Chapter 16

Use of Polyethylene Terephthalate Fibers for Strengthening of Reinforced Concrete Frame Made of Low-Grade Aggregate

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Additional information is available at the end of the chapter

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Abstract

This chapter presents an experimental finding on the use of waste materials for strengthening a reinforced concrete (RC) frame prepared with low-grade materials. Compressive, tensile and flexural strength of concrete specimens made of recycled coarse aggregate (RCA) and natural coarse aggregate (NCA) were evaluated to assess RCA suitability for structural use. Results show that the strength parameter decreases in all cases. In order to extend the application of RCA concrete to structural elements, three RC frames were prepared and tested under monotonic loading. The joint regions of one of the frame were cast using Polyethylene terephthalate (PET) fiber, i.e., PET fiber-reinforced concrete (PFRC). PET fiber (aspect ratio = 25) of 0.5% by weight of concrete used in the PFRC mix was obtained by hand cutting of post-consumer PET bottles. A reference specimen was also prepared using 100% NCA and subjected to a similar loading condition. The RCA frame resulted in a brittle mode of failure and lower load carrying capacity as compared to the reference specimen. However, the presence of PFRC improved the damage tolerance and load resisting capacity and hence seismic parameters such as stiffness degradation, ductility and energy dissipation increased. This indicates that PET fiber is a viable substitute for steel fiber as a low-cost material in improving the seismic performance of frame structures.

Keywords: reinforced concrete frame, concrete mechanical strength, recycled coarse aggregate, polyethylene terephthalate fibers, monotonic loading, seismic performance

1. Introduction

Major centers of demand for aggregates are often not completely satisfied by local supplies and large quantities have to be brought in from a considerable distance. With the passage of time it is likely that both the quantities imported and the distances transported will increase with detrimental effects on cost and environmental intrusion unless alternatives are considered. Using of low grade aggregates, if technically and economically suitable, have the dual advantage of reducing the amount of quarrying required and also of reducing the amount of land required for tipping. Generally the low grade aggregates are those aggregates which lose strength generally by more than 15% upon wetting. Aggregates obtained from a demolished concrete waste are considered as a low grade aggregate. Recycling of such waste is a beneficial from the viewpoint of environmental preservation and effective utilization of resources. The processed concrete waste (recycled aggregates) either fine or coarse has been use as a replacement of the natural aggregate for a number of years. Various researchers [1–3] showed that reduction in the mechanical strength is not much prominent, when recycled coarse aggregate (RCA) replacement is up to 30%. Further, results reported [4, 5] showed that RCA concrete exhibited a similar behavior, which can be adequately used in concrete technology application. Literature revealed that most studies on utilization of RCA in concrete production have been limited to mechanical strength evaluation. For confident utilization of RCA in the construction industry, its structural behavior ought to be investigated. Some past studies concerning the behavior of beams [6], columns [7] and beam-column joints [8], RC frame structure [9] manufactured from RCA were reported. Most of their findings on their structural behavior are positive. However, due to its brittle behavior of RCA the load carrying capacity of most of the RCA specimens gets reduced. This perhaps the reasons that RCA was not prominently use in structural elements.

In all RC framed structures, the beam-column joints play an important role in the overall response of the frame structures under strong influence of seismic attack. To enhance the seismic capacity of the frame structures, steel fibers reinforced concrete (SFRC) has been incorporated in the joint region [10]. Test results revealed that SFRC enhances flexural capacity, shear strength, ductility and energy dissipation capacity. In substitution of steel fiber polymeric fibers made of nylon, aramid, polypropylene, polyethylene and polyester has been used as concrete reinforcing materials. Various experimental studies [11–13] showed PET fiber has a potential use for enhancing the mechanical properties of concrete that can replace steel fiber. The fiber content generally varies from 0.1 to 1.0%. However, a fiber content of 0.5% by weight of concrete is reported as an optimum percentage [14]. Seismic parameters such as load resisting capacity, ductility, energy dissipation capacity and stiffness of beam-column connection improve when a concrete mix incorporating PET fiber is use at the joint region [15].

Due to various negative aspect possessed by recycled aggregate for concrete production, the seismic performance of frame structure made of RCA may be lower than those of conventional concrete. Like the conventional concrete, various techniques may be employed for improving the mechanical properties of RCA concrete. One such technique on a particularly use of PET fibers for enhancing the mechanical strength and energy dissipation capacity of RCA has been reported [16]. The study reveals that a significant enhancement in tensile, flexural and energy dissipation capacity was achieved. Also, PET fiber has a potential for arresting crack formation due to fiber-bridging action inside the concrete matrix. Thus, it is expected that use of PET fiber in the joint region of an RC frame would delay the crack formation and crack growth. This would result in enhancement of displacement ductility due to delayed bond failure and hence overall improved the seismic performance of the frame structures.

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Therefore, the main objectives of this study is to investigate the structural behavior of an RC frame prepared with RCA concrete and strengthened using PET fibers within the joint region and partly in both column and beams, which is the D-region as defined by ACI 318-08 [17].

2. Experimental program

2.1. Materials

Ordinary Portland Cement (OPC) of 43 grades conforming to IS: 8112 [18] was considered. The maximum size of natural coarse aggregate (NCA) was 16 mm. River sand was used as fine aggregate (FA) (0–4.75 mm size). The RCA's (5–16 mm size) are obtained from the demolished reinforced cement concrete (RCC) roof slab of 20 years old. The large pieces of the roof slab are transported to the laboratory and broken into pieces of aggregates smaller than 20 mm in size and sieved through a 16 mm sieve. The aggregates greater than 16 mm in size are further broken to a maximum size of 16 mm. All aggregates used in this study have been tested as per relevant codes [19, 20] and the physical properties are presented in **Table 1** and the particle size gradation is shown in **Figure 1**. The polymeric fiber type use for strengthening or enhancing the mechanical properties of concrete was PET fiber. The geometry of PET fiber considered was "straight slit sheet", which has the shape similar to those of steel fibers

Mix	Apparent density (kg/m³)	Bulk density (kg/m³)	Grading (mm)	Elongated particle content (%)	Water absorption (%)	Crush index (%)
NCA	2830	1560	5–16	5	0.97	5.81
RCA	1600	1130	5–16	10	5.30	12.73

Table 1. Physical property of NCA and RCA.

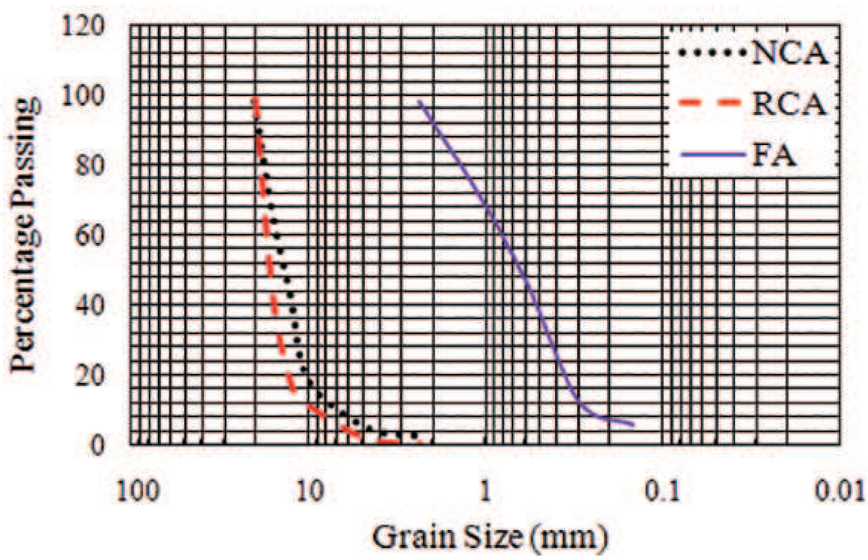

Figure 1. Particle size gradation.

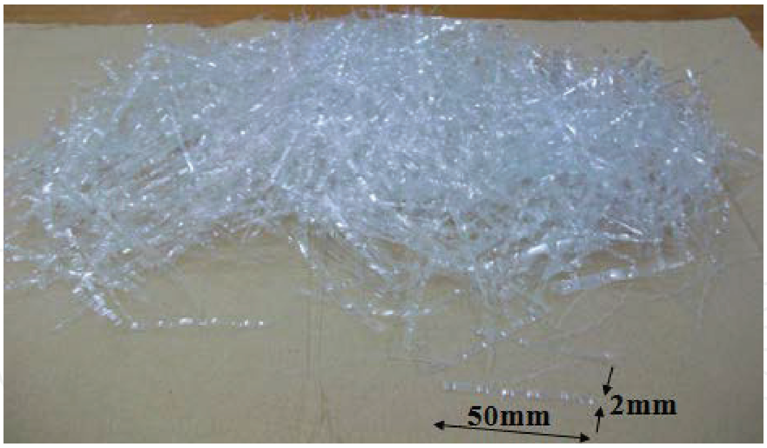

Figure 2. Straight slit sheet fiber of PET.

[21]. **Figure 2** shows the geometry of fiber use in this study, which were produced by hand cutting from post-consumer PET bottle of 1 liter capacity. The length of fiber is 50 mm, width is 2 mm and thickness is 0.5 mm with an aspect ratio (length/width) of 25. The specific gravity and tensile strength of PET fibers is found out to be 1.38 and 155 MPa, respectively.

2.2. Concrete mixture proportions

Table 2 presented the specimens and test parameters for characterizing the mechanical properties of concrete. Mix M0 is a control specimen (i.e., 100% NCA) while M100 is the mix with 100% RCA and M100-PET is the mixture of 100% RCA plus 0.5% PET fiber, i.e., PFRC All concrete mixes were prepared with the same w/c of 0.5 and the same degree of workability (slump value of 60 mm) evaluated according to IS 1199 [22]. The concrete mixes were designed for a characteristic cube compressive strength of 25 MPa which resulted in a target mean cube compressive strength of 31.6 MPa as per IS 10262 [23]. The concrete mixes were produced with 372 kg/m^3 of cement, 733 kg/m^3 of fine aggregate and 1087 kg/m^3 of coarse aggregate for a w/c of 0.5. To achieve a better workability, super-plasticizer dosage of 0.5 and 0.82% by volume of water was used in the mix of M100 and M100-PET, respectively. In each sample three specimens were cast. Specimens from the

Mixes	Cube (mm)	Cylindrical (mm)	Prism (mm)	Total mixture
M0	150 × 150 × 150	100Ø × 200	500 × 125 × 125	100% NCA
M100	150 × 150 × 150	100Ø × 200	500 × 125 × 125	100% RCA
M100-PET		100Ø × 200	500 × 125 × 125	100% RCA + PET fibers
Test parameter	Compressive strength	Splitting tensile strength	Flexural strength	

Table 2. Specimen used for evaluating the mechanical properties of concrete.

mold were removed after 24 h of casting and were kept in a water tank for 28 days curing before testing.

2.3. Selection and description of RC frame

In this study, a typical full scale residential building with floor to floor height of 3.0 m and the beam with effective span of 3.6 m were considered. The full scale RC frame are then scaled down to 1/3rd size for experimental investigation. The detailing of the frame is shown in **Figure 3**. The frame has been designed following the standard code of practice [24, 25]. A cross section of 100 × 100 mm and 135 × 100 mm for column and beam elements, respectively, was considered. High yield strength deformed (HYSD) bars of 8 mm diameter (Fe 500) were used as main bars in both column and beam. Following the code provision [24] a lateral tie of 6 mm diameter mild steel bars (Fe 250) at 25 mm c/c spacing was used in the special confinement zone of the column, while the remaining part was increased to 50 mm c/c. Similarly, the shear reinforcement in beam was of 6 mm diameter bar having spacing of 25 mm c/c near the beam-column joint for a length of 225 mm and a spacing of 40 mm c/c in the remaining part. The yield stress (MPa) and ultimate stress (MPa) for HYSD bars tested as per code provisions [18, 26] were found out to be 530 and 620 MPa, while the same for Fe 250 were 285 and 450 MPa, respectively. The detailed description of the specimens is given in **Table 3**.

2.4. Casting of RC frames

Three RC frames were casted. The specimens were designated as specimen S1, S2 and S3. Specimen S1 corresponding to mix M0 was treated as the reference specimen. Keeping the

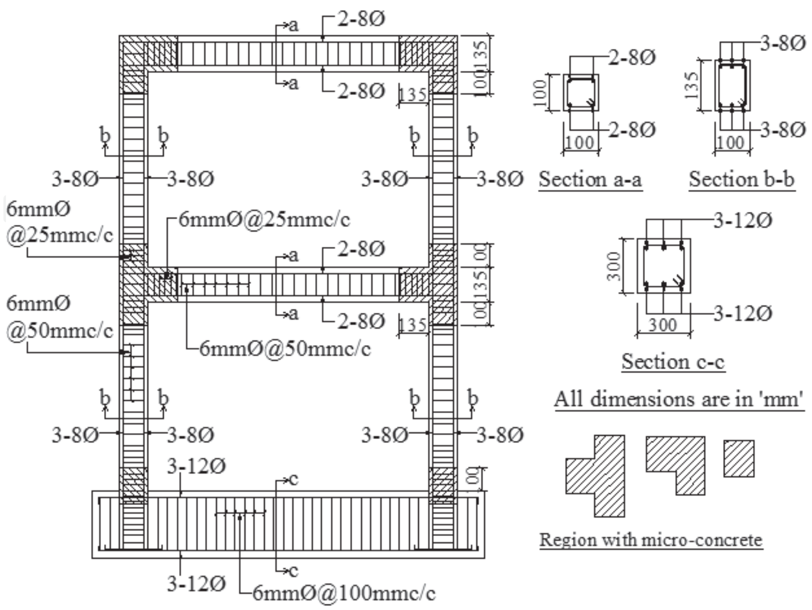

Figure 3. Reinforcement detailing of RC frame.

Beam			Column		
Span (mm)	Section (mm)	Longitudinal reinforcement	Length (mm)	Section (mm)	Longitudinal reinforcement
1200	100 × 135	2-8Ø - top2-8Ø - bottom	1000	100 × 100	3-8Ø – top bar3-8Ø – bottom bar

Table 3. Description of RC frame.

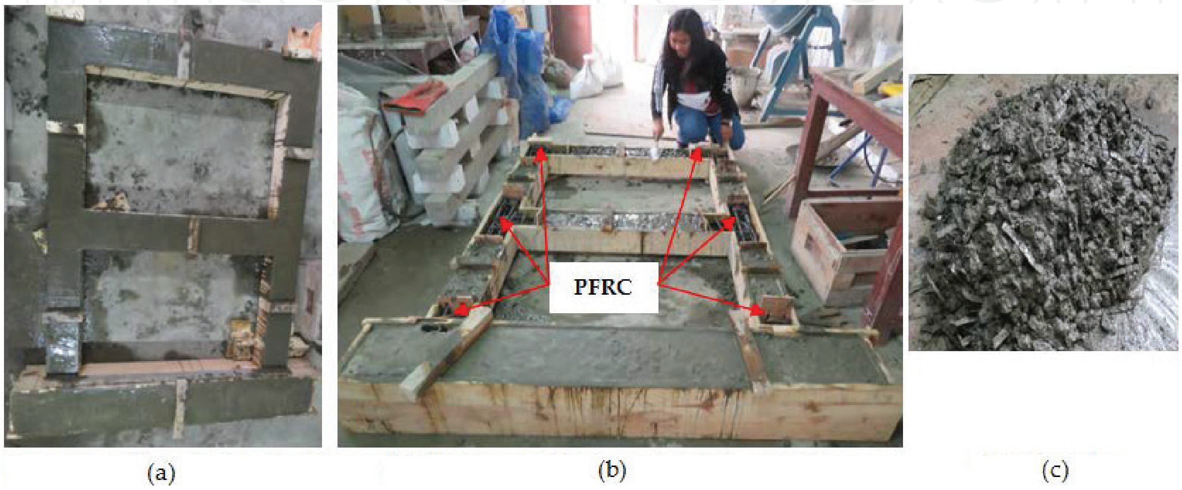

Figure 4. Casting of RC frame (a) M0 for S1 and M100 for S2 (b) M100 and PFRC at joint region for S3 (c) PFRC mix.

geometric dimensions, grade of concrete and steel, the amount and detailing of reinforcing bars constant as that of specimen S1 the other specimens S2 and S3 were casted using 100% of RCA concrete. However, the joint region of specimen S3 was cast with PFRC mix as per guideline [17]. **Figure 4** shows the casting of the frame.

2.5. Test set-up and loading sequence

Schematic diagram of the test set-up and the actual testing arrangement is shown in **Figure 5**. The test set-up consists of a loading frame of capacity 400 kN and a hydraulic jack of 100 kN capacity. The load was applied manually through the hydraulic jack mounted on the side of the frame. The foundation of the RC frame were held tightly in position with the help of hydraulic jacks and also with the help of mild steel plates which helped in clamping the foundation to the ground. Holes were punched into the mild steel plates which were fitted into the bolts (firmly established in the ground by concreting) with the help of nuts of appropriate size. Two dial gauges of 100 mm measuring range were used to measure the lateral displacement corresponding to the applied load. As shown in **Figure 5** the frame specimens were subjected to monotonic lateral loading at the side of the top beam. A hydraulic jack of capacity 100 kN was attached to the side of the loading frame and was used for applying the necessary lateral load to the specimens. A dial gauge was attached to the loading frame opposite to the hydraulic jack to measure the displacement undergone by the specimens

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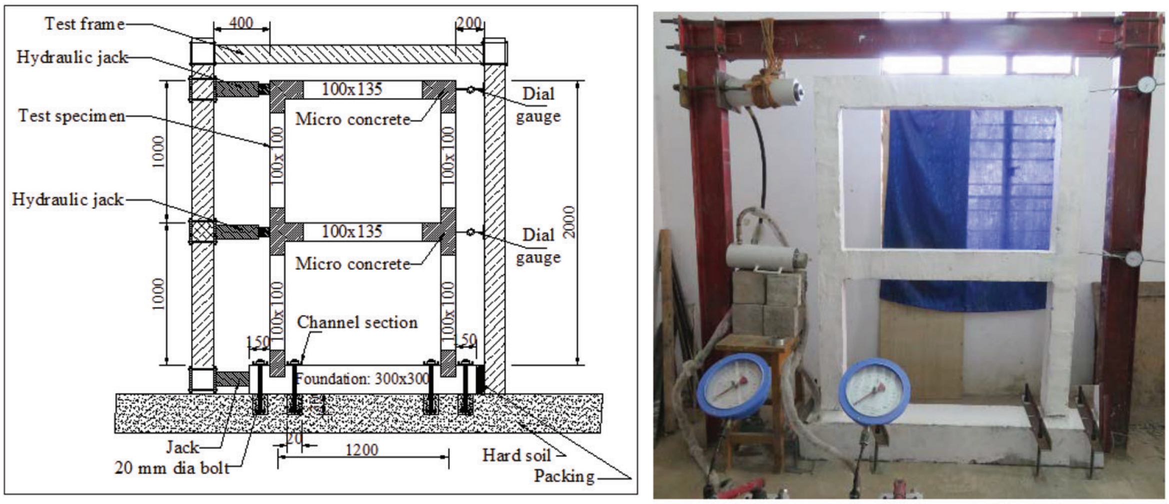

(a) (b)

Figure 5. Testing of RC frame (a) test set-up (b) actual testing arrangement.

corresponding to a particular load. A maximum displacement of 100 mm was applied in all the specimens.

3. Mechanical behavior of concrete due to addition of PET fiber

3.1. Results and discussion

At a *w*/*c* of 0.5, the slump measured as per IS 1199 [22] for M0 was 60 mm, while for M-100 was 40 mm, respectively. The high absorption of free water from the mixture during mixing process causes high water demand of the mix with increasing RCA contents. This shows that RCA concrete resulted in a significant effect on the workability of concrete. The addition of PET fiber in a M100 mix further reduced the workability of concrete about 58%. For a better comparison of the test results of concrete, it is essential for all concrete mixes to secure the same workability. Therefore, superplasticizer dosage of 0.5 and 0.85% by volume of water was used in M100 and M100-PET concrete, respectively.

The concrete specimen as presented in **Table 2** was used for evaluating the mechanical properties. Test parameters included are compressive strength, splitting tensile strength and flexural strength. Concrete cubes and prismatic specimens were tested for compressive strength and flexural strength [27], while a cylindrical specimen was tested for splitting tensile strength [28]. The test results presented in **Table 4** shows that all test parameters decreases in the range of 25–40% with mix of RCA concrete. However, the presence of 0.5% PET fibers in RCA concrete enhanced the compressive strength about 19%. The additions of PET fibers also enable a greater capability of resisting more tensile stress higher than the control specimens, PET fibers can restrain the crack propagation and traverse across the cracks to transfer internal force, as a result, the flexural toughness of the fibers concrete is improved which is the positive contribution of PFRC in an RC frame under seismic excitation.

Concrete Mix	Compressive strength (MPa)	Tensile strength (Mpa)	Flexural strength (MPa)	Total mixture
M0	39.25	4.55	3.58	100% NCA
M100	29.33	2.83	2.18	100%RCA
M100-PET	31.45	5.53	4.10	100% RCA + PET fibers

Table 4. Results of compressive, tensile and flexural strength of concrete specimens.

4. Behavior of RC frame due to addition of PET fiber: Results and discussion

4.1. Failure modes and load carrying capacity

Figures 6–8 presented the failure pattern of the specimens. It is observed that the initial crack formation in all the specimens mainly developed at the joint interface of beam and column. With further application of lateral load, a number of cracks were observed at the joint region and also the initial cracks widened more and more. The faster growth of cracks for specimen S2 which spreads away from the joint region reveals a brittle mode of failure as compared to specimen S1 and S3. Also as observed during experimentation specimen S2 lost its resistance after cracking whereas specimen S3 could sustain a portion of its resistance after cracking and able to resist more loads and produced a better ductility in the frame. The presence of a PFRC at the joint region for frame S3 delayed the crack formations as compared to specimen S2 and S1. Thus, **Figure 8** showed the minimum number of cracks at the joint region and wider cracks occur at the beam portion which is the desirable failure mode of frame structures.

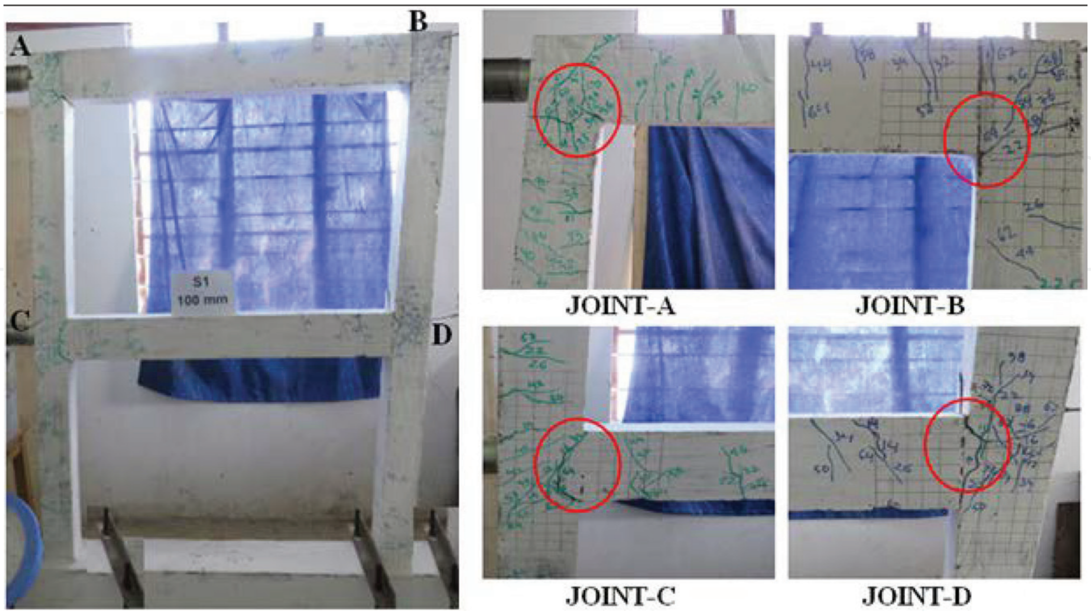

Figure 6. Failure modes of specimen S1.

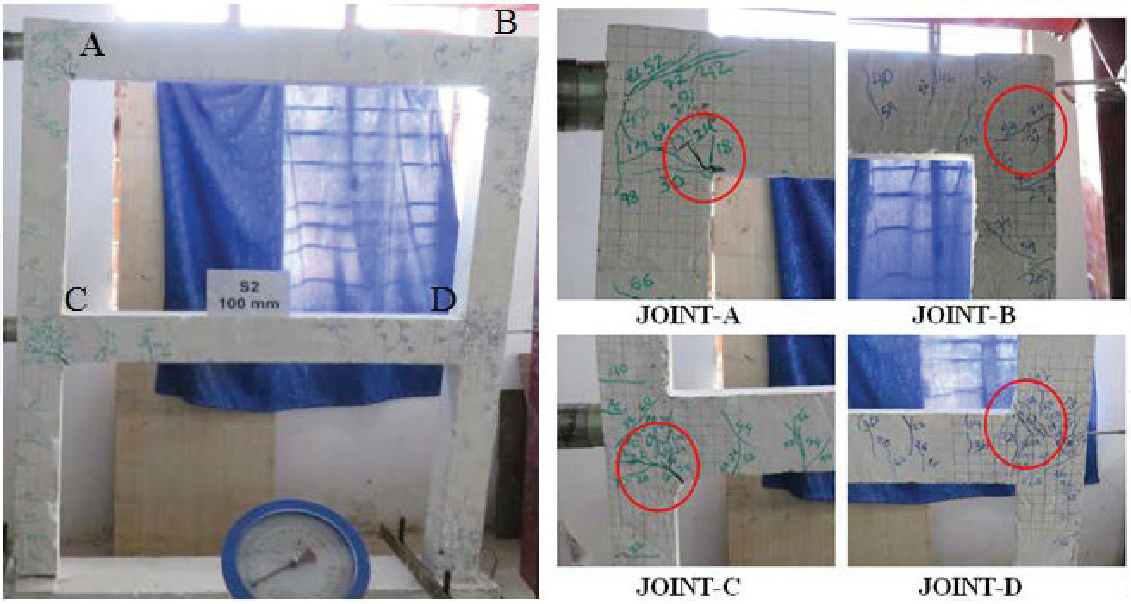

Figure 7. Failure modes of specimen S2.

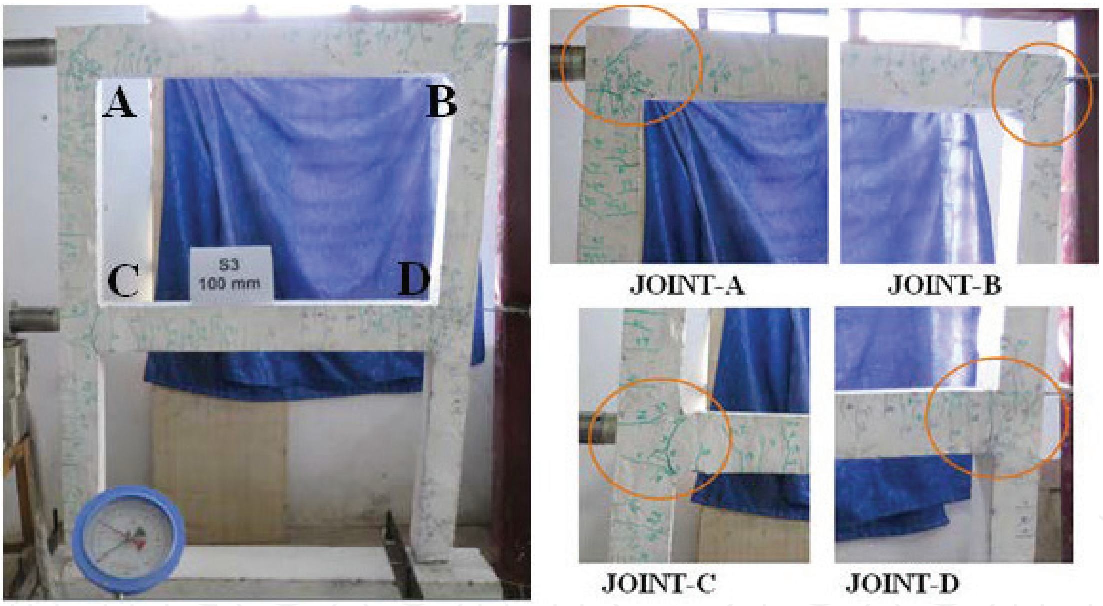

Figure 8. Failure modes of specimen S3.

The load capacity were noted for displacements starting from 1 up to 100 mm at an increment of 1 mm and the crack formations were noted for each set of displacements. **Figure 9** shows the load versus displacement curve. It can be observed that with increased in displacement, specimen S1 presented the highest load carrying capacity followed by specimen S3 and least with specimen S2. The higher load carrying capacity presented by specimen S3 at each displacement level in comparison to specimen S2 show an excellent contribution of PFRC in a RCA concrete frame which is well comparable to specimen S1. As presented in **Table 5** the addition of PFRC in an RCA concrete frame cause a strength reduction of only 6% in comparison to specimen S2 of 20%.

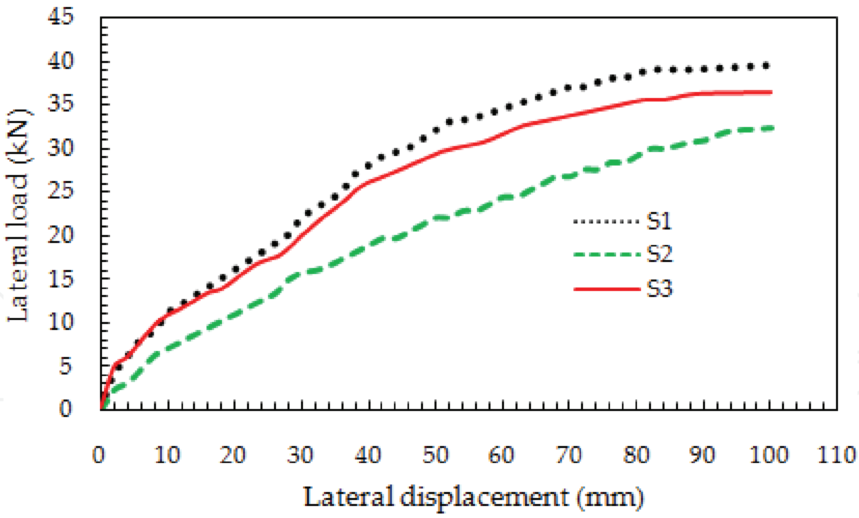

Figure 9. Load versus displacement curve of the frame.

Sl. no.	Test parameters	S1	S2	S3
1	Average load capacity, kN	39.50	31.50	36.50
	Reduction with respect to S1 (%)	—	20.25	6.00
2	Energy dissipation (kN-mm)	1304.00	825.00	1113.54
	Reduction with respect to S1 (%)	—	36.73	14.61
3	Ductility	2.00	1.26	1.65
	Reduction with respect to S1 (%)	—	37.00	17.50

Table 5. Capacity comparisons of RC frame specimens.

4.2. Evaluation of stiffness of the frames

Stiffness is an indicator of the response of a specimen and extent of strength degradation during loading. It is calculated as the slope of the line joining the peak capacity at a given displacement. The slope of this straight line is the stiffness of the specimens corresponding to that particular displacement amplitude according to Naeim and Kelly [29]. The stiffness is given in Eq. (1).

$$K = \frac{F - f}{D - d} \tag{1}$$

where, F is the maximum load of a particular specimen in the positive cycle, f is the maximum load of a particular specimen in the negative cycle, D is the displacement corresponding to the maximum load of a particular specimen in the positive cycle and d is the displacement corresponding to the maximum load of a particular specimen in the negative cycle. The present study adopted a monotonic increasing load and hence, the value of f and d are taken as zero. The drift angle is defined as the ratio of beam tip displacement to the length of the beam measured from the joint to the position of the dial gauge. The drift obtained by horizontal displacement

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of the beam ends are equivalent to the inter storey drift angle of a frame structure subjected to lateral loads. Drift ratio is calculated as given in Eq. (2).

$$\text{Drift ratio } (\%) = \frac{\Delta}{L} x100 \tag{2}$$

where, Δ and L are the applied displacement and the storey height of the frame measured from the top level of foundation to the top beam of the frame.

The performance of the specimen S3 due to the presence of micro-concrete at the joint region may be evaluated by comparing stiffness versus displacement with those of specimens S1 and S2. These plots are shown in **Figure 10**. Comparing these plots, similar degradations trends could be observed in all the specimens. Stiffness of the frames was gradually reduced during loading. This was occurred due to bond failure, minute cracks formed in the frame. Stiffness was getting reduced higher for specimen S2. The initial stiffness of specimen S1, S2 and S3 are 2.0, 1.1 and 1.7 kN/mm, respectively. Thus, the presence of PFRC at the joint region led enhanced the initial stiffness for frame S3 as compared to specimen S2. Further, it is also observed that the degradation in stiffness for specimen S3 is little slow with increase in lateral movement as compared to the specimen S2 which is well comparable to the specimen S1. This behavior may be attributed to the ductile properties imparted by the PET fibers at the joint region which bridge the initial crack of the joint region. The lower degradation is a desirable property in earthquake like situations. It was observed during the past earthquake that most of the RC structures failed due to sudden loss of stiffness with increasing lateral movement. Therefore, from these comparisons it can be concluded that the presence of PFRC at the joint region of the RC frame made with RCA improved the performance during seismic action.

4.3. Evaluation of energy dissipation capacity

The ability of a structural member to resist the fracture when subjected to static or to dynamic or impact loads depends to a large extent on its capacity to dissipate its energy. It was reported that the energy absorbed by a column before failure is correlated to the ductility of the column [30].

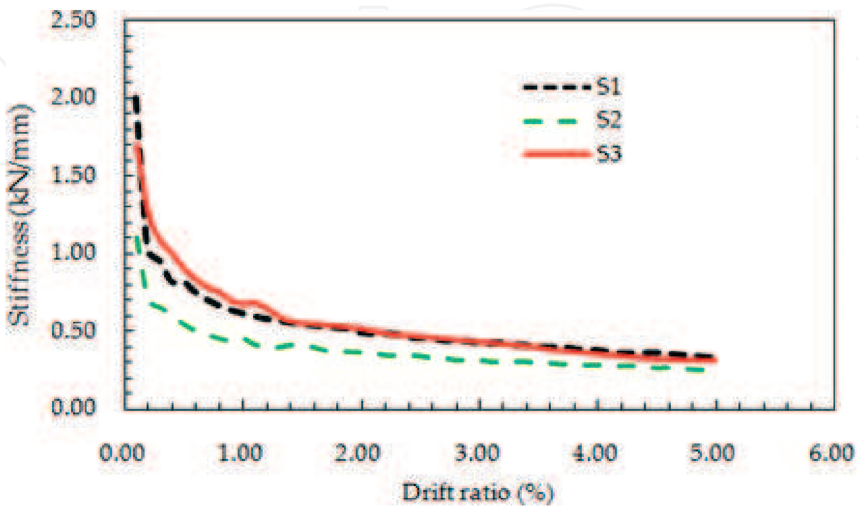

Figure 10. Stiffness degradation of the specimens.

This energy can be computed based on the area under the load versus displacement curve presented in **Figure 9** as implemented in several previous studies [31, 32]. The computed energies are tabulated in **Table 5**. RCA specimens (S2) without PFRC at the joint region presented the lowest energy dissipation capacity. The increase in energy dissipation of specimen S3 showed PFRC has a tremendous potential use in the joint region of the RC frame. The inclusion of PFRC at the joint region of an RC frame made of RCA concrete lead to an increase of energy dissipation to about 1.3 times (**Table 5**) with respect to S2. The increase in stiffness due to presence of PFRC at the joint region attracted more load corresponding to any drift angle for specimens S3, which prevent the initial crack propagations. Thus, the total area enclosed by the plot of load versus displacement was more for specimen S3 as compared to S2. This was perhaps the reason for improvement in energy dissipation. It may be noted that the energy dissipating capacity of specimen S3 as presented in **Table 5** is well comparable to specimen S1 (−15%) while for specimen S2 is 37% which demonstrated the benefit of using a recycled aggregate concrete in an RC frame strengthened with PFRC at joint region.

4.4. Evaluation of ductility of the frames

Ductility is basically the ability of a structure to accommodate deformations well beyond the elastic limit. It is the capacity to dissipate energy in hysteretic loops and to sustain large deformations. As the loads versus displacement curves for tested specimens do not have a distinct yield point, ductility capacity was determined using an idealized approximation procedure proposed by Shannag et al. [33] which has been explained in **Figure 11**. As shown in the figure, the yield displacement is calculated as the point of intersection between two straight lines drawn in the envelope curve. The first line was obtained by extending the line joining the origin and 50% of ultimate load capacity point of the curve, while the second line was obtained by drawing a horizontal line through the 80% of ultimate load capacity point. In the figure, δy represents the yield displacement. Horizontal lines drawn through the 80% of ultimate load capacity point intersect the curve at far end at points x. The abscissa of this point denoted by δu was taken as maximum displacement. The displacement ductility (μ) was calculated as the ratio of maximum displacement (δu) to the yield displacement (δy). The calculated values listed in **Table 5** clearly show a higher ductility for specimen S1. However, the presence of PFRC in

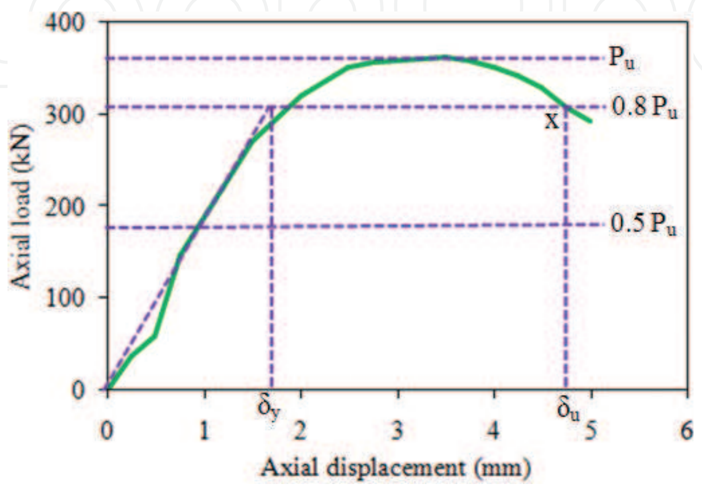

Figure 11. Procedures for ductility calculation.

specimen S3 show improved ductility value than that of specimen S2. The presence of PFRC at joint region postponed the crack development toward the beam and column region and finally it was led to higher ductility, which is well comparable to the control specimen S1 (−18%).

5. Conclusions

In the conclusion, by comparing the results obtained for the two concrete mixtures, it can be noted that, when the low grade aggregate i.e. the recycled coarse aggregate is used instead of natural coarse aggregate for concrete production, about 25–40% of mechanical strength (compressive, tensile and flexural strength) decreases. However, the presence of 0.5% PET fibers enhanced the compressive strength of RCA about 19%. The additions of PET fibers also enable RCA concrete a greater capability of resisting more tensile stress. The flexural toughness of the fibers concrete also improved which is the positive contribution of PFRC in an RC frame under seismic excitation.

In addition, on the basis of the results obtained through a monotonic loading test of an RC frame made of either RCA or NCA evaluated by means of parameter such as cracking patterns, stiffness degradation, energy dissipated and ductility. The faster growth of cracks which spreads away from the joint region reveals a brittle mode of failure for a frame made of RCA concrete. In the other hand when the joint region of an RCA frame is incorporated with PFRC the frame showed adequate structural behavior and exhibited a higher energy dissipation capacity and ductility and the lower degradation of stiffness, which is a desirable property in earthquake like situations. Therefore, it can be concluded that the, strengthening of joint region using PET fibers is found to have a significant contribution in improving the seismic performance of RCA frame structures.

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Conflict of interest

No conflict of interest to declare.

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