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Shear Strength of Reinforced Concrete Beams Made with Recycled Aggregate

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***Abstract* -** Using recycled concrete aggregate in new concrete mixes saves landfill space, reduces the need for gravel mining, and decreases pollution from transporting concrete to and from worksites. Recycled concrete aggregate may come from a variety of sources but the most common source is the demolition waste of old concrete structures. In this study, the recycled aggregate was obtained locally from Bee'ah's facility in Sharjah, UAE, and the percentage of coarse aggregate replacement in the concrete mix was either 50% or 100%, in addition to the control mix which included 100% natural aggregate. The target 28-day compressive strength based on 150mmx300mm cylinder was within the range 30-35MPa. The first phase of the study addressed the recycled aggregate tests and concrete mix design while the second phase involved shear strength of three half-scale reinforced concrete beams made with the recycled and natural aggregate. In the later part, the simply supported beams were tested under a single-point loading scheme inside a Universal Test Machine at a shear span-to-depth ratio of 1.5 to determine the load-deflection performance up to failure. Results of the study showed that the elastic stiffness, ultimate shear capacity and residual strength of steel reinforced beams made with 50% and 100% recycled coarse aggregate were comparable to those made entirely with natural aggregate and can be conservatively predicted by the theoretical equations of the ACI 318 code.

***Keywords*:** Aggregate, Experimental Test, Recycled Concrete, Shear, Sustainability.

1. Background and Motivation

Using recycled material in construction projects protects the natural resources and lowers the amount of construction waste produced and dumped into landfills. In concrete construction, there are various ways of using recycled materials. For example, the reinforcing steel rebars that are used in concrete are virtually 100% recycled from other metal products. Common Portland cement replacements used nowadays are fly ash, silica fume and ground granulated blast furnace slag. Crushed recycled glass has been employed in new concrete mixes as a fine aggregate replacement. Recycled coarse aggregate (RCA) from old concrete obtained from demolition of reinforced and prestressed concrete buildings, bridges, and pavements is often employed as replacement for natural aggregate. Since the coarse aggregate makes up the largest part of a concrete mix, there has been much interest lately in this material. By using RCA from demolition waste results in less greenhouse gases are released into the atmosphere, reduced leaching of chemicals into the watershed, and reduced costs associated with concrete disposal.

In the Emirate of Sharjah, United Arab Emirates, Bee'ah facility has been crushing old concrete rubbles from roads, bridges and buildings for years. The resulting material has been grouped and classified based on its size: (1) 5-14mm aggregate, (2) 14-20mm aggregate, (3) 25-50mm and (3) 0-5mm dust (i.e. fine aggregate). Such material is currently sold locally for use in non-structural applications. While studies around the world have shown that some recycled concrete has adequate strength characteristics, no research has been conducted on the locally produced recycled coarse aggregate by Bee'ah to determine if it is good enough for use in structural applications. The shear strength of concrete beams is of significant interest because shear failure is associated with an abrupt failure mode that often undermines the flexural performance of the beams; hence, this research considers such limit state for reinforced concrete beams made with RCA.

The objectives of this study are to: (a) test the quality of the recycled coarse aggregate from Bee'ah, (b) develop mix designs for concrete with 100% and 50% replacement of natural with concrete aggregate for a target compressive strength, (in the rage 20-25 MPa), (c) investigate the shear behaviour of reinforced concrete beams made with recycled concrete and compare their performance with control beams made with natural aggregate, and (d) check the feasibility of predicting the shear strength using the relevant structural code equations.

2. Literature Search

Fathifazl et al. [1] used the relative amount and properties of mortar and natural aggregate in RCA to proportion a concrete mix. Several beams were designed and tested to study the effect of the shear span-to-depth ratio and beam size on the serviceability and strength of RCA concrete beams without shear reinforcement. The results indicated that the shear performance of RC beams made with RCA can be comparable to that of beams made entirely with natural aggregates. The simplified methods of ACI, CSA, and Eurocode2 were found to be applicable to all beams. Choi et al. [2] investigated the effects of RCA on concrete shear strength by experimentally testing 20 beams with span-to-depth ratios, longitudinal reinforcement and RCA replacement ratios. The tests showed that the shear strength is reduced by up to 30% at 100% aggregate replacement ratio compared with the natural aggregate concrete. Al-Zahra et al. [3] tested 12 beams with different percentage of recycled concrete aggregates, shear reinforcement and shear spans under two concentrated loads up to failure. Tests results demonstrated that the shear strength decreases with an increase in the coarse aggregate replacement ratio. The predicted shear strength by the ACI code was overly conservative compared to the experimental values. Kim et al. [4] considered the size effect of shear strength in 12 reinforced concrete beams made recycled coarse aggregate without stirrups. The experimental results demonstrated that the strength of the specimens made of recycled aggregate decreased with a higher effective depth irrespective of the replacement ratio, and the strength reduction and crack patterns of the beams with recycled aggregates were similar to those of the beams with natural aggregates. Arezoumandi et al. [5] studied the shear strength of 12 full-scale concrete beams made either with 100% recycled concrete aggregate or natural aggregate. Statistical analysis was conducted to evaluate the relationship between the shear strength and presence of recycled aggregate. Results of these statistical tests showed that the 100% RCA beams possess approximately 12% lower shear strength compared with the NA beams. Ma et al. [6] carried out cyclic loading tests on steel reinforced recycled concrete columns. The test results showed that the ductility of the columns was related to the effective length, and it decreases with an increase in the RCA replacement percentage. While the capacity and stiffness of the columns significantly decreased as the shear span ratio increased, the ductility increased considerably. Katkhuda and Shatarat [7] tested 10 full scale reinforced concrete beams that were constructed without stirrups from natural aggregate, 50% and 100% recycled aggregate and 50% and 100% treated recycled aggregate. Test results showed that using treated recycled aggregate improved slightly the shear capacity of the beams in comparison with natural and untreated recycled aggregate. Theoretical predictions of the shear strength of the treated recycled aggregate beams were more conservative compared to the natural and untreated recycled aggregate beams regardless of the shear span-to-depth ratio. Choi and Yun [8] carried out experimental tests on RAC beams loaded in shear and compared the test results with those obtained from the ACI-318 code. It was found that the code equations can adequately predict the shear strength of recycled coarse aggregate concrete beams. Ignjatović et al. [9] conducted 9 experiments to study the shear behaviour of recycled aggregate concrete beams with and without shear reinforcement. The results showed that the shear strength of the beams with 50% and 100% of recycled concrete aggregate were very similar to that of the corresponding beam with natural aggregate. The shear strength of RAC beams can be conservatively predicted by codes with similar reliability as for the corresponding beams with natural aggregate. Rahal and Alrefaei [10] used experimental testing to determine the effects of the using RCA on the shear strength of 13 reinforced concrete beams tested in a two-point loading scheme at a shear span to depth ratio of 3. Based on the experimental results and available data from the published literature, it was determined that the "square root of the compressive strength of the concrete" term does not adequately account for the detrimental effects that the shearing strength undergoes when RCA are used.

3. Methodology

Phase I of the investigation focused on the evaluation of the physical and mechanical properties of the recycled and natural weight coarse aggregates used in the study. In Phase II, three 1.5 m-long reinforced concrete beams were subjected to high shear load inside a Universal Test Machine utilizing a 3-point loading scheme. The beams were simply supported at 100 mm from the edge and the load was applied through the actuator head at 400 mm from the one support and 900 mm from the other support. All beams had 150 mm by 300 mm cross-section and were adequately reinforced for flexure on the top by 2No. 10 bars (f_y=570MPa) and at the bottom by 2No. 16 bars (f_y=538MPa). They were transversely reinforced with No.8 closed stirrups (f_y=580MPa) at 100 mm spacing along 1000mm of the length and free from stirrups along the remaining 500 mm. Figure 1 shows the beam dimensions and reinforcement details. The beams were instrumented with strain gauges and loaded under displacement-controlled conditions at a rate of 0.5 mm/minute until failure, as shown in Fig. 2. One of the beams was made with a concrete mix utilizing 50% RCA, another with 100% RCA, and the third with 100% NCA. The observed ultimate shear strengths are compared with the theoretical predictions from the relevant structural design codes.

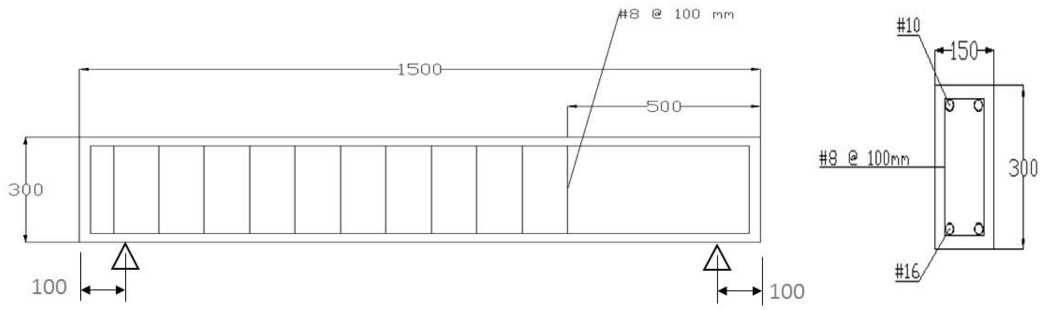

Fig. 1: Beam reinforcement details.

Fig. 2: Test setup inside the UTM.

4. Results

This section presents the results of natural and recycled coarse aggregate testing, as well as reinforced concrete beam experiments and theoretical predictions involving shear.

4.1. Material Properties

A variety of tests were conducted on the recycled and natural coarse aggregated utilized in the study, such as specific gravity, sieve analysis, crushing value, LA abrasion and absorption, as shown in Fig. 3.

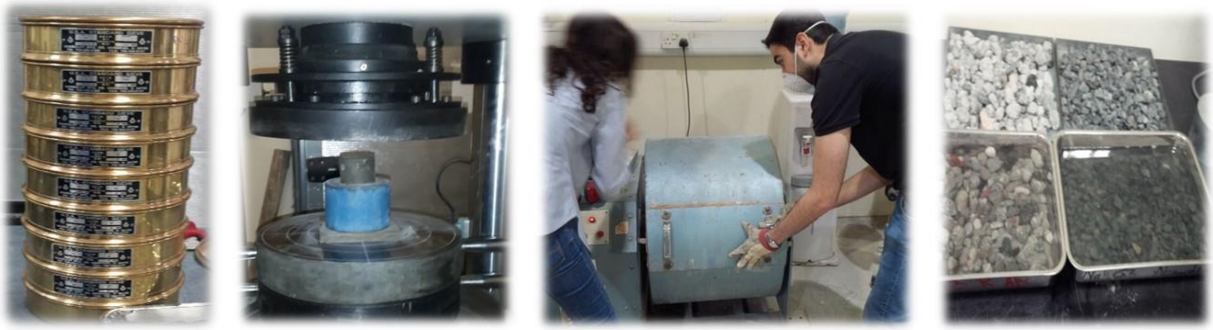

Fig. 3: Some of the tests conducted on the recycled aggregate.

Sieve analysis achieves the distribution of aggregate particles by size within a given sample. The obtained gradation is required to determine the relationship between blends, which is necessary for concrete mix design. The sieve analysis results for the recycled and natural coarse aggregate used in the concrete mix are presented in Fig. 4.

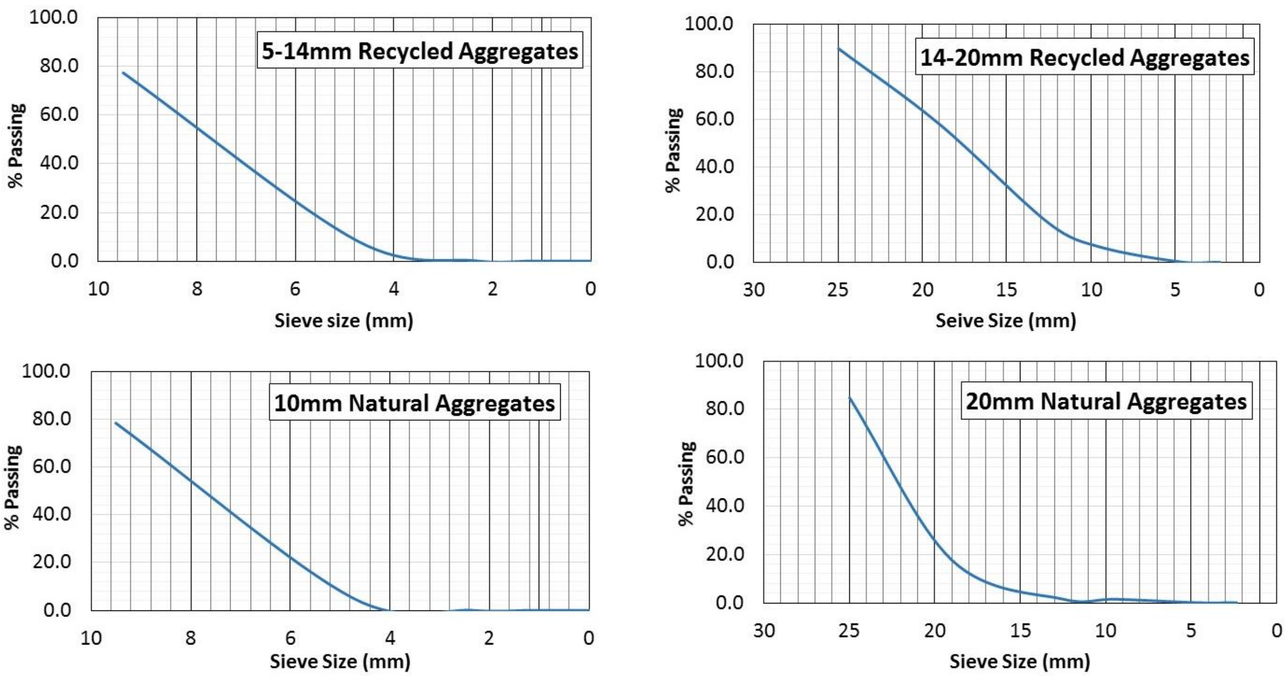

Fig. 4: Sieve analysis results of the recycled and natural aggregate.

Test results on the aggregate indicated that the specific gravity for the recycled aggregate was 2.40 and for the natural aggregate was 2.61. The absorption of the 10mm recycled aggregate was 5.6% and of the 20mm recycled aggregate was 4.7%. The corresponding values for the natural aggregate were 4.0% and 1.2%, respectively. The crushing values for the 10 and 20mm recycled aggregate were 18.4% and 17.3%, respectively. The corresponding values for the natural aggregate were 18.3% and 15.9%, respectively. Test results showed that the percentage loss from the LA abrasion test for the 10 and 20mm recycled aggregate were 20.6% and 30.7%, respectively. The corresponding values for the natural aggregate were 17.3% and 19%, respectively.

Three blends of the 10 and 20mm aggregate were considered from which the most appropriate blend was selected and tested experimentally. A trial and error procedure was then performed on concrete mixes utilizing 100% RCA, 50% RCA and 0% RCA (i.e. 100% natural aggregate) for a target cylinder strength within the range 30-35 MPa. The mix design proportions and corresponding cylinder compressive strength at the age of 28 days are provided in Table 1.

Table 1: Concrete mix design proportions and compressive strength.

Constituents	**Specific Gravity**	**0% RCA Concrete Mix**	**50% RCA Concrete Mix**	**100%RCA Concrete Mix**
Cement	3.15	21.3 Kg	21.6 Kg	21.8 Kg
Water	1	8.5 Kg	8.6 Kg	8.7 Kg
RCA 14-20mm	2.4	0	14.1	26.7 KG
RCA 5-14mm	2.4	0	3.5	6.7 Kg
NA 20mm	2.61	30.2 Kg	15.4 Kg	0 Kg
NA 10mm	2.61	7.6 Kg	3.9 Kg	0 Kg
Crushed Sand	2.59	16.2 Kg	16.4 Kg	18.0 Kg
Dune Sand	2.59	16.2 Kg	16.4 Kg	18.0 Kg
28-day f'_c	---	35.5 MPa	33.2 MPa	33.9 MPa

4.2. Shear Test Results

The load-deflection curves for the three concrete beams are superimposed on each other and presented in Fig. 5. Experimental testing of the beams showed that all the beams failed in shear by developing inclined cracks due to diagonal tension within the high shear region that did not contain stirrups, as shown in Fig. 6. As expected, the load-deflection relationship indicated a somewhat ascending linear trend up to the peak capacity. Within this region, the shear was carried by the uncracked concrete under compression at the top of the beam, cracked concrete below the top, and the dowel action of the longitudinal steel reinforcement. After reaching the peak capacity, all beams released almost 50% of the load. The residual capacity of the beams is mainly due to the arching action (i.e. strut and tie behaviour) between the location of the applied load and near support. The beam that was made with 100% NCA supported the highest load (136.5 kN), the beam that was made with 50% RCA supported the second highest load (116.6 kN), and the beam that was made with 100% RCA supported the lowest load (112.5 kN). The shear diagram of the tested beams showed that the maximum shear is equal to 0.69 times the applied load. This means that the ultimate shear capacity of the NCA, 50%RCA and 100% RCA concrete beams are equal to 94.2 kN, 80.5 kN and 77.6 kN, respectively. Note that the observed capacities are slightly affected by the fact that not all beams had the same concrete compressive strength, since f'_c of beam containing NCA was 35.5 MPa, 50% RCA was 33.2 MPa and 100% RCA was 33.9 MPa.

The shear strength provided by concrete in the ACI 318 code [11] is a function of the concrete compressive strength (f'_c), whether the concrete is normal or light-weight (□), effective longitudinal steel reinforcement ratio (□), geometry of the cross-section (b_w and d), applied shear on the beam and corresponding moment at ultimate conditions (V_u and M_u).

$$V_c = (0.16\lambda\sqrt{f'_c} + 17\rho\frac{V_u d}{M_u})b_w d \leq 0.29\lambda\sqrt{f'_c}b_w d \qquad (1)$$

The predicted capacity by the ACI 318 code showed low theoretical predictions when compared with the experimental results. The computed shear strength was equal to 41.5 kN for the NCA beam, 40.3 kN for the 50% RCA beam and 40.7 kN for the 100% RCA beam. The reason for the low shear strength predicted by the ACI code is that the considered beams were all tested at low shear span-to-depth ratio equal to 1.5 (i.e. deep beam classification), for which the equation in the ACI code does not consider the effect of arching. Nevertheless, the test results suggest that the ACI 318 code equation for shear can be conservatively used to design beams made with recycled aggregate produced by Sharjah's Bee'ah facility.

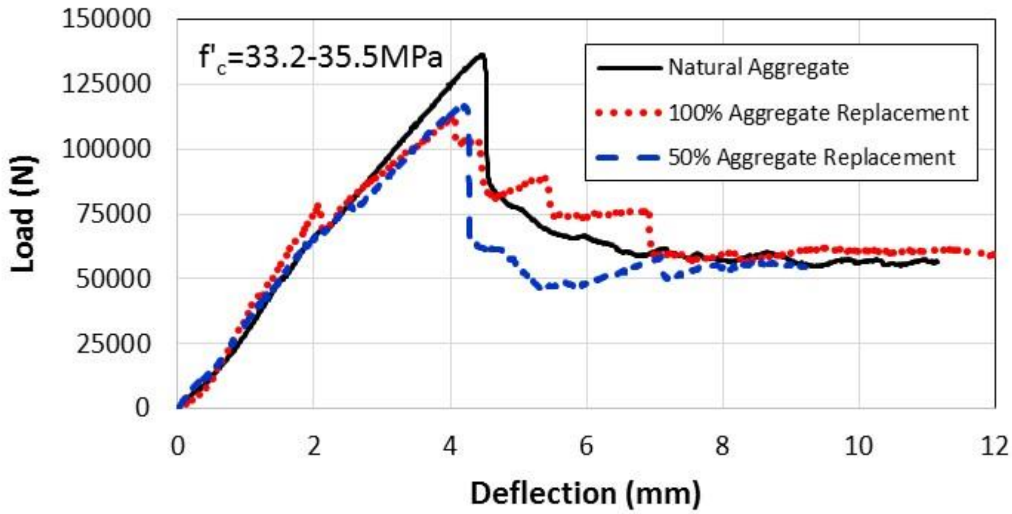

Fig. 5: Load-deflection relationships for the tested beams.

Fig. 6: Typical shear failure.

5. Conclusions

Results of this study with respect to concrete made with recycled coarse aggregate from Bee'ah lead to the following conclusions:

1.The quality and mechanical properties of the recycled coarse aggregate are relatively good when compared to natural coarse aggregate.

2.The developed mix designs for the concrete with NCA, 50%RCA and 100%RCA met the target strength of 30-35 MPa.

3.Reinforced concrete beams employing either 50% or 100% recycle coarse aggregate possess adequate ultimate shear capacity and residual strength when compared with the corresponding beam made with natural coarse aggregate.

4.The shear strength of reinforced concrete beams made with 50% or 100% recycle coarse aggregate can be conservatively predicted with the equations of the ACI 318 code when the shear span-to-depth ratio is equal to 1.5.

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