Mechanical and Post-Cracking Performance of Recycled Aggregate Concrete Incorporating Synthetic Fibers

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Abstract. Reuse of concrete waste in novel construction is becoming very important topic nowadays. This study focuses to examine the post-cracking and mechanical performance, fracture behavior, and micro-structure of fiber strengthened recycled aggregate concrete (RAC). For this purpose, crack mouth opening diameter (CMOD) tests were conducted on twenty-seven notched beam specimens (550 x 150 x 150 mm) having three replacement levels (i.e., 0, 50 and 100%) of recycled concrete aggregates (RCA) and three synthetic fiber dosages (i.e., 0, 0.5 and 1%). Different mechanical properties of all mixes were also examined following ASTM standards. Drop in the mechanical performance of RAC was noticed at higher RCA replacement levels. However, synthetic fiber reinforced RAC showed better performance as compared to plain RAC. Results also depict positive influence of synthetic fiber addition on the residual flexural tensile strength of concrete. Approximately, 129% and 380% rise in toughness index and fracture energy was also observed for 1% fiber incorporation in RAC. Moreover, scanning electron microscopic analysis also confirmed the synthetic fiber-mortar bond. Therefore, synthetic fibers enhance the post-cracking and mechanical performance of fiber reinforced RAC resulting into more ductile and energy absorbing sustainable concrete.

1. Introduction

Concrete is widely utilized in different construction projects around the globe, which is produced after using a huge quantity of natural resources. Concrete aggregates constitute around 60-75% of all the volume of concrete [1]. Annual consumption of natural coarse aggregates (NCA) in concrete production is about 20 billion tons and is predicted to double itself in the next 30 years [1]. On the other hand, huge amount of waste is produced from construction and demolition (C&D) activities worldwide. For instance, China and Australia produce 200 Mt [2] and 13.7 Mt [3] C&D waste each year. Similarly, US, Europe and Japan produce 900 Mt of construction and demolition waste per year [4]. Best possible solution of the problem is to reuse this construction and demolition waste to yield recycled concrete aggregates (RCA). Consequently, landfilling problems as well as exhaustion of natural resources may be reduced to a great volume.

A lot of studies are available in the open literature regarding the utilization of different wastes in the novel construction materials [5-15]. Recycling of C&D waste in the form of RCA to produce recycled aggregate concrete (RAC) have also been investigated by many researchers in the past [1, 4, 7, 16, 17]. Reduction in mechanical performance of recycled aggregate concrete (RAC) was reported in previous studies due to inferior properties of RCA [18, 19]. Approximately, 25%, 23% and 24% decrease in the compressive, flexural strength and split tensile strength was observed in fully RCA incorporated RAC [1, 7, 19]. Variety of RCA treatment techniques have been proposed by researchers to improve RAC

 DOI: 10.1088/1757-899X/829/1/012003
properties, including surface modification of RCA through carbonation or other techniques [20],
removing adhered mortar from RCA [17], modifying RAC mixing method [21-23], utilization of
contentious materials and incorporation of different fibers in RAC fibers [24-26]. Increase in the
mechanical properties was reported in the fiber reinforced RAC. For example, 13%, rise in the
compressive strength was observed for 0.75% steel fiber dosage [27]. Similarly, 4 and 31% surge in the
flexural strength and split tensile strength was also reported after incorporating 1% synthetic fibers [28].
Moreover, improved flexural performance and impact resistance of fiber strengthened concrete was also
reported due to utilization of synthetic fibers [29].

Nowadays different types of synthetic and steel fibers are utilized in variety of construction projects.
Synthetic fibers are used in different types of constructions for example tunnel linings and industrial
pavements due to lighter in weight, cheaper in cost, better distribution in concrete, improved impact
resistance and durability as compared to steel fibers [16, 30]. Synthetic fibers have been reported very
useful for normal concrete due to the associated better performance of resulting fiber reinforced concrete.
However, there is a scant literature available on the effect of synthetic fibers on the properties of RAC.
Consequently, more research is required to explore the mechanical and post-cracking properties of
synthetic-fiber strengthened RAC. The aim of this study is to explore the post-cracking and mechanical
properties of synthetic-fiber incorporated RAC. For this reason, nine different concrete mixes were
prepared and tested with 0, 50 and 100% RCA replacement and 0, 0.5 and 1% synthetic fiber dosage.

2. Materials and mixture proportion

NCA and RCA having maximum size 14 mm were utilized in this research. RCA was attained from
local concrete crushing plant having bulk density and water absorption 1413 kg/m$^3$ and 7.61% respectively.
NCA comprised of crushed basalt aggregates having bulk density and water absorption 1512 kg/m$^3$ and 2.06% respectively. The gradation of RCA and NCA is depicted in figure. 1.

![Figure 1. Gradation of NCA and RCA.](image1)

RCA used in this study had less than 1% 30% contaminants and brick pieces respectively. Therefore,
RCA can be categorized under class 1B [31-33]. Local sand from river source having specific gravity
value of 2.65 and Ordinary Portland cement (OPC) were used throughout the study. Polypropylene

![Figure 2. Polypropylene synthetic fibers.](image2)
synthetic fibers were used in this study had length, equivalent diameter, young’s modulus and density 57 mm 0.65 mm and 14 GPa and 0.91 kg/m³ respectively (figure. 2). A total of nine concrete mixes with three RCA replacement levels (0,50 and 100%) and three fiber dosages (0, 0.5, 1%) were prepared and tested to investigate the performance of synthetic fiber reinforced RAC (table 1). Oven dried aggregates were used in this study and additional amount of water was mixed to concrete mixes depending upon the water absorption capacity of the aggregates.

3. Sample preparation and test methods
Concrete mixtures were prepared using pan mixer as per ASTM C192 / C192M - 16a [34]. Three concrete prisms having size 150 x 150 x 550 mm and six 150 mm diameter cylinders having 300 mm height were prepared for all the nine mixes. To evaluate the post-cracking performance of synthetic fiber strengthened RAC, a 25 mm high notch was made in the concrete prisms and tested under three point bending test to record load and Crack mouth opening displacement (CMOD) as per EN 14651:2005 [35]. Moreover, 28 days compressive strength and split tensile strength was also determined in accordance with ASTM C39:2017 [36] and ASTM C496:2017 [37], respectively.

Residual flexural tensile strength describes the post-cracking performance of the concrete sample was calculated at different CMOD values using Equation 1.

\[ R_j = \frac{3F_j}{2bh^2p} \]  

Where, Fj and Rj are the and load and residual flexural tensile strength at different CMOD (i.e. 0.5, 1.5, 2.5 and 3.5 mm). Similarly, b, l and Hsp are the width of beam, span of beam and the height of beam exclusive of the depth of notch, respectively. The fracture energy (Gf) of concrete samples was determined using Equation 2 [38].

\[ G_f = \frac{W_0 + mg\delta}{A} \]  

Where W₀ denotes the area underneath the load-CMOD curve (N/m), mg is the beam weight among its supports (kg), δ is the peak deflection (m) and A is the area of fracture equivalent to [b(d - ao)] (m²), b, d and ao are the breadth, height of the notched beam specimen and height of notch, respectively. Toughness of all the fiber-reinforced samples were calculated using ratio of area underneath load-CMOD diagram of fiber-reinforced and plain concrete specimen [39]. Moreover, Philips XL30 scanning electron microscope (SEM) was used to investigate the micro-structure of fiber reinforced and plain concrete specimens.

4. Results and discussions

4.1 Mechanical performance of synthetic fiber reinforced concrete
Table 2 shows the average compressive and split tensile strength values of plain and synthetic-fiber strengthened normal aggregate concrete (NAC) and RAC concrete specimens. Drop in the compressive and split tensile strength values was noticed with rise in the RCA replacement percentage. For instance, 25% and 16% reduction of compressive and split tensile strength was noted for 100% RCA replacement. This reduction in mechanical performance of RAC may be attributed to the weak old mortar attached with the RCA surface [1, 40].

However, addition of synthetic fibers resulted in the improved mechanical properties of fiber-reinforced RAC. Addition of 1% synthetic fibers resulted in 5% and 30% rise in the compressive strength and split tensile strength of the RAC. Synthetic fibers improve the resistance of micro crack sliding [41] and help in transferring the stress from concrete to fibers [42] leading to improved mechanical performance of concrete. Similar improved mechanical properties of concrete due to fiber incorporation was also observed in past studies [25, 27].
Table 1. Mix proportion details.

| Group ID | R0    | R0P0.5 | R0P1 | R50  | R50P0.5 | R50P1 | R100 | R100P0.5 | R100P1 |
|----------|-------|--------|------|------|---------|-------|------|----------|--------|
| Cement (kg/m³) | 451.4 | 451.4  | 451.4 | 451.4 | 451.4   | 451.4 | 451.4 | 451.4    | 451.4  |
| Sand (kg/m³)   | 708.6 | 708.6  | 708.6 | 708.6 | 708.6   | 708.6 | 708.6 | 708.6    | 708.6  |
| NCA (kg/m³)    | 822.5 | 822.5  | 822.5 | 411.2 | 411.2   | 411.2 | ---  | ---      | ---    |
| RCA (kg/m³)    | ---   | ---    | 411.2 | 411.2 | 411.2   | 822.5 | 822.5 | 822.5    | 822.5  |
| Synthetic fibers (%) | ---   | 0.5    | 1    | ---  | 0.5     | 1    | ---  | 0.5      | 1      |
| Water (kg/m³)  | 185.1 | 185.1  | 185.1 | 185.1 | 185.1   | 185.1 | 185.1 | 185.1    | 185.1  |
| w/c            | 0.41  | 0.41   | 0.41 | 0.41 | 0.41    | 0.41 | 0.41 | 0.41     | 0.41   |
| Extra Water (kg/m³) | 17.0  | 17.0   | 39.8 | 39.8 | 39.8    | 62.5 | 62.5 | 62.5     | 62.5   |
| Slump (mm)     | 65    | 45     | 35   | 55   | 35      | 30   | 50   | 35       | 25     |

Table 2. Mechanical properties.

| Mechanical properties | Compressive strength (MPa) | Split tensile strength (MPa) |
|-----------------------|---------------------------|-----------------------------|
| R0                    | 49.65                     | 3.19                        |
| R0P0.5                | 50.20                     | 3.80                        |
| R0P1                  | 52.26                     | 4.53                        |
| R50                   | 41.48                     | 3.24                        |
| R50P0.5               | 43.29                     | 4.03                        |
| R50P1                 | 44.24                     | 4.39                        |
| R100                  | 38.16                     | 2.68                        |
| R100P0.5              | 40.16                     | 3.69                        |
| R100P1                | 41.60                     | 4.22                        |

4.2 Post-cracking properties

Figures 3-5 depict the load-CMOD diagrams of all the concrete samples having three different dosages of synthetic fibers. It can be noticed that rise in RCA replacement level in the concrete results into lower peak load. For instance, 18% drop in the peak load was observed for 100% RCA replacement. Lower peak load may be due to weak old adhered mortar with RCA, similar results were reported in the past studies [31]. Steep and brittle post-peak performance was noted for the plain concrete specimens as revealed in figures 3-5. However, ductile behavior was observed in the samples incorporating synthetic fibers with steeper post-peak curve of RAC samples as equated to virgin concrete samples. For plain concrete samples, the test was conducted till failure. However, all the synthetic fiber reinforced samples were tested till 4 mm CMOD value as per [43]. Increasing trend of peak load was noticed with the rise in fiber amount for all the RCA replaced specimens (figure 4). For example, 20% rise in the peak load was noticed for 50% and 100% RCA replaced synthetic fiber strengthened concrete specimens as compared to the plain concrete specimens.
Plain concrete specimens showed brittle type of failure. However, synthetic fiber reinforced specimens absorbed energy by bridging the cracks resulting in better post-peak behavior in the load-CMOD diagram. Moreover, through the descending branch of load-CMOD curve, synthetic fiber reinforced samples retrieved some of the load due to bond between concrete and fiber surface [44]. Comparable tendency was detected in past study [45]. Higher elongation potential, better bonding with the cracked concrete and medium tensile strength of synthetic fibers results into more energy absorption for large displacements leading towards better post cracking performance of concrete [46]. Therefore, synthetic fibers improve the ductility and post-peak behavior of resulting concrete specimens.
4.3 Fracture energy and toughness index

Figure 6 depicts the drop in the fracture energy of concrete samples with the rise in RCA replacement level. However, synthetic fibers improved the fracture energy of normal as well as RAC specimens. For example, around 22% drop in the fracture energy was observed by incorporating 100% RCA with the same fiber dosage (i.e. 1%). Moreover, 380 and 372% rise in the fracture energies was also noticed for NAC and RAC specimens with 1% synthetic fibers respectively. Surge in the fracture energy may be credited to de-bonding and stretching of synthetic fibers resulting in the prevention of crack propagation and higher absorption of energy [47].

Rise in the toughness value of concrete samples was noticed with the upsurge in synthetic fiber dosage (figure 7). For example, 123% rise in toughness was observed in the RAC specimens after the increase of synthetic fiber dosage from 0.5 to 1%. Moreover, RAC specimens depicted higher toughness index values as compared to normal concrete specimens. Similar increase in toughness values was also reported in past study [16].

![Fracture Energy vs RCA Replacement Level](image1)

**Figure 6.** Fracture energy of concrete specimens.

![Toughness Index vs Synthetic Fiber Dosage](image2)

**Figure 7.** Toughness of concrete specimens.
4.4 Scanning electron microscopy

Figure 8 and figure 9 depict scanning electron microscope (SEM) images of RAC showing porous old adhered mortar attached with RCA and the microstructural interface of mortar and synthetic fibers in the concrete respectively. The lower post-cracking and mechanical performance of RAC in this study may be related to the weaker porous old adhered mortar attached with RCA. Figure 9 also presents the rough surface of concrete along with smooth surface of synthetic fiber resulting in stronger fiber-matrix bond. Better fiber-matrix bond also resulted in improved post-cracking and mechanical properties of fiber-reinforced concrete as equated to plain concrete.

5. Summary and conclusions

Following conclusions were drawn based on this study:

- Drop in the mechanical properties was observed with the RCA incorporation. However, synthetic fibers improved the mechanical performance of RAC.
- Synthetic fibers increased the highest load in load-CMOD diagram for normal as well as RAC specimens. RCA incorporation in concrete reduced the peak load of concrete specimens. Moreover, plain concrete specimens showed brittle post-peak behavior as compared to fiber reinforced specimens.
- Residual-flexural tensile strength of the concrete specimens increased with upsurge in synthetic fiber dosage resulting in improved post-cracking performance of normal concrete as well as RAC.
- RAC strengthened with 1% synthetic-fibers exhibited rise in the toughness and fracture energy by 129 and 380% respectively.
- SEM examination of displayed the porous old adhered mortar attached with the RCA, which caused inferior concrete performance. Presence of synthetic fiber-concrete bond was also noticed, which enhanced the post cracking and mechanical performance of fiber-reinforced concrete.
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