Fracture Behaviour of Recycled Aggregate Concrete Beams – An Experimental Study

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Abstract: The purpose of this research is to assess the effect of recycled aggregates on the fracture energy properties of concrete under various notch depths. In this study, fracture energy of recycled aggregate concrete beams of size 700mmx150mmx150mm with notches of size 7.5mm, 15mm, 45mm and 75mm were provided to study the fracture energy properties like unstable fracture toughness and Crack Mouth Opening Displacement (CMOD). A clip gauge of 4-4mm range over a gauge length of 25mm was fixed across the notch at the bottom face of the beam to measure the crack mouth opening displacement (CMOD). Linear varying differential transformer (LVDT) of two numbers was used to determine the deflection of the specimens. Specimens of two water/cement ratios 0.5 and 0.45 were adopted to study the fracture energy and the results were compared. Fracture parameters such as unstable fracture toughness were predicted using empirical relations. Fracture studies elucidates that fracture energy dissipation increases with increase in the notch depth. Also, fracture energy dissipation and CMOD of recycled aggregate concrete is more compared to conventional aggregate concrete due to the higher water absorption capacity of recycled aggregates.

Keywords: Fracture energy, recycled aggregate, LVDT, CMOD, water absorption and Notch Depth.

1. Introduction
Manufacturing of concrete as a result of industrialization and urbanization rose up to 4 tonnes per capita annually [1,2]. Out of which 1/10th was demolished annually for renovation and dumped as waste in the landfill [3]. Also surprisingly it was found to be that C&D waste produced globally is getting merely equal to solid waste produced as per capita[4,5]. On other hand, demand in aggregates for construction purpose was found to be 3.8t per capita as per the WBCSD 2009. In past, C&D wastes have been mainly used in sub-base/base course layer for road construction. But later due to its huge production, use of C&D wastes in building construction is found to be more efficient than to be disposed on landfills [6]. In terms of its practical applications, the strength of recycled aggregate concrete is lower compared to conventional concrete which is due to various factors such as adherence of mortar on its surface, particle packing, and higher rate of water absorption etc. so the rate of dissipation of fracture energy and Crack Mouth opening displacement will be higher compared to conventional concrete. [7] Studied the role of size of aggregates on the fracture energy and fracture toughness of concrete beam under three point bending test. Studies report that fracture energy of concrete with larger size coarse aggregates is greater compared to smaller size coarse aggregates which is due to the increased cement paste-aggregate interface that experience higher bond stress leading to bond failure. With respect to Crack Mouth Opening Displacement (CMOD), the fair tail constant “A” could change the true fracture up to 11% if it is tested using CMOD instead of LVDT[8]. Increase in the size and content of the coarse aggregate is the major factor contributing towards the increase in the fracture energy of the concrete. It could be found that when Self Compacting Concrete (SCC) is used, specific fracture energy is lower compared to Normal strength concrete (NSC) which is due to the lower content of coarse aggregate in the self-compacting concrete [9]. Failure in recycled aggregate concrete is different compared to conventional concrete as the major contribution of fracture is around ITZ and properties of Recycled Aggregates (RA) used [10]. Mostly...
failure/ dissipation of fracture energy in RA will be more compared to Normal Aggregate (NA) when derived from the higher strength parent concrete [11]. With respect to Normal Aggregate Concrete (NAC), Recycled Aggregate Concrete (RAC) will have lesser stiffness and strength that presents decrease in the fracture energy and the size of the fracture zone [10]. Various models such as fictitious crack model, crack bond model, size effect model and double K fracture model were also being used to study the fracture toughness of NAC and RAC. Among which double K fracture model labels the complete fracture process starting from crack initiation to complete unstable fracture toughness [12]. Based on the previous studies, it is found that the frequency of research on the fracture properties of RAC is at a great lag; also the effect on notches of varying sizes on the fracture properties of RAC is at minimal level. This paper investigates the fracture properties of RAC under various notch depths such as 7.5mm, 15mm, 45mm and 75mm under varying w/c ratios such as 0.45 and 0.5. Each series includes concrete beams of size 700mmx150mmx150mm of varying notch sizes from 7.5mm to 75mm. CMOD using clip gauge set up and load displacement analysis using LVDT under single point bending test are analysed.

2. Experimental Programme

2.1 Materials
Ordinary Portland Cement (OPC) of 43 grades, river sand passing through 2.36mm sieve as fine aggregate, Gravel passing through 10mm and 20mm at 2:3 proportions as coarse aggregate, recycled aggregate collected from the demolished building of age 10 years passing through 10mm and 20mm at 2:3 proportions as coarse aggregate was used for this entire study. Potable water confirming to IS 456:2000 was used for mixing the concrete. Properties of various ingredients of concrete studied are shown in the table 1.

| S. No | Material Properties | Obtained Values |
|-------|---------------------|-----------------|
| 1     | Specific Gravity of Cement | 3.13            |
| 2     | Specific Gravity of fine aggregate | 2.63            |
| 3     | Fineness Modulus of fine aggregate | 2.76            |
| 4     | Bulk Density of fine aggregate | 1642 Kg/m³     |
| 5     | Specific Gravity of Coarse aggregate | 2.63            |
| 6     | Fineness Modulus of Coarse aggregate | 7.06            |
| 7     | Bulk Density of Coarse aggregate | 1666 Kg/m³     |
| 8     | Specific Gravity of Recycled aggregate | 2.73            |
| 9     | Bulk Density of Recycled aggregate | 1631 Kg/m³     |

2.2 Preparation of Recycled Aggregates
Recycled Aggregates collected from a demolished building site at CSIR-SERC of the age of 10 years were collected. Initially recycled aggregates were collected in the form of large boulders from the site through trucks. Later the gravels were broken down into an easily portable size using large sized hammers. Further the large size boulders were then reduced to a size of 10mm and 20mm and used for the manufacturing of concrete. Recycled Aggregates were broken down to a suitable sizes using Jaw Crusher Machine as shown in the figure 1. Initially the aggregates were soaked in water for 24 hours and dried in open atmosphere before it is to be used in the manufacture of concrete.
2.3 Preparation of test specimens
A total of 48 No. beam specimens of sizes 700mmx150mmx150mm was prepared to study the fracture energy properties of RAC. Notches were prepared at the bottom of the specimens of depth 7.5mm, 15mm, 45mm and 75mm. Near the notch clip gauge is set up to measure the Crack Mouth Opening Displacement (CMOD). Clip gauges are kept at a distance of 5cm from both corners of the specimen to hold the Linear Varying differential transformer (LVDT) in position.

2.4 Methodology
Fracture energy study and unstable fracture toughness of concrete beams under single point loading were performed on beam specimens of sizes 700mmx150mmx150mm at the age of 28 days. Prepared test specimens were subjected to single point loading on a simply supported set up. Two LVDT’s connected were used to measure the displacements of the specimen. This set up is subjected to gradual single point loading. This set up is connected to a system and operated manually. Breaking point of the specimen with CMOD, LVDT values were generated and analysis was done to study the peak load of occurrence of fracture under each notch depths.
2.5 Fracture Energy
Fracture energy test conducted on beam specimens of size 700mm x 150mm x 150mm at the age of 28 days was be computed based on the amount of energy required to create crack of unit surface.

\[ G_f = \frac{W}{b(d-a)} \]  

W = Area under the curve; b = breadth of beam (mm); d = depth of beam (mm); a= Notch depth at bottom of beam (mm).

2.6 Unstable fracture toughness
Unstable fracture toughness was computed based on the parameters such as maximum load to the specimen and initial crack length propagated due to the applied maximum load. Theoretically it was computed by

\[ K_{IC}^{un} = \frac{3P_{max}\sqrt{\pi a}F_1(V_c)}{2D^2B} \]  

\[ F_1(V_c) = \frac{1.99-V_c(1-V_c)(2.15-3.93V_c+2.7V_c^2)}{(1+2V_c)(1-V_c)^2} \]

V_c = ac/D; S = Span of beam; B = Breadth of beam; D = Depth of beam; F_1(V_c) = Geometry factor

3. Results and Discussions
3.1 Effect of w/c ratio on fracture energy properties of Recycled Aggregate Concrete
Fracture energy properties of beam specimens for both 0.45w/c and 0.5w/c at the age of 28 days under various notch depths such as 7.5mm, 15mm, 45mm and 75mm are shown in the table 2. From the results, it is found that fracture energy of RAC is lower compared to NAC at both w/c ratios and at all notch depths. With respect to 0.5 w/c ratio, fracture energy of NAC is 7.6% more compared to RAC at 7.5mm notch depth; fracture energy of NAC is 20.19% more compared to RAC at 15mm notch depth; fracture energy of NAC is 19.22% more compared to RAC at 45mm notch depth; fracture energy of NAC is 32% more compared to RAC at 75mm notch depth. With respect to 0.45 w/c fracture energy of NAC is 46.67% more compared to RAC at 7.5mm notch depth; fracture energy of NAC is 27.96% more compared to RAC at 15mm notch depth; fracture energy of NAC is 29.21% more compared to RAC at 45mm notch depth; fracture energy of NAC is 15.9% more compared to RAC at 75mm notch depth. Also it is found that fracture energy of NAC is more compared to RAC as the w/c ratio reduces and as the notch depth increases and as a result the fracture energy gets decreased.
### Table 2. Fracture energy of RAC

| w/c ratios | SPECIMEN ID | Fracture Energy (N/m) |
|------------|-------------|-----------------------|
|            |             | 7.5mm | 15mm | 45mm | 75mm |
| 0.45       | NAC         | 235.7 | 164.27 | 161.14 | 113.66 |
|            | RAC         | 125.69 | 118.34 | 114.07 | 95.55 |
| 0.5        | NAC         | 160.81 | 153.12 | 145.5 | 143.22 |
|            | RAC         | 148.58 | 122.19 | 117.53 | 97.33 |

### Figure 4. Fracture energy of RAC

3.2 Effect of Notch depth on Unstable Fracture Toughness of Recycled Aggregate Concrete

Unstable fracture toughness of beam specimens for both 0.45 w/c and 0.5 w/c at the age of 28 days under various notch depths such as 7.5mm, 15mm, 45mm and 75mm are shown in the table 3. From the results it is found that the $K_{IC_{un}}$ of RAC is lower compared to NAC, but as the w/c gets reduced the $K_{IC_{un}}$ of RAC is found to be more compared to NAC. At 0.5 w/c, $K_{IC_{un}}$ of NAC is 20.64% more compared to RAC at 7.5mm notch depth; $K_{IC_{un}}$ of NAC is 21.9% more compared to RAC at 15mm notch depth; $K_{IC_{un}}$ of NAC is 23.29% more compared to RAC at 45mm notch depth; $K_{IC_{un}}$ of NAC is 24.18% more compared to RAC at 75mm notch depth. At 0.45 w/c, $K_{IC_{un}}$ of NAC is 3.09% more compared to RAC at 7.5mm notch depth; $K_{IC_{un}}$ of NAC is 3.26% more compared to RAC at 15mm notch depth; $K_{IC_{un}}$ of NAC is 3.45% more compared to RAC at 45mm notch depth; $K_{IC_{un}}$ of NAC is 4% more compared to RAC at 75mm notch depth.

### Table 3. Unstable Fracture Toughness

| Specimen Id | $A_c$ (mm) | $K_{IC_{un}}$ (MPa m$^{1/2}$) |
|-------------|------------|-------------------------------|
| NAC-0.5     | 7.5mm      | 1.942                         |
|             | 15mm       | 1.916                         |
|             | 45mm       | 1.893                         |
|             | 75mm       | 1.843                         |
| NAC-0.45    | 7.5mm      | 2.162                         |
|             | 15mm       | 2.356                         |
|             | 45mm       | 2.519                         |
|             | 75mm       | 2.637                         |
| RAC-0.5     | 7.5mm      | 1.541                         |
|             | 15mm       | 1.496                         |
|             | 45mm       | 1.452                         |
|             | 75mm       | 1.397                         |
| RAC-0.45    | 7.5mm      | 2.095                         |
3.3 Effect of notch depth and magnitude of loading on CMOD

3.3.1 Normal Aggregate Concrete. Effect of notch depth and rate of loading on crack mouth opening displacement for conventional aggregate concrete at 0.45 w/c and 0.5 w/c are shown in the figure 5. From the results, it is found that width of crack opening for 0.45 w/c ratio is 0.9 whereas for 0.5 w/c ratio the width of crack opening is found to be 0.55. Load carrying capacity of concrete at 0.5 w/c ratio is found to be 12.2% more compared to those at 0.45 w/c ratio.

![Figure 5. CMOD Analysis for NAC](a) ![Figure 5. CMOD Analysis for NAC](b)

3.3.2 Recycled Aggregate Concrete. Effect of notch depth and rate of loading on crack mouth opening displacement for both recycled aggregate concrete at 0.45 w/c and 0.5 w/c are shown in the figure 6. From the results, it could be inferred that that the breaking of RAC-0.5 specimen occurs at 12097N for 7.5mm notch depth. Also the load carrying capacity at RAC 0.5 w/c ratio is less than the NAC 0.5 w/c ratio specimens. This is because of the weak bond interface in recycled aggregate concrete specimens. Henceforth the CMOD value of 7.5mm notch specimen is 0.55 which is lesser than 7.5mm notch depth of NAC-0.5. In case of 0.45 w/c, it could be seen that that the breaking of RAC-0.45 specimen occurs at 11045N for 7.5mm notch depth. The load carrying capacity at RAC 0.45 w/c ratio is less than the RAC 0.5 w/c ratio specimens. This is because of the water absorption capacity of mortar present on the top surface of recycled aggregates. Also the CMOD is more for 45mm notch specimen which is around 0.6 which is lesser than NAC-0.45.

![Figure 6. CMOD Analysis for RAC](a) ![Figure 6. CMOD Analysis for RAC](b)
4. Conclusion
From the experimental study, it be could be clear that for 0.45 w/c ratio as the notch depth increases the fracture energy values decreases. This is because as the notch increases the load spreading area gets decreased, which will reduce the load carrying capacity. This will ultimately reduce the fracture energy. At 0.45 w/c ratio the fracture energy of Normal aggregate concrete is 46.67% more than Recycled aggregate concrete at 7.5mm notch depth, 27.96% for 15mm notch depth, 29.21% for 45mm notch depth and 15.93% for 75mm notch depth. This is mainly due to the presence of cement particles on the surface of Recycled aggregate which reduces the bond interface between the constituents of concrete. At 0.5w/c ratio, the fracture energy of Normal aggregate concrete is 7.6% more than recycled aggregate concrete at 7.5mm notch depth, 20.199% for 15mm notch depth, 19.22% for 45mm notch depth and 32.04% for 75mm notch depth. From the tabulated values it could be seen that fracture energy values of recycled aggregate concrete at 0.5 w/c ratio is more than 0.45 w/c ratio. This is mainly due to the water absorption capacity of recycled aggregate concrete. At 0.5 w/c ratio, there will some enough water to form strong cement matrix bond between the aggregates, whereas it will be less at 0.45 w/c ratios. Also from the unstable fracture toughness value it could be clear that the as the notch depth increases the fracture toughness value decreases at 0.5 w/c ratio and increases as the notch depth increases for 0.45 w/c ratio. But in case of Recycled aggregate the fracture toughness is lesser compared to normal specimens. This is mainly because of presence of adhered mortar on the surface of aggregate which will reduce the interfacial bond. This will ultimately reduce the toughness of the specimen. On a whole, recycled aggregates can be utilized as a aggregates in concrete to certain replacement levels satisfying the strength and fracture properties. On the other hand, better performance can also be achieved by subjecting the recycled aggregates to pre-treatments to remove the adhered mortar on the surface of the aggregates.

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