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Mechanical Characterization of Recycled Aggregate Concrete

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Abstract

Experimental study was carried out to investigate the mechanical properties of recycled aggregate concrete prepared with recycled aggregates obtained from local precast concrete industry and the findings of this study are presented in this paper. Five different concrete mixtures were prepared: one control mixture containing only natural aggregates and four mixtures of recycled aggregate concrete (RAC) containing natural and recycled aggregates at 25%, 50%, 75% and 100% replacement levels of natural aggregates. The results of mechanical tests such as compressive strength, modulus of elasticity, Load versus CMOD response, fracture energy in tension and compression are presented. The results indicate that at 25% replacement level, mechanical properties of RAC are almost similar to that of control concrete mix, however, mechanical properties of RAC are degraded when natural aggregates are replaced with recycled aggregates at replacement level greater than 25% and degradation is increased with the increase of replacement level

Key Words: concrete; natural aggregates; recycled aggregates; mechanical properties

1. Introduction

Rapid development in concrete technology has led to the adoption of modern construction techniques and materials such as pre-stressing, composite construction and high strength concrete, etc. The previously constructed structures using ordinary concrete are being replaced with more efficiently designed structures at a faster pace due to the ever increasing need of space and aesthetics.

A large volume of concrete debris is being produced due to the demolition of structures whose design life has been expired, or which have been damaged by natural calamities such as earthquake, floods and heavy winds. The testing of concrete specimens in commercial testing laboratories is another source of concrete debris. Surplus concrete produced in ready-mix concrete batching plants is also wasted at times. This waste concrete poses serious environmental hazards due to mostly being dumped in landfills. The decreasing space for landfills and the scarcity of natural resources of aggregates encourage the reuse of this waste concrete.

One of the ways being employed these days to reuse this wreckage effectively is to use this debris as aggregate for new concrete which is named as "recycled aggregate concrete (RAC)" [1,2].

Extensive research is being carried out globally on the use of such recycled aggregates as an alternative to natural aggregates because it is an efficient way to ensure sustainable development, environmental preservation and effective utilization of resources [3,4].

A series of experimental investigations on the mechanical properties, durability and the structural performance of RAC have been carried out in the last two decades to suggest the possible utilization of this waste material in construction industry so as to avoid threat to environment.

Research conducted in the field of RAC so far has revealed in general, lower modulus of elasticity, compressive and bending strengths, lesser durability resulting from higher permeability and more water requirements to achieve same workability, when compared with natural aggregate concrete [3,5,6].

One of the major factors affecting the properties of RAC is the source concrete from which recycled aggregates are prepared. The water absorption of recycled aggregates increases with an increase in strength of parent concrete of recycled aggregate, while it decreases with an increase in maximum size of aggregate [7]. The recycled coarse aggregates from a concrete with compressive strength of 50MPa result in same tensile and compressive strengths as achieved by using natural coarse aggregates [8]. The ratio of mortar pieces in recycled aggregate significantly affects the properties of RAC and it has an inverse relation with the achieved strength [7].

In one of the research studies focused on the properties of concrete made with recycled aggregates from partially hydrated old concrete, Amnon Katz [9] reported a significant difference between properties of RAC made of aggregates of different particle size groups.

In order to maintain the same slump as that for conventional concrete, RAC requires more water which results in concrete with lower strength [8].

In this paper, results of an experimental investigation carried out to study the mechanical properties of RAC made using recycled aggregates obtained from waste concrete from precast industry are presented. The compressive strength of parent concrete of recycled aggregates was 35MPa.The mechanical properties of RAC which were studied include compressive strength, static modulus of elasticity, fracture energy (compression and tension) and the load versus crack mouth opening displacement (CMOD) response. Although significant research work has been carried out on the mechanical properties of RAC in the past, but very less information is available on the fracture energy of RAC in tension and compression. The discussion available in this paper on the values of fracture energy in tension and compression of RAC makes this contribution original and different from the previous studies carried out on the mechanical properties of recycled aggregate concrete.

2. Experimental Program

2.1 Materials

2.1.1 Cement and Fine Aggregates

In this study, ASTM Type I Portland cement and Lawreancepur sand as fine aggregates were used to prepare the concrete mixtures. The properties of cement and fine aggregates are given in Table 1 and Table 2, respectively.

2.1.2 Natural Coarse Aggregates

Locally available Margala crushed stone with maximum particle size of 13 mm was used as coarse aggregates to prepare all concrete mixes investigated in this study. The properties of coarse aggregates are described in Table 3.

Table 1 Properties of Cement

Properties	Cement (OPC)
Standard consistency	31
Initial Setting time (min)	105
Final setting time	2h - 5min
Soundness (mm)	7
Fineness (%)	8
3-Days compressive strength using mortar cubes (MPa)	14.8

Table 2 Properties of Fine Aggregates

Properties	Lawrancepur Sand
Max. Aggregate Size (mm)	4
Water Absorption Capacity (%)	0.9
Moisture Contents (%)	0.4
Specific Gravity	2.61
Rodded Density (kg/m^3)	1641
Fineness Modulus	2.4

2.1.3 Recycled Coarse Aggregates

Concrete cubes and cylinders are generally used to find out compressive strength of the concrete to be used in the production of pre-stressed precast concrete structural products by the precast industries. After testing, these cubes and cylinders become waste. Recycled aggregates used in this study were obtained by crushing these cubes and cylinders obtained from the local precast concrete industry in Lahore. Keeping in mind the importance of strength of parent concrete for the recycled aggregates, cubes of 35MPa concrete strength were obtained from the industry and crushed and passed from separator to obtain coarse aggregates of maximum particle size of 13 mm. Recycled coarse aggregates are shown in Fig.1 and their properties are given in Table 4.

Table 3 Properties of Natural Aggregates

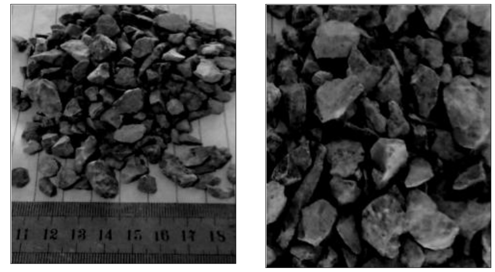
Properties	Margala Crush
Size used (mm)	4 to13
Water Absorption Capacity (%)	0.99
Specific Gravity	2.65
Loose Bulk Density (kg/m^3)	1289
Rodded Bulk Density (kg/m^3)	1445
Aggregate Impact Value (%)	19

Table 4 Properties of Recycled Aggregates

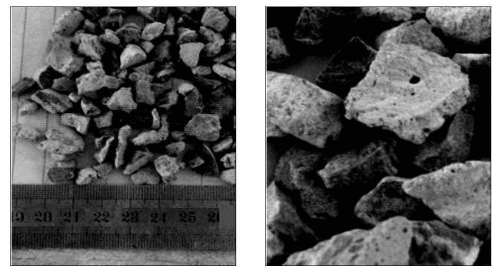
Properties	Recycled Aggregates
Size used (mm)	4 to13
Water Absorption Capacity (%)	2.15
Specific Gravity	2.53
Loose Bulk Density (kg/m^3)	1171
Rodded Bulk Density (kg/m^3)	1290
Aggregate Impact Value (%)	24

2.2 Concrete Compositions

Five different concrete compositions were designed: one control composition with only natural aggregates and four compositions of RAC with 25%, 50%, 75% and 100% recycled aggregates. Type and quantity of all other constituents of five concrete mixtures were kept same. Keeping in mind the greater water demand of recycled aggregates compared to natural aggregates, both natural and recycled aggregates were used in saturated surface dried (SSD) conditions. The water cement ratio of 0.6 was kept same for all five concrete compositions. The detail about the nomenclature of concrete compositions along with the quantities of natural and recycled aggregates is given in Table 5. Among different nomenclature of concrete mixes, CC-0 stands for **C**ontrol **C**oncrete containing 0% recycled aggregates and RAC-25 stands for **R**ecycled **A**ggregate **C**oncrete containing 25% recycled aggregates.



Natural Aggregates



Recycled Aggregates

Fig. 1: Natural and Recycled Aggregates

Table 5 Concrete Compositions

Sr. No	Concrete Composition	Natural Aggregates (%)	Recycled Aggregates (%)
1	CC-0	100	0
2	RAC-25	75	25
3	RAC-50	50	50
4	RAC-75	25	75
5	RAC-100	0	100

2.3 Test Specimens

For each concrete composition, cylinders (300 mm height and 150 mm diameter) and prisms (100 x100x500 mm) were cast. The cylinders were used to determine the modulus of elasticity, compressive strength and fracture energy in compression of the concrete. The prisms were used to determine the fracture energy in tension and to study the load-CMOD response. All the test specimens were prepared using steel molds and compaction was done on vibrating table. After casting, all molds were covered with plastic sheets for 24 hours to avoid the evaporation of moisture. All concrete specimens were cured for 28 days under wet conditions in curing room after de-molding.

2.4 Tests

2.4.1 Compressive Strength

The compressive strength test was performed on cylindrical test specimens following the procedure specified by ASTM C39 [10]. A total of three specimens were tested for each composition of concrete. The tests were performed on 1000 kN Shimadzu UTM in Test Floor Laboratory of Civil Engineering Department, U.E.T Lahore, Pakistan. The tests were displacement controlled with loading rate of 2mm/min. The compressive strength of all five concrete compositions investigated in this study was determined at the age of 28 days.

2.4.2 Static Modulus of Elasticity (E-value)

E-value of the concrete was determined using cylindrical specimens according to ASTM C 469 [11] at the age of 28 days. The tests were performed on 1000 kN Shimadzu UTM at a loading rate of 2mm/min. The testing setup used for the determination of modulus of elasticity is shown in Fig. 2. Two LVDTs were used for vertical displacement measurement and the load was recorded with load cell of 50 Tons capacity. All data from LVDTs and Load cell were recorded by computer based data acquisition system.

2.4.3 Fracture Energy in Compression

For determination of fracture energy in compression, data of E-value test in terms of stress and displacement were used. The fracture energy in compression is area under stress versus displacement curve after the peak [12] as shown in Fig.3.

2.4.4 Fracture Energy in Tension

For determination of fracture energy in tension of concrete, standard procedure specified by Japan Concrete Institute [13] was followed. This method requires testing of notched prismatic specimen under three point bending as shown in Fig.4. The three point bending tests (3PBT) were performed using 1000kN Shimadzu UTM at a loading rate of 0.5mm/min. The required specimen details according to this standard are shown in Fig. 5. The test specimens were notched after hardening of concrete. The setup for the measurement of crack mouth opening displacement (CMOD) with the help of LVDT employed in this study is shown in Fig. 6. Load versus CMOD curves were plotted using the data obtained through 3PBT on concrete prisms. The area under load-CMOD curve (Fig.7) was calculated and denoted by W_0. The area which contributed to load bearing (b x h in Fig.5) was measured and this area was denoted by A_{lig}.

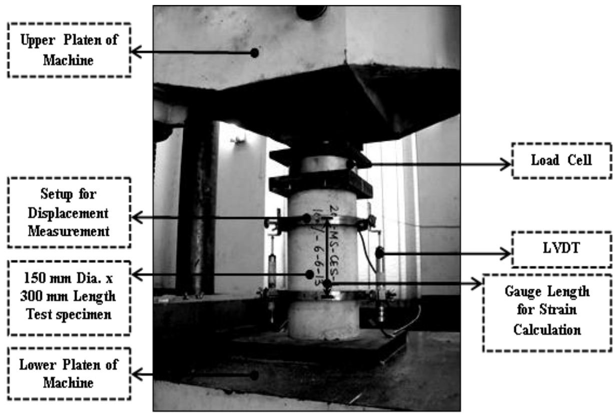


Fig. 2 Experimental Setup for E-value Test

The fracture energy in tension was then calculated using the following expression;

$$G_F = \frac{0.75W_o + W_1}{A_{lig}} \tag{1}$$

Where,

$$W_1 = 0.75(\frac{S}{L}m_1 + 2m_2)g.CMOD_c \tag{2}$$

G_F = *fracture energy (N-mm/mm^2)*
W_1 = *work done by dead weight of specimen and loading jig (N-mm)*
m_1 = *mass of specimen (kg)*
S = *loading span (mm)*
L = *total length of specimen (mm)*
m_2 = *mass of jig not attached to testing machine but placed on specimen until rupture (kg)*
g = *gravitational acceleration (m/sec^2)*
$CMOD_c$ = *crack mouth opening displacement at the time of rupture (mm)*
B = *width of the broken ligament (mm)*
H = *depth of the broken ligament (mm)*
A_{lig} = *Area of ligament*

2.4.5 Load-CMOD Response

Test results of 3PBT on notched prismatic specimens were used to study the load vs CMOD response of RAC.

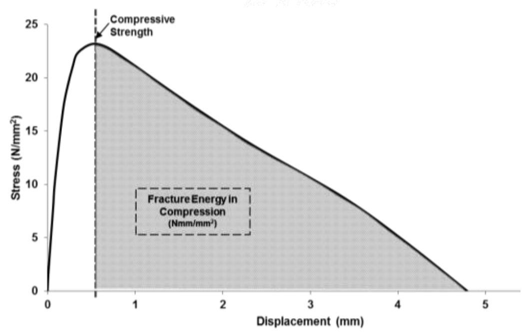


Fig. 3 Fracture Energy in Compression [12]

Fig. 4 Three Point Bending Testing Setup

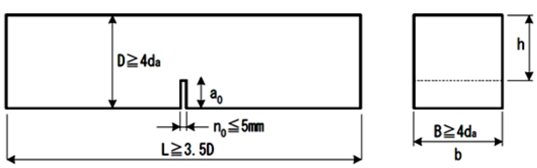


Fig. 5 Specimen Details According to [13]

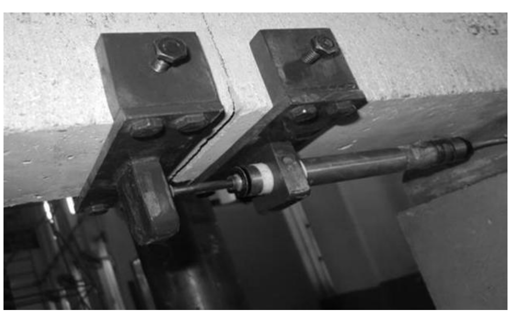


Fig. 6 Setup for CMOD Measurement

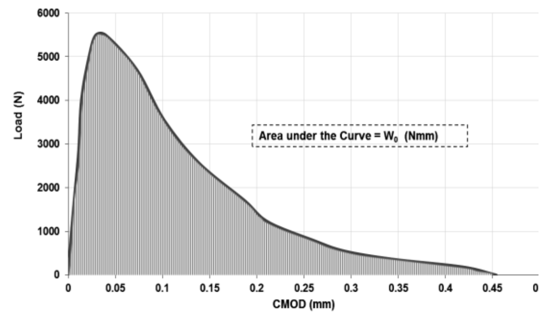


Fig. 7 Area under the Load-CMOD Curve for Fracture Energy in Tension

3. Results and Discussion

The results of different mechanical tests performed on control concrete and RACs show that properties of concrete are degraded by the replacement of natural aggregates by recycled aggregates and the degradation in values of mechanical properties increases with the increase of percentage replacement level. In the following section of this paper, results of mechanical testing are presented and discussed.

3.1 Compressive Strength

The results of compressive strength test are shown in Fig. 8. It is clear in this figure that the compressive strength of concrete gradually reduces with increase in percentage of recycled aggregates present in the concrete. Up to 25% replacement of natural aggregates by recycled aggregates, the compressive strength is almost same. However, at replacement level greater than 25%, compressive strength is gradually decreased. The maximum decrease of 20% in compressive strength was observed in concrete made using 100% recycled aggregates. Since the untreated recycled aggregates were used in this study, due to presence of cement mortar on the surface of these aggregates, ITZ have more chances of flaws development [14] resulting in lesser compressive strength of RAC. Moreover, crack development in recycled aggregates during their preparation from used cylinders and cubes of concrete may also be another reason of less compressive strength.

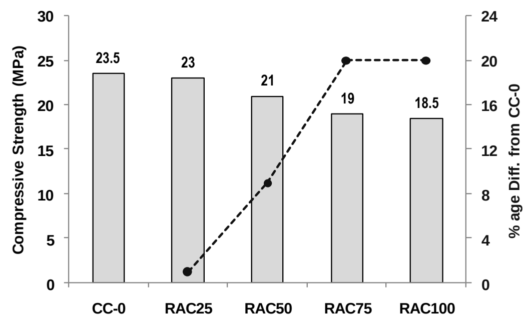


Fig. 8 Compressive Strength Of concrete

3.2 Modulus of Elasticity

The value of static modulus of elasticity of RAC has almost the same trend as in case of compressive strength results as shown in Fig. 9. Up to a replacement level of 75%, E value of RAC was dropped by 9% compared to E value of natural aggregate concrete. The drop in E value of RAC was 18% at 100% replacement of natural aggregate by recycled aggregate. This decrease in values of modulus of elasticity is mainly due to the significant quantity of cement mortar attached to recycled aggregates which makes the concrete more porous and less stiff. High porosity of concrete negatively affects the ability of aggregates to restrain matrix strain [15].

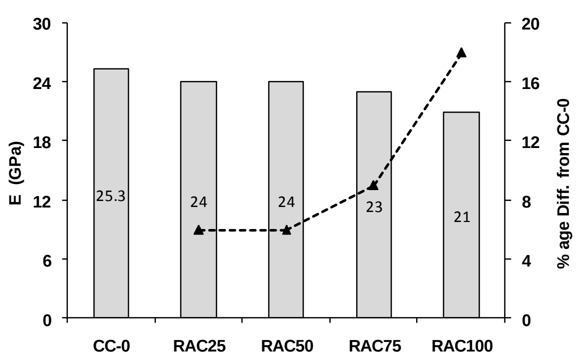


Fig. 9 Modulus of Elasticity

3.3 Fracture energy in Compression

The results of fracture energy in compression for the five concrete mixes are shown in Fig. 10. It is evident that with replacement of natural aggregates by recycled aggregates, fracture energy in compression is decreased. Moreover, it is observed that fracture energy in compression gradually decreases with increase in quantity of recycled aggregates in concrete. Reduction in branching and meandering of cracks during the failure process is the main reason of less fracture energy in case of concrete containing recycled aggregates.

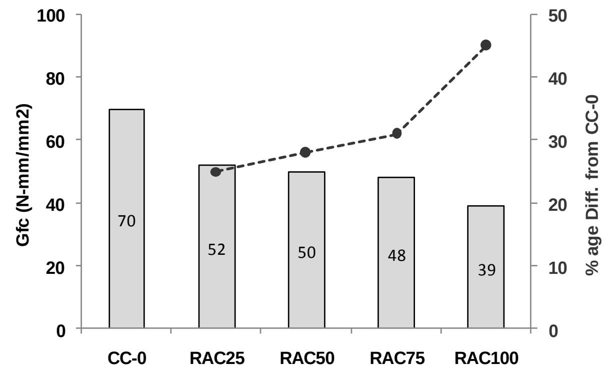


Fig. 10 Fracture Energy (G_{fc}) in Compression

3.4 Fracture Energy in Tension

The fracture energy in tension is generally decreased with increase in percentage of recycled aggregates as shown in Fig. 11. At 25% replacement level, almost same value of fracture energy in tension was obtained. At replacement levels greater than 25%, fracture energy in tension was gradually decreased with increase in percentage replacement of natural aggregates with recycled aggregates. Maximum drop in fracture energy in tension was 38% at 100% replacement level, in comparison with natural aggregate concrete. The drop in values of fracture energy in tension of recycled aggregate concrete is because of the weaker ITZ between recycled aggregates and new cement paste.

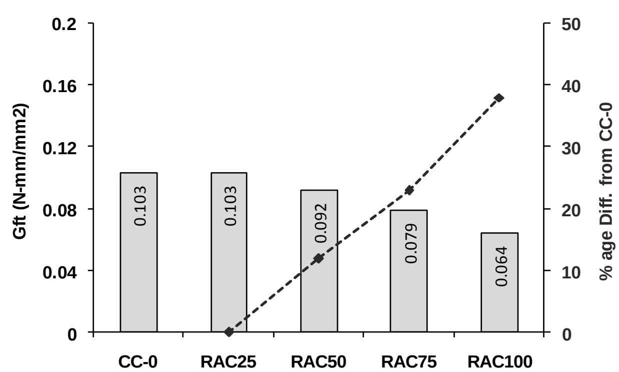


Fig. 11 Fracture Energy in Tension

The percentage decrease in compressive strength, modulus of elasticity, fracture energy in tension and fracture energy in compression of recycled aggregate concretes in comparison of control is given in Table 6.

Table 6 %age Decrease in Properties of RAC

Concrete Mix	%age decrease in comparison of CC-0			
	Comp. Strength	E-value	G_{fc}	G_{ft}
RAC-25	1	6	25	0
RAC-50	9	6	28	12
RAC-75	20	9	31	23
RAC-100	20	18	45	38

3.5 Load -CMOD Response

Load CMOD response curves of control and RACs are shown in Fig.12. it is evident in this figure that overall trend in the load CMOD curves of concrete made with recycled aggregates is similar to that of control concrete. The maximum load carrying capacity of the concrete in flexure was observed to be decreased gradually with the increase of recycled aggregates quantity in the concrete. The maximum drop in the peak load compared to control concrete was observed in concrete made using 100% recycled aggregates which was 30%. The drop in the peak load was 6% in case of concrete made by 25 % replacement of natural aggregates by recycled aggregates. It is interesting to mention that the CMOD value was almost similar at peak load in all five composites. Form the post peak behavior of all composites; it has been observed that no significant change in the ductility of concrete takes place by replacing the natural aggregates with recycled aggregates even up to 100%. The steepness of softening branch of Load-CMOD curve after the peak of all RACs was similar to that control concrete.

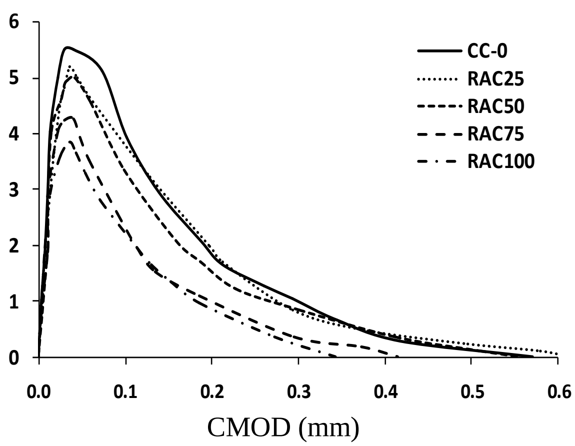


Fig. 12 Load-CMOD Curve for Five Concrete Compositions

4. Conclusions and Future Work

Five different mixtures with different degree of substitution of recycled aggregates have been studied. The important conclusions are stated as follows

- The compressive strength of RAC is decreased with an increase in recycled aggregate content. A maximum decrease of 20% is observed for concrete having only recycled aggregates.
- The static modulus of elasticity of RAC is lower than that of natural aggregate concrete. It decreases gradually up to 9% for RAC with 75% recycled aggregates and for concrete with 100% recycled aggregates, the drop is 18%.
- Recycled aggregate replacement percentage has a considerable influence on the fracture energies, both in tension in compression. A gradual decrease in value of fracture energy in tension is observed with increase in percentage of recycled aggregates and a maximum drop of 38% for concrete with 100% recycled aggregates. No change in the value of fracture energy in tension was noticed with concrete containing 25% recycled aggregates. Fracture energy in compression is significantly reduced by replacing the natural aggregates with recycled aggregates; 24% reduction was observed with concrete containing 25% recycled aggregates. Maximum reduction of 45% in the value of fracture energy in compression was exhibited by the concrete made with 100% recycled aggregates.
- Peak load value in flexure is decreased by replacing the natural aggregates with recycled aggregates. However, the CMOD value at peak load in flexure remains almost un-changed.

The future research in continuation of this study will focus on the energy dissipation capacity of reinforced concrete beams made using recycled aggregates and subjected to reverse cycling flexural loading.

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