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Mechanical properties of recycled coarse aggregate beams reinforced with steel fibers

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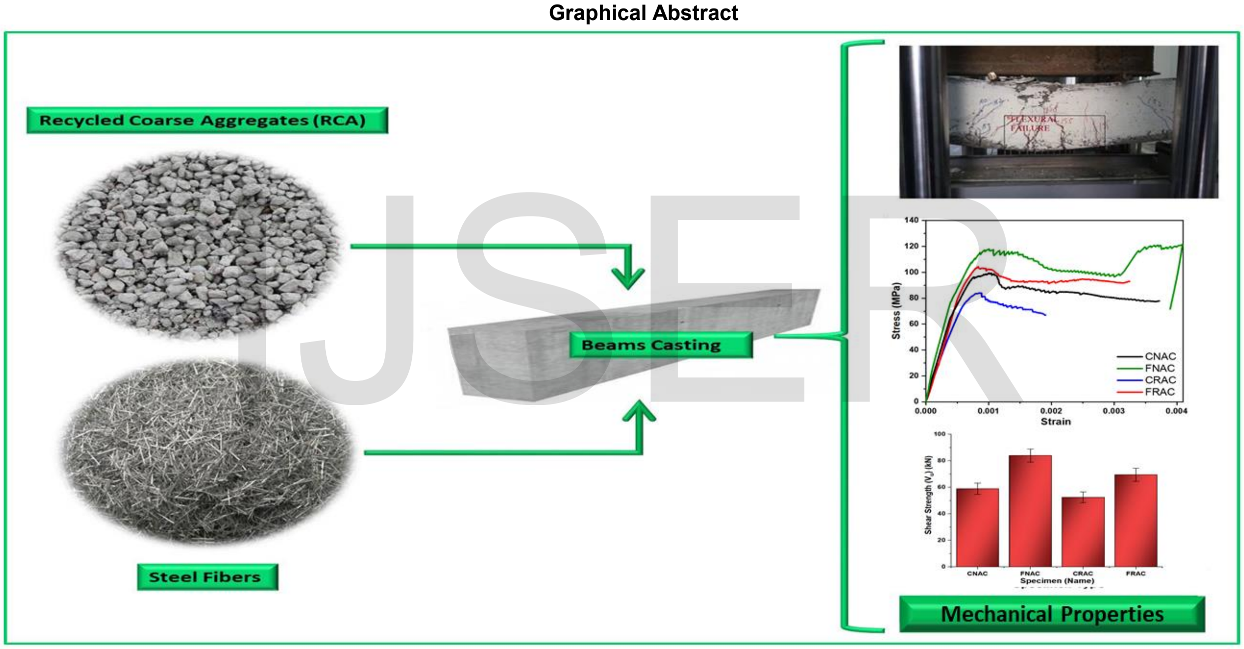
— Continuous quarries of natural resources are contributing towards the environmental degradations. Natural stone aggregates being the primary ingredients of concrete have a very high demand in the construction sector of every country. Unfortunately, this high demand is leading towards the depletion of such natural resources. Therefore, it is needed to save the natural resources by adopting some alternatives in place of natural stone aggregates. In this study, we have replaced the natural coarse aggregates (NCA) with the recycled coarse aggregates (RCA) from the old and demolished constructions. Furthermore, in order to overcome the blemishes in bonding and strength development of RCA concretes, the steel fibers were incorporated. Then the compression strength, flexural behaviour and shear strength was investigated in reinforced concrete (RC) beams. This study shows that the RCA beams with steel fibers (FRAC) give higher failure loads and have higher strain energy compared to the control natural aggregates without fibers (CNAC). Moreover the steel fibers were responsible for changing the failure modes from shear compression to flexural, for both of the CNAC and control RCA concrete (CRAC). Thus, it can be said that the combination of steel fibers and RCA in concrete elements can significantly enhance their ductility.

Index Terms— Recycled coarse aggregates (RCA), shear failure, flexural failure, shear compression, steel fiber, reinforced concrete beams, strain energy

Graphical Abstract



1 INTRODUCTION

ALL over the world, the second most used material is concrete, after water. To sustain its suitability and adaptability with respect to the changing environment, the production of concrete must align with the aim of conserving natural resources, protecting the environment, economizing construction costs in order to ensure sustainable utilization of energy.

To achieve this target, major emphasis must be laid on reusing wastes and by-products by incorporating them in concretes used for new constructions. Because disposal of the concrete waste has become a harsh social and environmental problem and it is turning into a burden on the world's natural resources and an increasingly expensive problem for solid waste management. Recycled elements used in concrete should present such behavior that is

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appropriate for structural mechanical properties. Structural demolishing wastes has huge potential for producing recycled coarse aggregates (RCA) by crushing the discarded concrete beams, slabs and other concrete elements, up to a required size suitable for casting purposes. The practice of recycling results in a range of environmental and economic benefits, like; (i) reduction in costs for the transportation of waste to the landfill (ii) cheaper source of aggregate than newly mined from natural habitat (iii) reduction in landfill space required for concrete debris (iv) diminishes the need for gravel mining [1]. Moreover, high-grade aggregates sources for roads construction are usually available only at specific hilly areas, thus recycling aggregates can reduce the associated economic and environmental cost impacts related to the longer haulage distances. The disposal of all the concrete waste has become a harsh social and environmental problem turning it in a burden on the world's natural resources and an increasingly expensive problem for solid waste management [2]. In addition to other natural resources, the global demand of coarse aggregates is also increasing day by day, from 2011 to 2019 there was 9.8% increase in the global aggregates demand. In US alone, there is 136 million ton annual production of demolition and construction waste [3]. Moreover, 30% of total waste of Pakistan is coming from only the buildings construction [4]. Therefore it is needed to recycle these wastes to reduce the carbon foot print of environment. It is needed to research and test the effectiveness of RCA in the construction field to have an ECO friendly industry [5] [6] [7].

Previous researches show that the mechanical properties of concrete (shear, compression and flexural strength) are reduced by the use of RCA because of the weaker bonding of old waste aggregates with the cement paste [8] [9]. Therefore, we have introduced an energy efficient and sustainable solution to overcome the RCA flaws by the incorporation of steel fibers. Consequently, this remedy can help in elevating the mechanical properties of concrete and conserving or maintaining the world's natural resources.

2 MATERIALS AND EXPERIMENTAL PROCEDURES

RCA of maximum size 19 mm were derived from pre-stressed concrete beams which were collected from Izhar Construction (Pvt.) Ltd, Pakistan. The Lawrancepur sand with finesse modulus (FM) 2.3 and Sargodha crush were used as the fine aggregates and natural coarse aggregates (NCA) respectively. The physical properties of NCA and RCA are elaborated in Fig. 1, which were determined according to BS 812-105, BS 812-110, ASTM C29 [10] and ASTM C127 [11]. The Maple leaf cement, ASTM C150 Type I [12], sand and coarse aggregates ration were 1:1.12:2.12 with water to binder ratio of 0.4. In order to maintain the slump of 75-100 mm "Chemrite 520-BA" super-plasticizer was used as 0.2% by weight of cement. The 0.46 mm diameter and 25 mm long steel fibers (2% by the weight of specimen) were also incorporated in some formulations to enhance the shear strength and modulus of rupture or toughness of beams [8]. The grade 60, #13 and #10 rebars were used as the main and hanger steel bars respectively as shown in Fig. 2. The #10 bars were again used as the stirrups of beams and were placed at a center to center distance of 150 mm. Then concrete was mixed in a drum mixer followed by dry and wet mixing respectively.

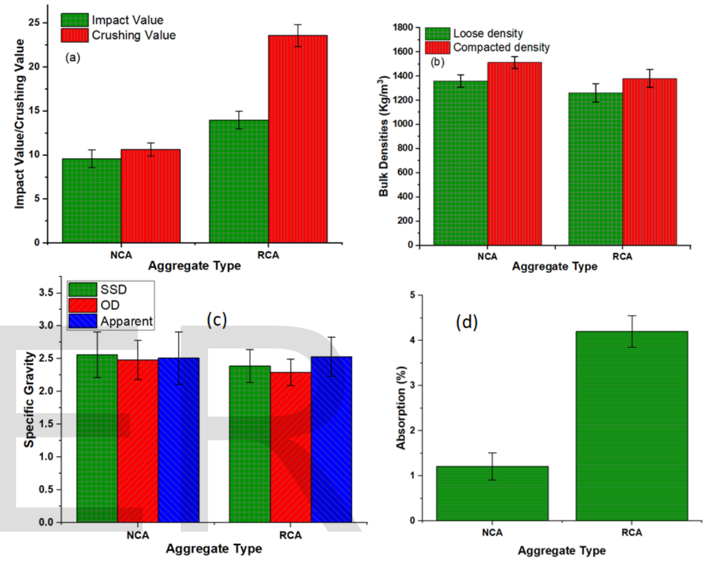


Fig. 1. Physical properties of coarse aggregates (a) Impact and crushing values (b) Loose and compacted bulk densities (c) Specific gravities (d) Water absorption

There were total four different formulations of concrete and for each formulation three reinforced concrete beams of size 1.68×0.22×0.12 m^3 were casted where the shear span (a) to depth (d) ratio was kept 1.5. These specimens were prepared as; (i) control natural aggregates concrete (CNAC), (ii) fiber natural aggregates concrete (FNAC), (iii) control recycled aggregate concrete (CRAC) and (iv) fiber recycled aggregate concrete (FRAC) specimens. The reinforced concrete beams were designed for 100kN load with the concrete cover of 25 mm on each side.

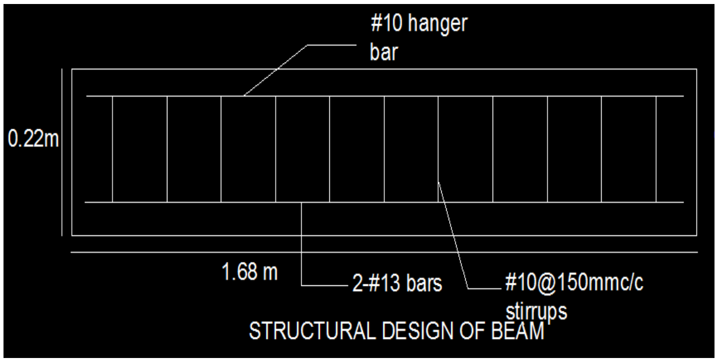


Fig. 2. Structural design of RC beams

The compressive, shear and flexural response of each specimen was monitored with loading rate of 2MPa/sec and the load-deflection curves were plotted, where the deflection at mid span of the beam was measured with the help of deflection gauge. Then flexural strength or modulus of rupture (MOR) and rupture/flexural strains were also calculated by using the expressions given in ASTM C78 [13], shown in (1) and (2).

$$Flexural\ Strength = MOR = \frac{3FL}{2wh^2} \quad (1)$$

$$Flexural\ Strain = \frac{6Dh}{L^2} \quad (2)$$

Where; F is the maximum load, D is the deflections, w, h and L are the width, height and clear length of specimen respectively. Then pre-peak and post-peak energy or strain energy stored by the material up to the 1st crack generation and the rupture point respectively, of each specimen was calculated by taking the area under the stress-strain curves. The modulus of toughness was also determined by taking the under the curve area up to the fracture point, which represent the overall energy capacity of specimen needed to fracture that particular beam. The toughness indexes indicates the opening and closing of cracks due to applied external loads and inter locking pressure of aggregates respectively. It was calculated by using the expression given in (3).

$$Toughness\ Index = \frac{a_1}{a_2} \quad (3)$$

Where, a_1 is the area under the stress-strain curves up to the fracture point of MOT and a_2 is the area under stress strain curves up to the proportional limit.

The 28 days compressive strength according to ASTM C39 [14] and shear capacity of different types of beams was also examined and compared to interpret the effect of steel fibers on the failure modes of concretes having natural and recycled aggregates.

3 RESULTS AND DISCUSSIONS

3.1 Physical properties of aggregates

The results of different phisical properties of NCA and RCA are represented in Fig.1. The RCA have comparatively high impact and crushing values than the NCA which means RCA have low resistance to sudden impact and crushing (Fig. 1(a)). We can say it will be lesser suitable for important construction projects if added directly without the addition of any extra property modifiers. Similarly, it has 7 to 8% lesser loose and compacted densities respectively compared to the NCA (Fig. 1(b)). But there is only slight difference in the specific gravities of both type of aggregates as shown in Fig. 1(c). On the other hand the water absorption of RCA was surprisingly high compared to the NCA so extra water was added at the time of wet mixing of concrete (Fig. 1(d)). High water absorption is also the indication of poor quality and fragility of aggregates which should be mitigated before employing into the concrete mix.

3.2 Crack pattern of RC beams

The propagation of cracks in to the RC beams was also monitored as shown in Fig. 3(a-d). In the start or former to crack origination, the width of cracks openings for all places were small. In the CNAC beam, there were wider diagonal cracks developed in the shear span region followed by the concrete crushing in the compression zone. Which indicated the shear-compression failure. But with the incorporation of fibers (FNAC specimen), changed the failure pattern to pure flexure where small width flexural cracks were well distributed in the tension zone. The cracks took significant time to open up wider due to the yielding of steel fibers. In CRAC beams the failure pattern was also similar to the CNAC beam but failure occured at smaller loading values. But by the addition of fibers (FRAC specimen) the failure again converted to flexure with crushing of concrete from top fibers or compression zone. The crack initiation and propagation pattern ia also supported by previous research findings [15].

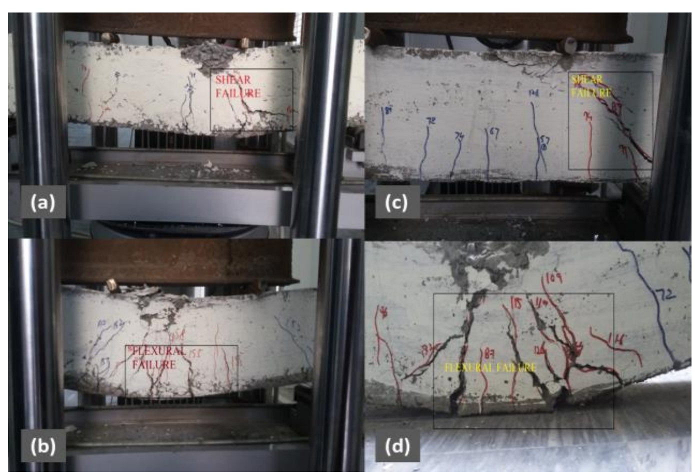


Fig. 3. (a) Fracture behavior of CNAC beam **(b)** Fracture behavior of CFRC beam **(c)** Fracture behavior of RCAC beam **(d)** Fracture behavior of FRAC beam

3.3 Flexural behavior of RC beams

Fig. 4(a) representing the comparison of load-deflection curves of all specimens. The first segment of all load-deformation curves is up to the point of first crack which represents the un-cracked beam. It can be seen from the curves that the FNAC beam has maxiumum load taking ability and the first crack appeared around 140kN of loading. It means that steel fibers were hindering the propagation of cracks and the beam was sustaing even at higher loads and higher displacements. The CNAC was taking lesser loads but it was giving higher deflections compared to the CRAC, moreover its behavior was ductile compared to the CRAC specimen. The CRAC showed the copartively brittle behavior and failed at smaller loads due to weaker bonding of RCA with cement paste and quality drawbacks of intertranition zone (ITZ). On the other hand, the FRAC showed the intermediat trend of FNAC and CNAC which is representing that the fiber reinforcement in RCA concrete is efficient in elevating the flexural response of RC beams even better than the CNAC beams.

After the first crack, the slope of the load-deflection curves starts to decrease due to the gradual concrete cracking with increasing number of cracks developed in the tested beam specimens. With further increase in the applied load, the longitudinal reinforcements start to yield and then the slope of the curves significantly decline beyond the yielding point. In this stage, with a small increment in the applied load the deflection suddenly increases and meets the maximum load-carrying capacity. And the concrete crushing takes place with an abrupt drop in the load level. All of the samples showed the similar trend but at different loading values expect the FNAC beam where the load was redistributed and it again started to bear load due to the crack bridging of fibers and then suddenly failed.

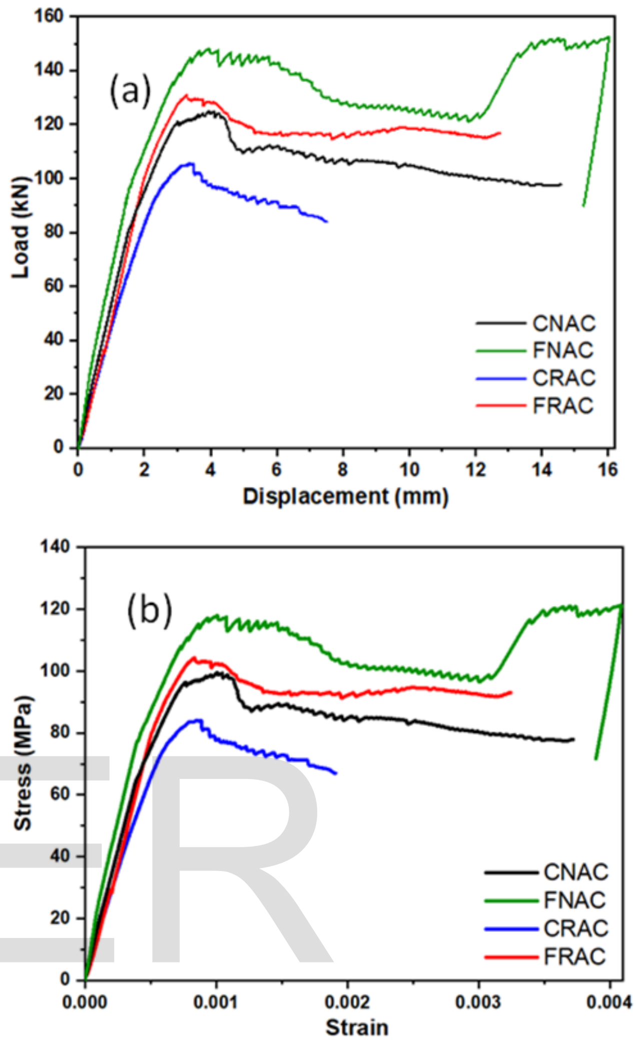
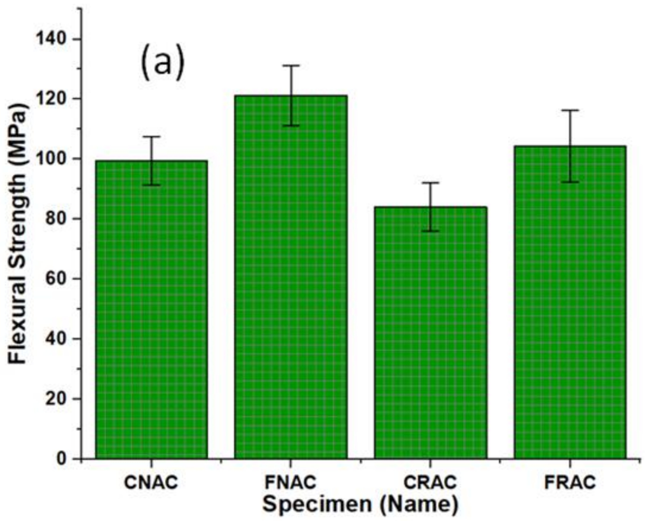


Fig. 4. (a) Load-deflection curves of all beams **(b)** Stress-strain curves of all beams

The stress-strain curves are shown in Fig. 4(b), which are representing the similar behavior as for load-displaement curves for each specimen because both terms have direct relation with each other.

The maximum flexural strength or modulus of rupture (MOR) and rupture strains from the stress-strain curves were obtained and compared for analysis as shown in Fig. 5(a,b). The FNAC sample is about 16% efficient in flexural strength compared to the CNAC where only the steel fibers are the reason to elevate this property. But CRAC have about 12% less flexural strength due to weaker ITZ and due to the lesser lubrication provided by the cement paste to the RCA compared to the NCA. On the other hand the flexural strength of FRAC was higher than the CNAC and CRAC, but lesser than the FNAC. Therfore, it can be summarized that the steel fibers addition in CRAC can overcome the drawbacks of ITZ in terms of enhancing the flexural properties.



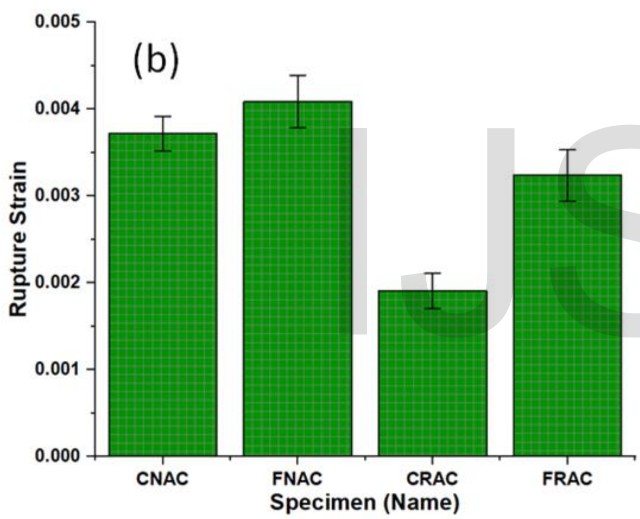


Fig. 5. (a) Maximum flexural strength and **(b)** rupture strain of all beams

Fig. 5(b) is representing the rupture strains of all beams, the FNAC and CRAC are following the trend of flexural strength results but the FRAC have lesser rupture strain value than the CNAC in regardless of the high flexural strength. This behavior indicates that FRAC have comparatively lesser strain absorbing capacity and its behavior becomes little fragile at higher strain values.

The area under the stress-strain curve is a representation of the amount of energy absorbed by the respective specimen. Fig. 6(a) representing the stored strain energies by each specimen up to the proportional limit, from proportional limit to fracture point and overall from zero loading to fracture point. Which are labled as the pre peak energies, post peak energies and modulus of toughness (MOT). The FNAC is showing higher amount of absorbed energy before and after the cracking compared to all remaining samples, which is the indication of ductile behavior of the FNAC in addition to the maximum flexural strength among all other samples. The CRAC have minimum values for all of the strain energies which is accordance to its overall stress-strain trend. But FRAC showed better strain energy absorption capacity than the CRAC which is even approximate to the CNAC beam. The rise in energy can be attributed to the embedment of the fibers at cracking regions which allowed larger deformations in the beams.

The toughness index of all beams is shown in Fig. 6(b). Both of the fiber reinforced beams show higher toughness index than the respective control specimens. But the quantitative increase in FRAC is more than the FNAC beam it means that the effect of fibers in RCA concrete is higher in terms of enhaching toughness of beams. As can be seen that the FRAC have highest toughness index despite of having lesser strain energy. Therefore, it can be said that the FRAC beam is sufficienly tough in bending and also show comparable results of ductility as well.

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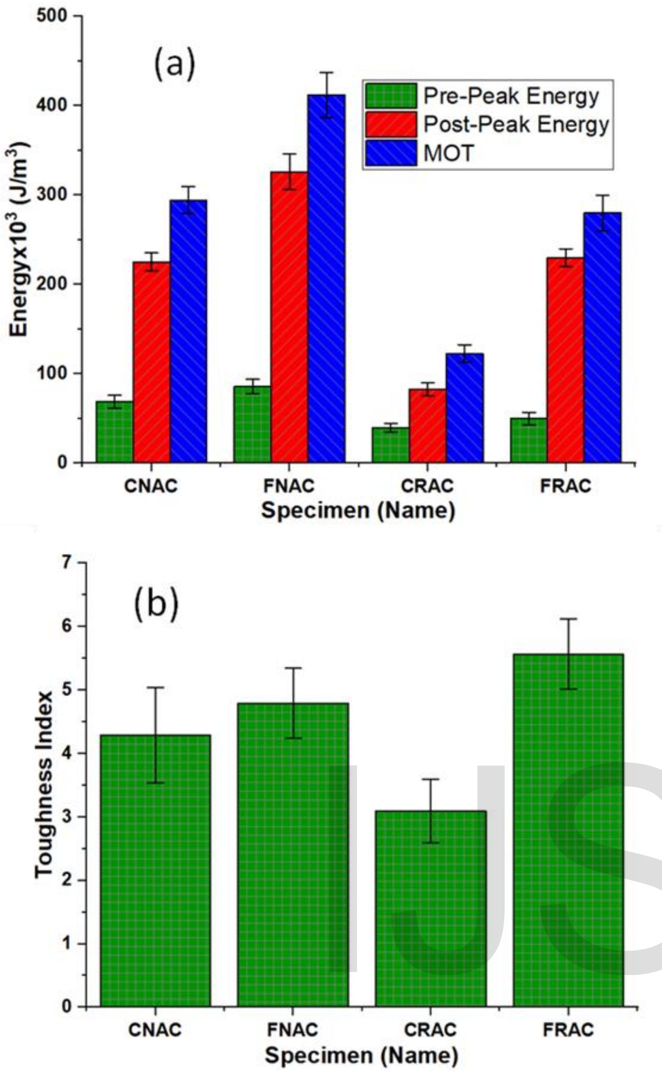

Fig. 6. (a) Pre/post peak energies and modulus of toughness (MOT) of each specimen **(b)** toughness index of all beams

3.4 Compressive strength

The compressive strength ressults are lso confirming the flexural strength results for each sample, as can be seen from Fig. 7. Research shows that the type of aggregates are also very crusial when talking about the compressive strength of cementitious composites [15], this is also confiremed by this study as well.

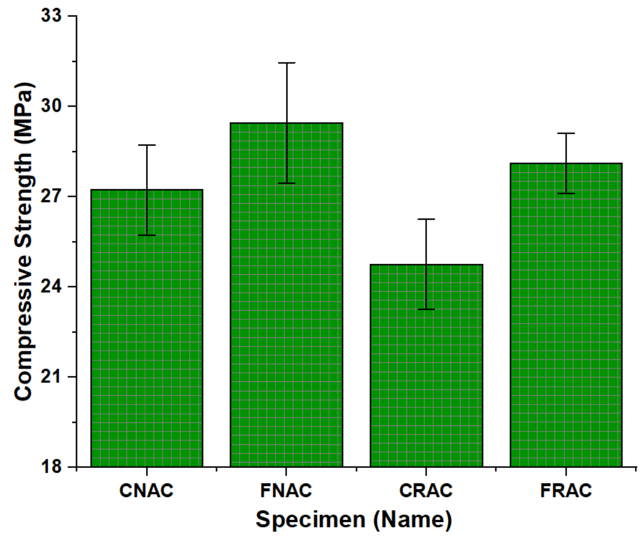

Fig. 7. The compressive strengths of all specimens

Addition of fibers in CNAC enhanced 7.6% strength but addition of fibers in RAC enhanced it by 12%. As again it can be noticed that the enhancement of strength in RCA concrete is higher compared to the NCA concrete, on the addition of fibers. It might be due to the higher compressive strength of steel fibers instead of the aggregates or the cement paste. And the strength of FRAC was higher than the CNAC sample but it was opposite for the case of fiber less (CRAC) specimen. Because in that case the overall compressive strength was dependent upon the quality of ITZ, bonding of aggregates with cement paste and strength of aggregates. Whereas, all of these properties do not adequetly govern for the RCA and RCA concretes without the modifiers [8] [9].

3.5 Shear behavior

The concrete shear strength is a fucntion of its 28 days compressive strength (fc') [16] but recent studies show that it is also much dependent on the aggregates type as well [15].

The shear strength comparison of all specimens is represented in Fig. 8. The value of experimental shear of FNAC was 29.76 % more than the CNAC beam which is due to the bridging effect of the steel fibers [15] [17].

The value of shear strength of CRAC was lesser than the all other specimens and it was about 11.01% lesser to the CNAC because it was composed of RCA. This result indicates that the RCA did not show the proper bonding with cement paste and the initial RCA testing, like higher water absorption capacity of aggregates also support this finding that RCA has porous and spongy structure. Therefore, internal interconnecting voids spaces and poor bonding with larger ITZ between aggregates and cement paste leads to the easiest fracturing of beams, in flexure, compression and shear.

The FRAC beam showed 15.1% enhanced shear capacity compared to the CNAC beam. The steel fibers are responsible for this highe strength which had strong bonding with the cement paste and they were also contributing in deflecting the cracks by diverting or branching the cracks, therefore this beam behaved better than the CNAC and CRAC beams. Fibers in RAC enhanced the shear strength by 27.7%.

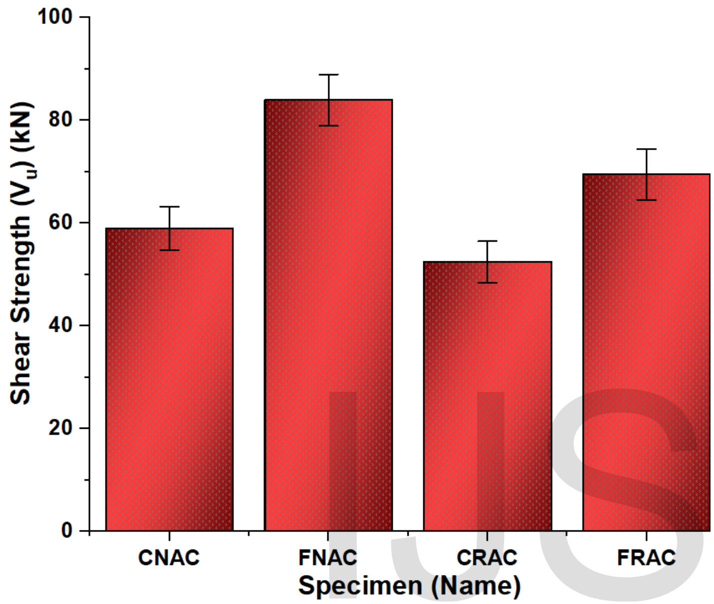

Fig. 8. The shear behavior of all specimens

4 CONCLUSIONS

This study provides a comprehensive evaluation of a sustainable concrete made with RCA and steel fibers through large scale tests on reinforced concrete beams. These conclusions can be drawn based on the experimental observations:

a) Incorporating fibers increase the compressive strength of RAC beams due to the crack bridging characteristics of steel fibers.
b) The fiber reinforced recycled aggregates RC beams can resist higher deflection than the natural and recycled aggregate beams without fibers.
c) The steel fibers in RCA concrete make the strain energies comparable to NCA concrete and prevent the brittle failures.
d) Fibers in RCA beams induce higher toughness values thus lead towards the ductile behavior.
e) Steel fibers enhance 27.7% shear strength capacity of RCA concrete compared to the RAC without steel fibers.
f) The addition of steel fibers to both the RCA concrete and NCA changed the failure mode from shear compression to flexural failure which indicates that the utilization of fibers with RCA concrete can lead to ductile behavior of reinforced concrete beams.

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