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Experimental Investigation Into The Shear Behaviour Of Reinforced Recycled Coarse Aggregate Concrete Beams

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***Abstract*—The current study deals with the behaviour in shear of reinforced recycled coarse aggregate concrete beams. The recycled coarse aggregates (RCA) were sourced from crushed bricks obtained locally; these were used to replace natural coarse aggregates for five different concrete mixes in the proportions 0%, 25%, 50%, 75% and 100%. In addition forty five simply supported 600 mm long concrete beams with shear-span to effective depth ratios of 1.56, 1.85 and 2.27 were subjected to increasing three-point loading up until ultimate failure. Furthermore in order to assess the compressive strength of the concrete, one hundred and five 100 mm cubes were tested at 7, 14, 21 and 28 days after manufacture. It was found that there was an approximately linear decrease in slump with increasing RCA replacement levels as expected for the tests at the specified days. For the ultimate strength tests, the reinforced RCA concrete beams of 25% to 100% replacement content exhibited crack patterns very similar to the control. The common crack configurations across the beams were flexure-shear cracking, although the majority of the RCA concrete beams failed in shear-compression. The inclination angle of the diagonal cracks from the horizontal ranged from 25^{o} to 41^{o}. The shear strength decreased with increase in the RCA content as well as with increasing shear-span to depth ratios for all beams. It was suggested however that additional tests would be required to provide a more comprehensive picture of the response of reinforced RCA concrete beams in shear.**

Keywords—recycled; coarse; aggregates; compressive; shear; strength; replacement

I. INTRODUCTION

The adoption of recycled coarse aggregates has been seen in recent years as a necessary step in order to adequately address the environmental sustainability problem in civil and infrastructural engineering. In fact there is an increasing awareness within the construction and building industry globally that the utilization of recycled coarse aggregates to some degree, in lieu of natural coarse aggregates for the manufacture of concrete, goes a long way towards mitigating or reducing the stark short fall in the availability of non-renewable natural aggregates [1]. Recycled coarse aggregate concrete (RCAC) has been utilized in a number of low grade and low risk applications including roads and pavements, noise barriers, bulk fills and embankment protection. It has been stated that there are still additional potential applications of RCAC in the form of composites based on the incorporation of materials such as fly ash and diverse forms of fibres, etc. [2].

The mechanical properties and characteristics of RCAC have been the subject of numerous investigations in the past. These studies had in the earlier stages largely embraced the compressive, flexural and tensile strengths; more recently to some extent, durability considerations have been examined ([3], [4], [5]). In contrast, relatively fewer investigations have been carried out to study the behaviour under shear of recycled aggregate concrete structures such as beams and even slabs. Such studies are deemed important because for example in reinforced concrete beam design, shear failures may be sudden and explosive with little warning, a situation that could certainly undermine the flexural performance of such beams. A further consideration is the growing need for maintenance, repair or replacement of critical and ageing infrastructures such as highways, bridges and buildings as these systems approach the end of their service lives, aided by increasing urbanization as well as population and traffic growth. Consequently for the afore-mentioned reasons, a brief survey of previous research on the shear behaviour of recycled aggregate concrete beams will now be undertaken.

Ji et al. [6] reported tests on three reinforced concrete simply supported beams incorporating recycled aggregates to replace natural aggregates in the proportions 0%, 50% and 100%. The beams were subjected to four-point loading. It was found that one of the flexural cracks developed into a diagonal crack close to one support, or a diagonal crack developed suddenly at mid-height but within the shear span. In all cases, brittle failure occurred shortly afterwards. It was concluded that RCAC beams behaved in a similar manner in shear compared to beams with natural aggregates. Li [7] summarizing the work carried out previously by Chinese investigators stated that the recycled concrete aggregate (RCA) content played an important role in the shear capacity of recycled aggregate concrete (RAC) beams. There was a reduction of 10% to 17% in shear capacity for beams comprising concrete with 50% and 100% RCA contents compared to normal weight concrete. Furthermore, reductions in shear strengths up to 30% were observed in RAC beams for replacement contents in the range 0% to 100%. On the whole, three failure modes – diagonal compression, shear compression and diagonal tension failure were observed, dependent on the shear-span to depth ratio (a/d) in the RAC beams, similar to natural aggregate concrete beams.

Choi et al. [8] tested twenty RAC beams with shear-span to depth ratios (1.50 – 3.25), longitudinal reinforcement ratios (0.53% – 1.61%) and recycled aggregate contents of 0%, 30%, 50% and 100%. Their results suggested that the concrete shear strength reduced by up to 30% at 100% replacement ratio. The influence of replacement levels of RCA on the shear performance of reinforced concrete beams without shear reinforcement was examined by Yun et al. [9] who conducted large scale tests on beams of dimensions 0.4m x 0.6m x 6m with a shear-span to depth ratio of 5.1, and RCA replacement contents of 0%, 30%, 60% and 100%. The results showed that shear strengths and deflections were only slightly affected by the varying RCA replacement percentages. Furthermore the RCA concrete beams exhibited similar cracking patterns and failure modes to those of normal concrete, although shear failures were more sudden and explosive in the RCA specimens.

An investigation on the shear strength of reinforced concrete beams with 100% RCA was conducted by Arezoumandi et al. [10] using twelve full scale specimens. It was concluded that the RAC and natural concrete beams behaved similarly in respect of crack development and load-deflection response. However their analysis demonstrated that the 100% RCA beams had approximately 12% lower shear strength in comparison to the normal concrete beams. Aly et al. [11] tested sixteen simply supported 2m span beams subject to four-point loading in order to assess the effect of RCA levels and shear-span to depth ratios amongst others, on the shear behaviour of RCAC beams. The shear capacity of tested specimens was found to increase as the RCA ratio increased up to 50%. Beyond this level, a reduction in shear capacity was observed. Also as expected, there was a reduction in shear strength with increase in shear-span to depth ratios, and beams with lower shear-span to depth ratios exhibited higher inelastic deflections at failure.

Khergamwala et al. [12] studied the shear behaviour of RAC beams with 25% and 50% recycled aggregate ratios by weight in lieu of natural aggregate. Three different shear-span to depth ratios (a/d) of 1.5, 2.5 and 3.5 were employed. It was concluded that the shear capacity of the RAC beams were comparable and somewhat superior to that of natural concrete. Crack widths of RAC beams were larger than those of the control specimens. The RAC beams with a/d ratios of 1.5 had roughly twice the shear capacity of specimens with a/d ratios of 2.5 and 3.5. Ignjatovic et al. [13] investigated the shear behaviour of RAC beams with and without shear reinforcement by means of nine full scale simply supported beams subject to four-point loading. RCA replacement ratios of 0%, 50% and 100% were used in addition to three different shear reinforcement ratios of 0%, 0.14% and 0.19%. It was found that the shear behaviour and shear strength of the beams with 50% and 100% RCA were very similar to the conventional concrete specimens.

The shear strength of reinforced RAC beams without shear reinforcement was studied by Choi and Yun [14]. Replacement ratios of 0%, 30%, 60% and 100% were utilized and a/d ratios of 2, 2.5, 3, 4 and 5 were employed. They concluded that load-deflection, deflection shape, shear deformation, failure mode and shear strength of beams comprising 100% RAC were similar to those of the natural concrete aggregate beams. Tabsh and Yehia [15] subjected three simply supported 1.3 m span beams to high shear loading by means of a three-point loading arrangement. An (a/d) ratio of 1.5 was utilized. They found that the load-deflection behaviour and the ultimate shear capacity of the beams comprising 50% and 100% recycled coarse aggregate were comparable to the control specimen. The influence of recycled concrete aggregates on the shear strength of reinforced concrete beams was investigated by Cardoso et al. [16]. Tests were conducted on six reinforced concrete beams with RCA replacement ratios of 0%, 30% and 100%. In addition a database of results from 170 tests on beams with RCA was examined. It was concluded that substitution of conventional concrete aggregates by RCA had relatively little impact on the shear strength.

Setkit et al. [17] tested eight RAC beams and two control normal concrete beams without stirrups under four-point loading, using an a/d ratio of 3.10 and employing RCA replacement ratios of 0%, 25%, 50%, 75% and 100%, in addition to longitudinal reinforcement ratios of 1.16% and 1.81%. Furthermore a database from the literature of 128 RAC beams without shear reinforcement was examined. They concluded that the shear failure modes of RAC and conventional concrete beams were similar, although the crack inclination angles of the latter were slightly higher. Also the normalized shear stress of the 100% RAC beam was only 6% lower than for the normal concrete, using a longitudinal reinforcement ratio of 1.16%. Based on a longitudinal reinforcement ratio of 1.81% however, the normalized shear stress of both types of concrete beams was very similar.

It is apparent from the preceding discourse on the literature that there is no unanimity in respect of the influence of the RCA replacement ratios on the shear strength of RCAC beams. However there appears to be broad agreement as per the behaviour of such beams when subjected to shear loading. In general, such beams exhibit similar response to the conventional concrete specimens. A survey of the literature also reveals that very little work has been carried out in the Southern African sub-continent on the shear behaviour of RAC beams. Consequently the present study has been embarked upon, the emphasis being on the utilization of materials sourced locally or at least within the Southern African region. It is hoped that the current investigation will be a useful addition to the relatively small but growing body of work on the shear behaviour of reinforced RCAC beams.

II. EXPERIMENTAL PROCEDURES

A. *Materials, Beam Specimens and Casting*

Ordinary Portland Cement Type I with a 28-day compressive strength of 32.5 MPa and manufactured by PPC Ltd. was used for the present investigation. The fine aggregate employed was commercial crushed sand passing through a 4.75 mm sieve and possessing a fineness modulus of 3.12. The natural coarse aggregates were sourced locally from Kgale Quarry. These were aggregates passing through a 13.2 mm but retained on a 4.75 mm sieve. The recycled coarse aggregates were obtained from bricks bought from Kwena Concrete Products. Initially these bricks were crushed by means of a hammer, and subsequently, a crushing machine was used to cause further reduction in the material sizes. In general aggregates passing through a 19 mm sieve but retained on a 4.75 mm sieve were adopted. The crushed brick materials were used to replace the natural coarse aggregates in fractions of 0%, 25%, 50%, 75% and 100% by weight. The particle size distribution for the fine aggregates is shown in Fig.1, while those for the natural coarse and recycled coarse aggregates are shown in Fig. 2.

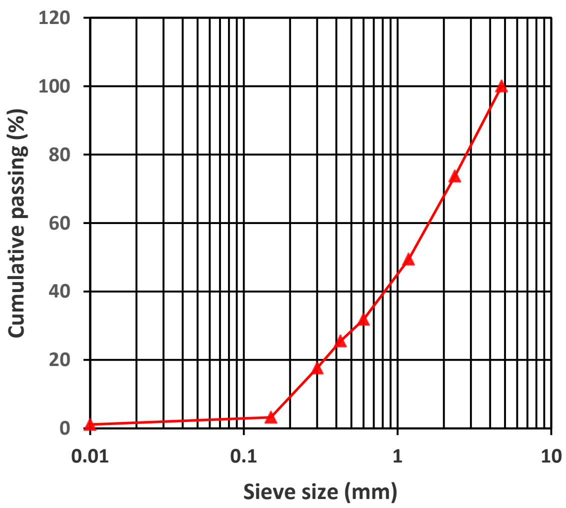


Fig. 1: Particle size distribution for fine aggregate

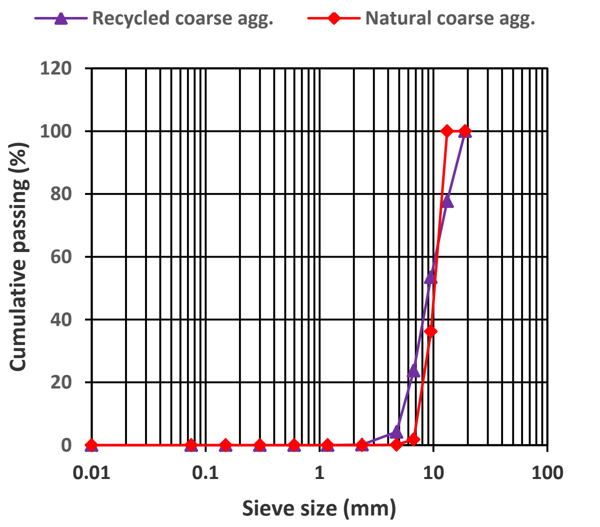


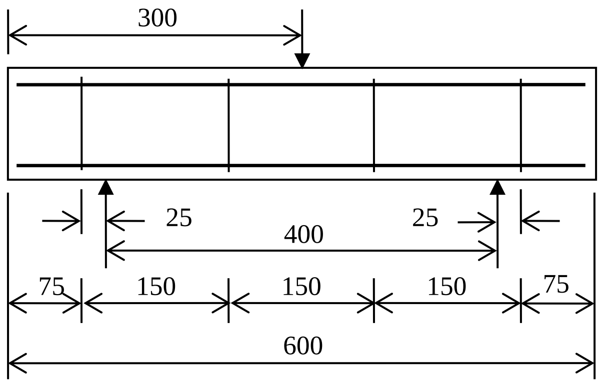
Fig. 2: Particle size distribution of natural and recycled coarse aggregates

Mix design and proportioning were in accordance with the Department of Environment (DoE) revised procedure [18]. The Structures and Materials laboratories of the Department of Civil Engineering at the University of Botswana were used for the preparation and manufacture of all mixes. Preliminary water absorption tests revealed that the natural coarse aggregates (NCA) and the recycled coarse aggregates (RCA) had water absorptions of 0.406% and 5.58% respectively. However these considerations were not taken into account in the subsequent mix design. For the latter, a characteristic strength of 25 MPa at 28 days and a target mean strength of 32 MPa were chosen, since this selection was deemed representative of the strength for medium to high rise buildings. Details of the control mix proportions are shown in Table 1. However four additional concrete mixes corresponding to the different RCA replacement fractions of 25%, 50%, 75% and 100% by weight were employed, The NCA which had a nominal size of 13.2 mm was varied for the different percentages of recycled aggregates in order to observe the trend in the mechanical properties of the RAC. However the water-cement ratio was kept constant at 0.57. Prior to casting, slump tests were carried out for all the different concrete mixes.

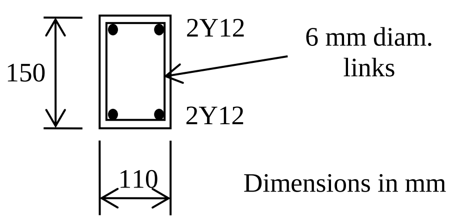
TABLE 1: CONTROL MIX PROPORTIONS FOR ONE CUBIC METRE OF FRESH CONCRETE

Materials	Amount (kg.)
Cement (32.5 Type I)	232.4
Fine aggregate (crushed sand)	1,060
Natural coarse aggregates	975.1
Water	132.3

A total of 105 concrete cubes of 100 mm sizes was cast for the compressive strength testing. Furthermore a total of 45 reinforced concrete beams each 600 mm long was fabricated in three sections of 110 mm x 110 mm, 110 mm x 130 mm and 110 mm x 150 mm respectively. The major variables in the beam specimens were the beam cross-sections, the shear-span to depth ratios (a/d = 1.56, 1.85 and 2.27) and the replacement levels of recycled coarse aggregates – 0%, 25%, 50%, 75% and 100%. All the 600 mm long concrete beams were reinforced in accordance with BS 8110 [19] and EC2 [20] code provisions. The beam specimens were fabricated with two 12 mm diameter high yield deformed longitudinal reinforcement bars with characteristic strength of 460 MPa in both the compression and tension zones. Furthermore 6 mm diameter mild steel bars with characteristic strength of 250 MPa at spacings of 150 mm centre to centre were utilized as shear links. All beams contained minimum shear reinforcement in order to prevent the occurrence of premature shear failure. A concrete cover of 10 mm was adopted for all specimens. Fig. 3 and Table 2 provide details regarding the beams. All cast specimens whether cubes or beams were vibrated on a vibrating table and covered afterwards with damp hessian for 24 hours. Subsequently they were demolded and placed in a curing tank for the required number of days prior to testing.



(a) Longitudinal section



(b) Cross-section

Fig. 3: Beam specimen section dimensions for a shear-span to depth ratio of 1.56

TABLE 2: TEST MATRIX FOR CONTROL BEAM (a/d = 1.56)

Beam*	b x d (mm)	a/d	f_{cu} (MPa)	ρ_w	No.
A1	110 x 88	2.27	25	0.0234	3
A2	110 x 108	1.85	25	0.0190	3
A3	110 x 128	1.56	25	0.0161	3

*B - 25% RCA, C - 50% RCA, D - 75% RCA, E -100% RCA

B. *Testing Procedures*

The testing of the hardened concrete 100 mm cubes to determine the influence of the RCA percentage replacement on the compressive strength was carried out at 7, 14, 21 and 28 days after casting, using an Amsler test machine. Loading was applied at a constant rate up until failure, in accordance with the South African standard SANS 5863:2006. In respect of the beam testing procedure, all the forty-five beams were tested under a symmetric three-point loading up until ultimate failure by means of a universal testing machine as shown in Fig. 4. The loading was applied at a constant rate and the corresponding mid-span deflection was recorded at specified loading increments by means of a dial gauge located underneath the beams. During testing, the behaviour of all beam specimens was closely monitored in addition to the development of cracking. The loads to initiate the first visible flexural cracking as well as to cause ultimate failure were noted in all cases.

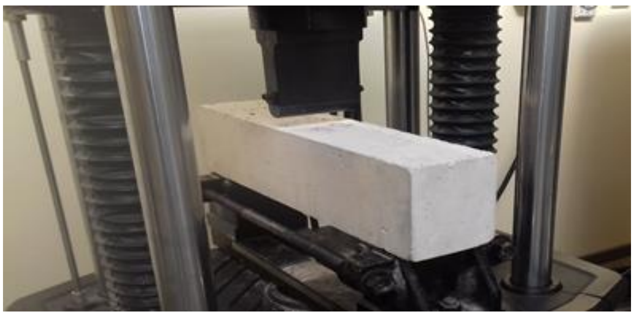


Fig. 4: Experimental test set-up for beam specimens

III. RESULTS AND DISCUSSION

A. *Slump Tests*

These tests were carried out for each of the five different mixes employed in the experimental programme. For each mix, three slump tests were done and an average value was calculated. The variation of slump with increasing RCA fraction is depicted in Fig. 5. It is apparent that there is an almost perfectly linear decrease in slump with increasing RCA percentages from 0% up to 75% replacement levels. Beyond this point however, the rate of decrease appears more modest. Overall, compared to the control mix, there was a slump reduction of about 25% to 81% corresponding to 25% to 100% replacement. These results are consistent with those of previous investigators including Gumede and Franklin [22], Rao et al. [23] and Masood et al. [24]. The trend could be explained by the fact that the water absorption for the RCA was about 5% higher as compared to the reference natural aggregate or NCA. Therefore concrete cast with recycled aggregates should have more water added for workability.

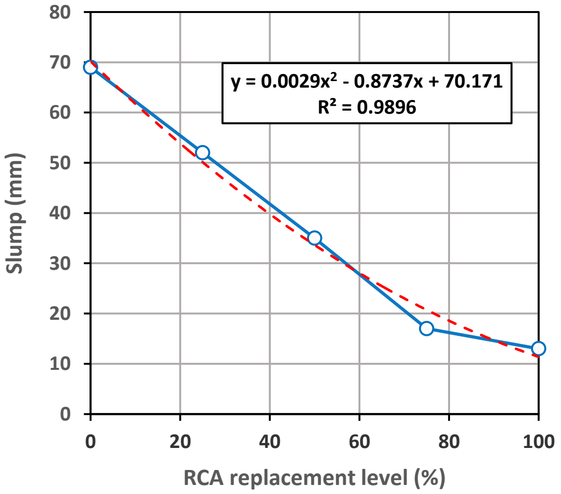


Fig. 5: Variation of slump with recycled aggregate fraction (%)

B. Compression Tests

The variation of average compressive strength based on a mean of three test results with the RCA percentage for the curing periods of 7, 14, 21 and 28 days, is shown in Fig. 6.

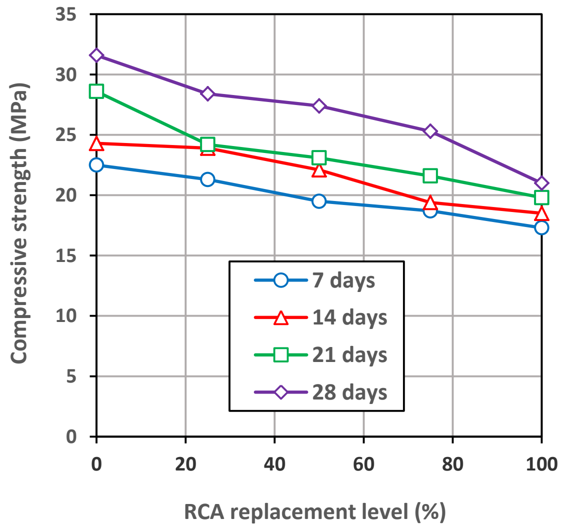


Fig. 6: Variation of compressive strength with recycled aggregate fraction (%)

It is quite obvious that for all specified days the compressive strength decreases with increase in the RCA replacement levels. The decreases are roughly linear as previously demonstrated by a number of researchers including Kumutha and Vijai [25], Khergamwala et al. [26] and Gumede and Franklin [22]. In the current study, at 100% RCA fraction, the 28-day strength was 67% that of the control concrete. It could be inferred that concrete made with 100% RCA would require a relatively high proportion of cement in order to achieve the specified compressive strength, thus making it not a viable economic proposition.

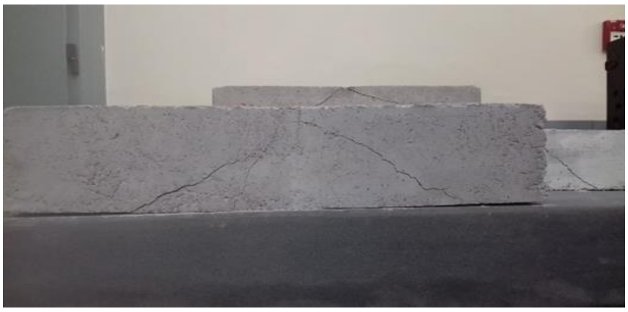
C. Crack Patterns and Failure Modes

During the shear loading tests the cracking patterns and their propagation in all beams were observed and noted. Both the loading at which first cracking appeared as well as the ultimate shear were recorded. In Figs. 7(a)–(e) representative crack patterns at failure for the RCA replacement levels of 0%, 25%, 50%, 75% and 100% respectively, are presented.

(a) 0% RCA

(b) 25% RCA

(c) 50% RCA



(d) 75% RCA

(e) 100% RCA

Fig. 7: Crack patterns at ultimate shear failure for various recycled aggregate fractions

In general for all cases the initial flexural cracks developed into a flexural-shear or diagonal crack. For the beams with 0% to 50% RCA replacement fractions, subsequent to the formation of the diagonal crack, further load increases caused the propagation of the latter crack into the concrete compression zone at or just adjacent to the central loading point, leading to shear-compression or crushing failure of the concrete at this location. With respect to the 75% RCA specimens, close inspection suggested some evidence of diagonal tension failure; however the diagonal crack appeared to have propagated along the steel of the tension reinforcement. The fact that this reinforcement was not hooked would mean the destruction of bond in this region and certain collapse. For the beams with 100% RCA replacement levels, there was some evidence of segregation in the concrete, possibly due to the higher water absorption of the RCA and the lack of adjustment of the water-cement ratio to take this effect into account. This notwithstanding, Fig. 7(e) does suggest that shear-compression failure occurred even for the 100% RCA reinforced beams.

In addition to the above, it was noted that the angle of inclination of the diagonal cracks ranged from 25^{o} to 41^{o}. However there was no trend in this respect in relation to the RCA replacement levels. Furthermore the shear responses of the beams with 25%–100% RCA fractions were quite similar to those of the conventional concrete specimens, and they conformed to well-documented shear transfer mechanisms (for example, Kong and Evans [[27]. In general the behaviour of the recycled aggregate specimens was in broad agreement with the observations of several investigators such as [6], [8], [9], [13], [14] and [15]. The prevalent occurrence of shear-compression failures in the present tests is almost certainly due to the range of shear-span to depth, or a/d ratios employed, that is 1< a/d < 2.5.

D. *Effect of RCA fractions on shear strength*

For each of the control specimens designated A1, A2 and A3, three beams were tested as highlighted in Table 2. The same was applicable to the RCA specimens designated B, C, D and E, and representing RCA replacement levels of 25%, 50%, 75% and 100% respectively. The variation of the average shear strength with replacement levels of recycled aggregates is shown in Fig. 8 for all the three beam sections employed, that is, 110mm x 150mm, 110mm x 130mm and 110mmx 110mm.

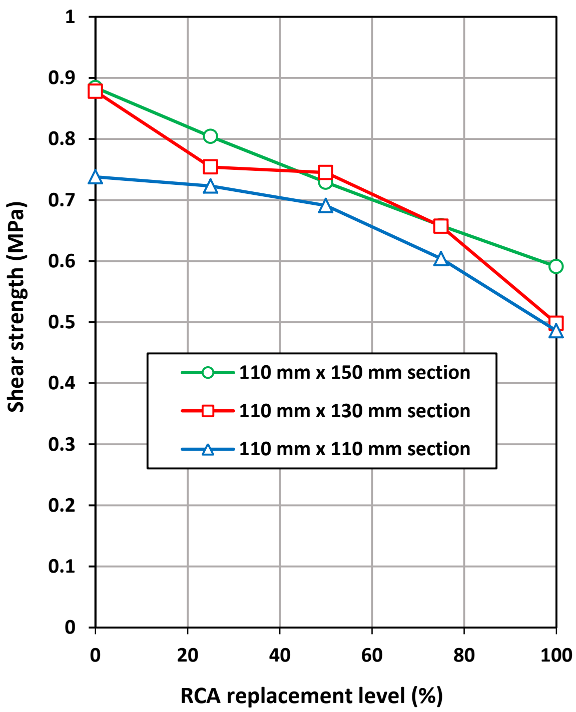


Fig. 8: Variation of shear strength with recycled aggregate fraction (%)

It is clear that there is a progressive decrease in the ultimate shear strength as the RCA percentage fraction increases. For example in respect of the beam section 110mm x 150mm, the average shear strength of the 100% RCA specimen decreased by 33% as compared to the control beams. With regards to the beam sections 110mm x 130mm, the shear strength of the 100% RCA specimens decreased by 43%. The corresponding decrease with reference to the 110mm x 110mm beam sections was 34%. These values are higher than those reported by Li [7] and Arezoumandi et al. [10] who noted maximum decreases of 30% and 12% respectively. The values are also somewhat higher than those found by Choi et al. [8] who observed decreases of up to 30%. These latter results are of some interest here, since the beam specimens employed had shear-span to depth ratios in the range 1.50–3.25, which is not too dissimilar to the one utilized in the present investigation. However the longitudinal reinforcement ratios used for both studies were quite different. Choi et al. [8] made use of RCA beams with reinforcement ratios of 0.53%–1.61%, while the present investigators used a range of 1.61%–2.34%. It is quite conceivable that these differences contributed to the current results, although the effect of the longitudinal reinforcement ratio on the ultimate shear strength was not the primary subject of interest in the current study.

In addition to the foregoing, it was found that over the range of the shear-span to depth ratios used in the present investigation, that is 1.56–2.27, shear strength decreases of approximately 16.5%, 10.1%, 5.2%, 8.2% and 17.8% were observed for the 0%, 25%, 50%, 75% and 100% RCA replacement levels. However as before, the influence of the shear-span to depth or a/d ratio was not the major issue of inquiry in the current study. Nevertheless it should be stated at this stage that additional testing would be necessary in order to furnish a more comprehensive picture of the response of reinforced RCA beams to shear loading.

IV. CONCLUSIONS

The present investigation was conducted in order to assess the response of recycled coarse aggregate concrete beams subjected to increasing shear loading up until ultimate failure. The RAC beams contained varying percentages of RCA employed as replacement for natural coarse aggregates. All the tested beams contained nominal shear reinforcement in order to preclude the occurrence of premature shear failure. Based on the tests carried out, the following conclusions have been drawn.

1. With increasing RCA replacement fractions from 0% to 75%, there was an almost linear decrease in the slump. It is suggested that at higher RCA percentage levels, additional water may be required to ensure adequate workability.
2. The compressive strength decreased with increase in the RCA replacement levels for all specified curing periods of the concrete. In respect of the 28-day strength, the compressive strength of the 100% RCA concrete was only approximately 67% of the strength of the conventional concrete.
3. For the beams utilized in the current study, with shear-span to depth ratios in the range 1.56–2.27, shear-compression was the prevalent or common mode of failure.
4. The shear behaviour of the beams with 25%–100% RCA fractions was similar to those of normal concrete specimens and conformed to well-documented shear transfer mechanisms contained in the literature.
5. It was observed that the ultimate shear strength progressively decreased with increase in the RCA percentage fraction. In comparison to control or conventional concrete beams, the ultimate shear strength of 100% RCA concrete beams decreased by 33%–43%. This range was higher than those reported by some other investigators.
6. It is proposed herein that additional testing should be carried out in order to obtain a more complete picture regarding the behaviour of nominally reinforced RCA beams subjected to increasing shear loading. Such testing is warranted in order to obtain accurate assessment of the influences of the shear-span to depth ratio as well as the longitudinal reinforcement ratio on the ultimate shear strength.

ACKNOWLEDGMENT

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