

The main concept of the free falling hammer involved changing the potential energy of the weight at the moment of release into kinetic energy at the moment of impact. The energy that was lost by the free falling hammer was equal to the energy that was gained by the concrete beam. The kinetic energy that the weight exerted on the specimen was equal to the impact energy absorbed by the concrete beam at the moment of impact. The testing apparatus is shown in Fig. 4. On each occasion during testing that the free falling weight was dropped unto the beam specimen, the device was lifted upwards in order to check for cracks or any irregularities. The testing procedure was closely monitored and controlled, and the number of blows that initiated the first cracking as well as produced ultimate failure was recorded.

Fig. 4: Free falling weight test and concrete beam

III. RESULTS AND DISCUSSION

A. Crack patterns

The free falling load caused cracking to initiate from the bottom of the beams as expected. The cracks did not begin exactly at mid-span, where the hammer hit the beam, but nearly adjacent. With subsequent blows from the hammer at a constant mass and rate, vertical cracks formed from the bottom to the top compression fibres of the beam. These cracks formed from both sides of the beams until they met at the top to form one complete crack that caused the whole beam to fail in the regions adjacent to mid-span. In general, the mean number of blows needed to cause initial cracking varied from approximately 14 to 6, for the RCA replacement ratios of 0% and 100% respectively. However to produce ultimate failure of the beam specimens, the mean number of blows ranged from approximately 18 to 8, for the RCA replacement fractions of 0% and 100% respectively. Typical crack patterns on the bottom face, on the compression face and immediately at ultimate failure are shown in Figs. 5, 6 and 7 in that order.

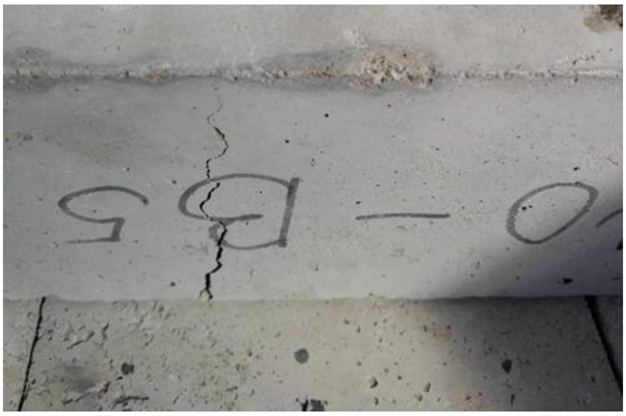

Fig. 5: Initial crack on bottom face of beam

Fig. 6: Cracking on top compression face of beam

Fig. 7: Crack pattern at ultimate failure

B. Impact tests

The impact testing was conducted with one specimen for 3, 7, 10, 14 and 21 days of curing for the 0%, 20%, 40%, 60%, 80% and 100% RCA replacement fractions. The average number of blows needed to cause initial cracking and ultimate failure was recorded. These tests were performed in order to investigate the frequency of impact loads that were required to produce failure of the beam specimens at the different RCA replacement ratios. With all specimens subjected to the same impact energy of 7.47 Joules and possessing a constant thickness of 100 mm, the mean impact resistance over the range of days was determined for the different RCA fractions. Fig. 8 shows the relationship between the mean number of blows to initiate cracking or to cause ultimate failure, and the RCA percentage fraction. It is apparent that in either case, the mean number of blows reduced as the RCA percentage in the concrete mix increased. Quite obviously beam specimens with 100% natural coarse aggregates proved to be the strongest, while those specimens with 100% RCA fractions were the weakest in respect of mean impact resistance.

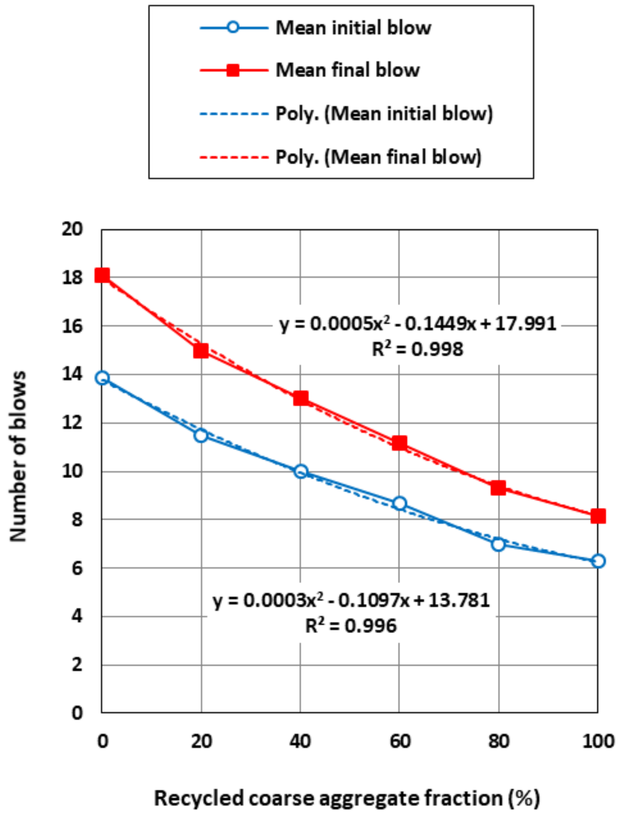

Fig. 8: Variation of mean number of blows with recycled coarse aggregate fraction

In Fig. 9 the variation in the mean additional blows required after first cracking to produce ultimate failure against the RCA percentage fraction is shown. It is apparent that the mean additional blows progressively reduced as the RCA percentage increased. In fact at least 4 additional blows were required for the specimens with 100% natural coarse aggregates, while approximately 2 extra blows were needed for beams with 100% RCA fractions. It is evident from Fig. 9 that the residual impact strength reduced as the RCA percentage increased.

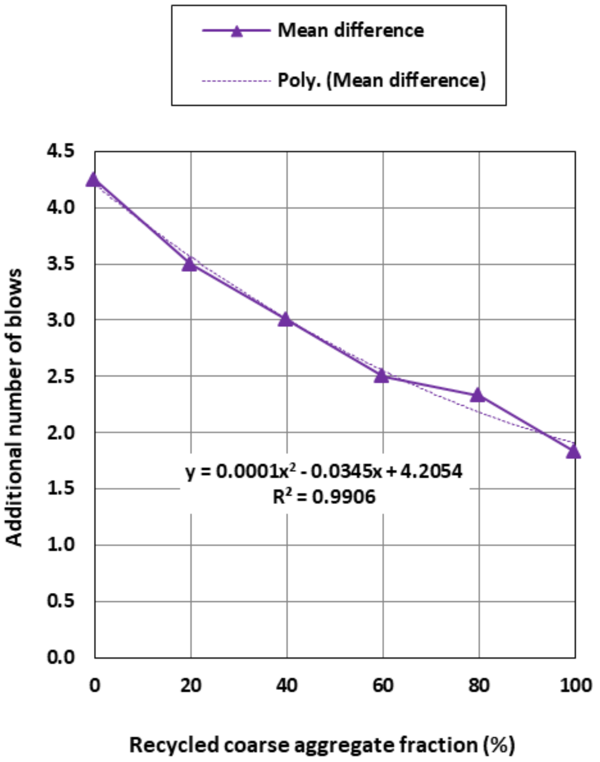

Fig. 9: Variation of additional number of blows with recycled coarse aggregate fraction

The results exhibited in Figs. 8 and 9 are in line with the findings of [7] and [15] who argued that the weak interface between the RCA and the cement paste could have contributed to the propagation of fracture in the concrete. In addition, the complementary studies of the present investigators [28] confirmed that the introduction of RCA definitely influenced the mechanical strength of the concrete. The results are also in agreement with those of [19] who stated that the critical compressive strain of RCAC was smaller than that of NAC specimens, and that the specific energy absorption of RCAC was lower than that of NAC specimens. Consequently it was concluded that the deformation capacity of RCAC was weaker than that of NAC, while the energy absorption capacity of RCAC was lower than that of NAC.

A further consideration worth noting at this stage was the fact that calculations not presented herein showed that the mean residual strength impact ratio over the range of curing days was 1.306 for the RCA fraction of 0% and 1.296 for the RCA fraction of 100%. In fact for the different RCA fractions employed in the present study, namely 0%, 20%, 40%, 60%, 80% and 100%, the mean residual strength impact ratio was 1.304, with a standard deviation of 0.0154. The foregoing notwithstanding however, it may be prudent to conduct additional impact tests in order to furnish a more complete assessment of the response of RCAC beams with varying RCA replacement ratios.

In respect of the effect of the aggregate type on the impact strength of RCAC, it should be stated here that the natural coarse aggregates utilized in the present study were obtained from crushed granite rock, while the RCA was sourced from crushed mortar bricks. Although the type of coarse aggregate does have an effect on the compressive strength of concrete as observed by [29] and [30] amongst others, it has not been demonstrated that the same is true for the impact strength and for the trend of results exhibited in Figs. 8 and 9. Furthermore concerning the influence of aggregate gradation on the impact strength, while the studies by [22] and [23] implied that gap-graded aggregates and increasing levels of voids in RCAC would negatively affect the impact strength of RCAC, there was no conclusive evidence that this indeed was the explanation for the results in the present study. It is apparent that further impact testing would be necessary in order to fully comprehend or establish the effect of gradation and aggregate type on the impact strength of RCAC.

IV. CONCLUSIONS

The work detailed herein was carried out in order to determine the short-term impact resistance of recycled coarse aggregate concretes containing different percentages of RCAs used as a replacement for natural coarse aggregates. The impact strengths were evaluated after curing at 3, 7, 10, 14 and 21 days. From the investigations carried out, the following conclusions have been drawn.

1. The mean impact resistance over the range of curing days for both initial cracking and ultimate failure decreased with increase in the recycled coarse aggregate replacement levels.
2. The difference in the mean number of blows necessary to initiate the first cracking and to cause ultimate failure reduced with increasing percentages of RCA fraction in the concrete.
3. The mean residual strength impact ratio over the range of curing days was approximately constant at a value of 1.30, regardless of the RCA percentage employed in the concrete mix.
4. Additional tests on impact loading of beam specimens are recommended in order to provide a more complete assessment of the response of RCA concrete beams, as well as to fully comprehend the effect of gradation and aggregate type on the impact strength of recycled coarse aggregate concretes.

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