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Mechanical characterization of rubberized fiber reinforced recycled aggregate concrete for bridge barriers

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ABSTRACT: Traffic accidents are a common phenomenon in highways and bridges. These accidents not costs only human lives, but also result in significant economic loss. Improving the impact resistance and cushioning capacity of road-side barriers in the event of a traffic accident can play a significant role in minimizing these losses. The application of crumb rubber derived from scrap tires along with polypropylene fiber can increase the energy absorption capacity and impact resistance of concrete. Furthermore, the use of recycled coarse aggregate as a partial replacement of natural coarse aggregate can reduce the amount of material directed to landfills as well as produce eco-friendly sustainable green concrete. The research present in this paper evaluates the performance of rubberized fiber-reinforced recycled aggregate concrete in terms of compressive strength, splitting tensile strength, quasi-static flexural strength, and impact resistance. A mix of 30% recycled coarse aggregate and 5% crumb rubber is used as a partial replacement of natural coarse and fine aggregate, along with 0.5%, 1%, and 2% polypropylene fiber. The results indicate that rubberized fiber-reinforced recycled aggregate concrete has enhanced mechanical properties compared to the control concrete. The outcomes of this pilot study will pave the way for utilizing recycled coarse aggregate and crumb rubber in concrete road/bridge barriers to increase the energy absorption capacity and reduce the potential damage in the event of a traffic accident.

1 INTRODUCTION

Traffic accidents are a prevalent but often neglected public safety issue, and the cause of 1.35 million fatalitiesand 50 million injuries worldwide every year (WHO 2020). It is also predicted that these figures will increase significantly within the next 20 years. It is thus crucial to identify ways to minimize these traffic accidents and prevent the loss of life and resources. The use of concrete road barriers has become increasing popular in highways and bridges, as it can play a significant role in reducing these accidents. However, these barriers are required to resist enormous and instantaneous impact loads. In this respect, they are designed to resist vehicle impacts and prevent them from overturning by dissipating their impact energy (Fadaee & Sennah 2017), such that efforts to augment the impact resistance and energy absorption capacity of road-side barriers will improve their effectiveness. Fattuhi & Clark (1996) suggested the use of rubberized concrete in roadside barriers as a means of augmenting the impact resistance. This rubberized concrete has been particularly useful in applications where high strength is not a significant concern, i.e. pipe heads and bedding, artificial reef, trench filling, and pavement (Mutsuddy 2017). It also offers excellent vibration damping for applications such as foundation pads for heavy machinery and railway stations. The use of rubberized concrete in these types of structures allows them to absorb more energy from the impact loads, and thus saves lives and resources (Mut-suddy2017).Furthermore, considering transportation and fuel costs, it is advantageous to use light-weight concrete in these types of non-structural components. Researchers have found that the use of lightweight concrete in road barriers can improve their durability properties compared to conventional concrete in terms of freeze-thaw durability properties, alkali-silica reaction, and sulphate attack (Burke & Drake 2002, Holm & Ries 2006). A test program carried out at the University of Sherbrook used glass fiber-reinforced polymer (GFRP) bars in bridge barriers as a novel, low-maintenance design, as these bars are more corrosion-resistant than conventional steel(El-Salakawy et al. 2001). They performed a pendulum impact test (see Figure 1a) and concluded that the behavior of GFRP-reinforced bridge barriers is very similar to conventional steel-reinforced barriers in terms of energy absorption and ultimate strength (El-Salakawy et al. 2001). Figure 1b shows the pattern of the cracks of the tested barrier reinforced with GFRP bars.

(a) (b)

Figure 1. (a) Pendulum impact test on barrier, and (b) cracks pattern of the tested GFRP reinforced barrier (El-Salakawy et al. 2001)

It can be expected that continued rapid urbanization will drive significant global demand for natural aggregates. Meanwhile, a huge amount of construction waste is produced worldwide from the demolition of old infrastructure, and millions of waste tires are disposed of by consumers and ultimately accumulate at landfills (Huda &Alam 2014, Tamanna 2018, Hossain et al. 2019). In this context, researchers have sought solutions to exploit the structural potential of these waste materials while addressing the disposal problem by reusing them in concrete. Prior research has shown that crumb rubber (CR) tends to decrease compressive strength, splitting tensile strength, and flexural strength of concrete (Tamanna et al. 2020, Hossain et al. 2019, Meherier 2016, Eldin & Senouci 1994). According to ASTM C825 (2006), the compressive strength of the concrete used in roadside barrier is generally less than 30 MPa, which can be easily achieved using a certain percentage of rubber particles in the concrete mixture (Meherier 2016). Rubberized concrete also exhibits higher toughness and ductility (Ismail and Hassan 2016), more energy dissipation capacity (Khaloo et al. 2008, Zheng et al. 2008), enhanced resistance to cracking and spalling (Ismail & Hassan 2017), as well as freezing and thawing (Gesoğlu et al. 2014) compared to natural aggregate concrete (NAC). Studies conducted by Topcu (1995) and Topcu & Avcular 1997 found that rubberized concrete has higher energy absorption capacity under both compressive and tensile loading, and also increases the impact resistance compared to NAC. Other researchers have found that recycled coarse aggregate (RCA)can reduce the compressive strength and increase the water absorption capacity of the recycled concrete due to the adhered mortar on the RCA surface (Bai et al. 2020, Duan & Poon 2014). Still others have found out that RCA can produce concrete with greater strength than the concrete made of natural coarse aggregate(Huda & Alam 2014, Verian et al. 2018, Choi and Yun 2012).

The use of RCA and rubber particles can reduce the self-weight of concrete due to their lower specific gravity compared to NCA and NFA (Meherier 2016, Huda & Alam 2014). Due to its resulting lower density, the use of this innovative concrete material can reduce the fuel cost associated with transporting it a given distance as transportation cost being a matter of high concern in highway and bridge construction. As previously mentioned, the use of RCA and CR decreases the splitting tensile strength and flexural strength, but these can be improved significantly by incorporating fiber into the concrete mix. Considering that concrete is a brittle material that performs poorly in tension, the use of steel fibers can enhance the tensile capacity, impact resistance, and dynamic fracture toughness of concrete (Bindiganavile & Banthia 2005, Mutsuddy 2017). In this regard, Alfayez (2018) worked with RCA, CR, and steel fiber investigating the impact resistance of rubberized fiber-reinforced recycled aggregate concrete (RFRRAC). Alfayez observed that both CR and steel-wire fiber in recycled concrete can increase the impact resistance capacity. Fiber can also increase the ductility, residual tensile, and flexural strength of concrete (Pająk & Ponikiewski 2013) while decreasing segregation and increasing its cohesiveness (Tamanna 2018). Mutsuddy (2017) compared the bond performance between concrete containing both CR and steel fiber and sand-coated GFRP bar. The study observed reduced bond strength of the concrete corresponding with an increase in the CR replacement level as well as with the incorporation of fiber into the mixture. Mohebi et al. (2019), meanwhile, found no significant improvement in pullout test by adding polypropylene (PP) fiber, whereas Hamad et al. (2001) reported that the bond strength increased with increasing steel fiber content. Past studies have investigated the combined effect of RCA, CR, and fibers (Alfayez 2018, Hossain et al. 2019, Tamanna 2018). However, all past studies investigating concrete made of RCA, CR, and PP fiber employed concrete cylinders and small scale prisms. The inadequacy of adequate test data on reinforced RFRRAC beams makes it difficult to identify the flexural response and ductility which is a pre-requisite for practical applications. Therefore, the main objective of this paper is to investigate various mechanical properties of RFRRAC and evaluate the compatibility of using the potential of these waste materials inroad-side or bridge barriers through large beam testing.

2 EXPERIMENTAL INVESTIGATION

The experimental investigation constitutes of determination of mechanical properties of the concrete mixes in terms of compressive strength, splitting tensile strength, quasi-static flexural strength, and drop weight impact resistance of concrete containing RCA, CR, and PP fiber, as well as the flexural response of large concrete beams.

2.1 *Materials and Mix Proportion*

For designing and developing the different concrete mixes Portland Composite Cement (PCC), NCA, NFA, RCA, CR, and water are used. No water-reducing admixture is used. NCA and NFA are replaced partially with RCA by weight and CR by volume at 30% and 5%, respectively. Locally available NCA and NFA are used with a maximum nominal size of 19 mm and 4.75 mm, respectively. The RCA is collected from a demolished old building and manually crushed down to a maximum size of 19 mm. The CR particles are prepared from the waste tire which is supplied by a local company. The sieve analysis of coarse aggregates and fine aggregates are presented in Figure 1. All the physical properties of materials are determined according to ASTM standards and summarized in Table 1. The PP fiber is obtained from a Japanese supplier and its specification is presented in Table 2.To determine the flexural responses of RC beams, mild steel (MS) is used as a reinforcing bar. The summary of the mechanical properties of the MS rebar is presented in Table 3.

A total of four mixes are prepared to quantify the compressive, splitting tensile, and quasi-static flexural strength of RFRRAC including a control mixture. In these mix designs, the RCA and CR replacement levels are fixed at 30% and 5% respectively and the inclusion of PP fiber contents is 1% and 2% of the total volume of concrete. On the other hand, four RC beams (two control beams and two RFRRAC beams) are cast where 0.5% PP fiber is used in RFRRAC beams with two different reinforcement ratios such as of 0.59% and 1.60%. The guidelines provided by Wong & Ting 2009 was followed to ensure a minimum compressive strength of different concrete mix. All the materials are used in saturated surface dry (SSD) condition. Table 4 presents the mix proportion of each of the constituents. A separate name for each batch is given, for instance, batch code R30C5F2 refers to 30% RCA content 5% CR content with 2% PP fiber. In RC beam combinations the specimens are designated as R30C5F0.5L/H where L or H refers to low reinforcement ratio (0.59%) or high reinforcement ratio (1.60%).

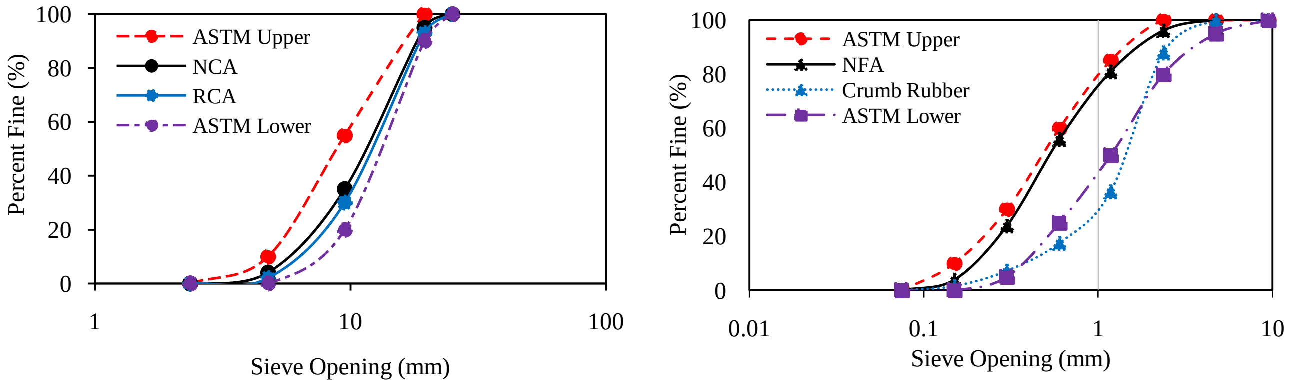


Figure 2. Gradation curve of (a) natural coarse aggregate (NCA) and recycled coarse aggregate (RCA) (b) natural fine aggregate (NFA) and crumb rubber (CR).

Table 1. Physical properties of constituent materials.

Variables	NCA	RCA	NFA	CR
Bulk Specific Gravity (SSD)	2.71	2.51	2.41	1.18
Bulk Specific Gravity (OD)	2.70	2.44	2.36	-
Absorption Capacity (%)	0.48	3.23	1.8	1.3

Table 2. PP fiber specifications.

Variables	PP fiber
Specific gravity (g/cm^3)	0.91
Fiber Length (mm)	12
Tensile Strength (MPa)	480
Elastic Modulus (GPa)	7.0

2.2 *Specimen Preparation*

All the specimens are prepared according to ASTM C192-17 (ASTM, 2017). 100 mm × 200 mm cylinders are used to determine the compressive and splitting tensile strength. For quasi-static flexural test and drop weight impact test 500 mm × 100 mm × 100 mm prisms are prepared whereas the RC beam specimens are 1500 mm in length having a cross-section of 150 mm × 200 mm.

Table 3. Mechanical properties of reinforcing steel.

Sl. No.	Diameter (mm)	Yield Strength (MPa)	Ultimate Strength (MPa)	Elongation (%)
1	10	550	640.7	21
2	4.5	530	610.2	14

Table 4. Concrete mixture proportion per cubic meter.

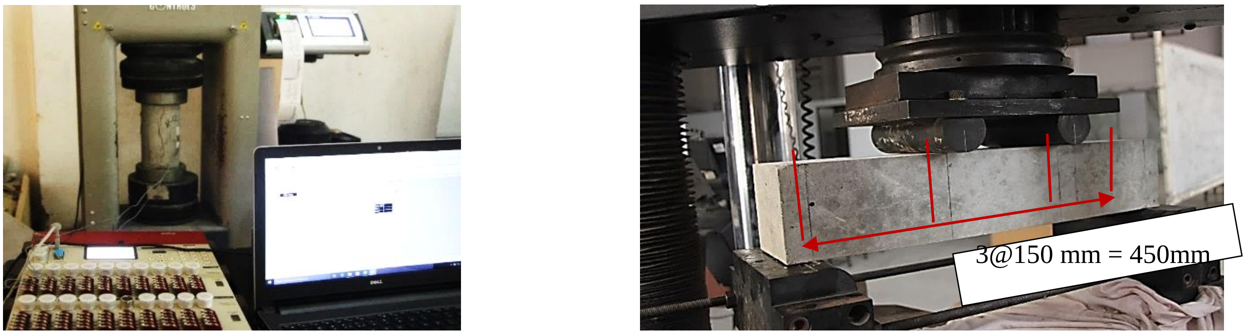
Combination No	Combination Name	Water (kg)	Cement (kg)	NCA (kg)	NFA (kg)	RCA (kg)	CR (kg)
1	$R_0C_0F_0$	163.8	427.1	990.2	678.7	0.0	0.0
2	$R_{30}C_5F_1$	163.8	427.1	693.1	662.1	297.0	16.6
3	$R_{30}C_5F_2$	163.8	427.1	693.1	662.1	297.0	16.6
4	$R_0C_0F_0$L/H	188.0	428.0	1015.0	638.0	0.0	0.0
5	$R_{30}C_5F_{0.5}$L/H	188.0	428.0	710.5	622.4	304.5	15.62

Note: R=Recycled Coarse Aggregate; C=Crumb Rubber; F=Polypropylene Fiber.

2.3 *Test Setup*

2.3.1 *Compression, Splitting Tensile and Quasi-Static Flexural Test*

The compressive strength test is done as per ASTM C39-18 (ASTM, 2018) at 7, 28, and 56 days. The loading rate is maintained by 0.25 ± 0.05 MPa/s. Strain gauges were used at the surface of 56 days specimens in both longitudinal and transverse directions at the mid-height of the concrete cylinders. The cylinders are sulfur capped before testing to ensure plane surfaces to avoid the eccentricity of loading. The splitting tensile and flexural strength tests are done according to ASTM C496-14 (ASTM, 2014) and ASTM C1609-19 (ASTM, 2019), respectively at 28 days. A displacement rate of 0.15 mm/min is used in the quasi-static flexural strength test. The overall experimental set up is given in Figure 3.

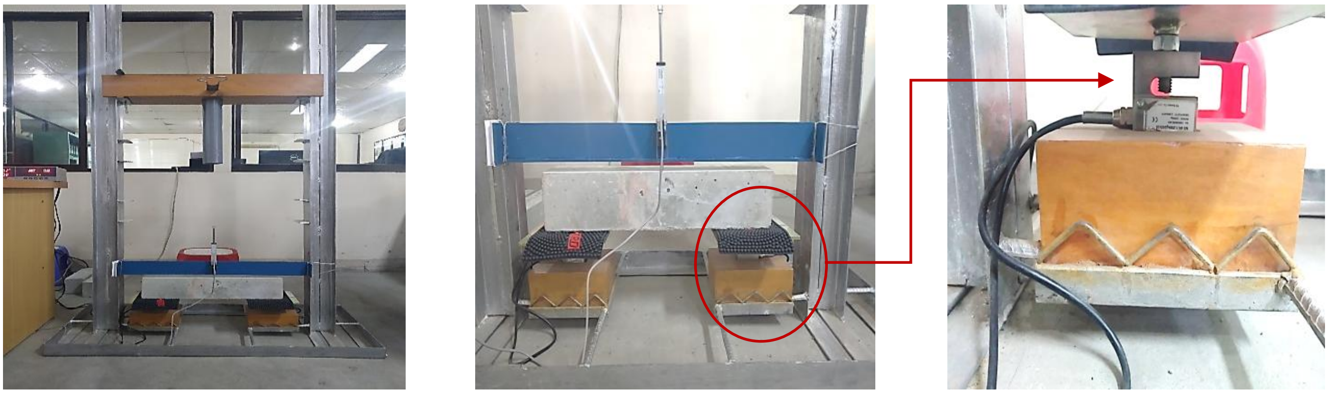


(a) (b)

Figure 3. Test set-up for quasi-static testing; (a) compression test set-up, and (b) quasi-static flexural test set-up.

2.3.2 *Repetitive drop-weight impact test*

Figure 4 illustrates the drop-weight impact test at 28 days where the weight of 0.988 kg is being dropped at the mid-point from a height of 0.893 meters creating an energy of 8.66 J. Two load cells are used at the supports. After dropping the weight, the number of drops that are required to break the beam is counted with a stopwatch. The mid-point deflection of the beam is measured by using Displacement Transducer. The transducer is placed over the beam in such a way so that when the beam is deflected, the tip of the transducer can also be moved along the deflection, and thus the motion is converted into a variable electrical current, voltage or electric signals. Then the transducer is connected with an amplifier and the data is taken through the data acquisition system from the amplifier.



(a) (b) (c)

Figure 4. Test set-up for repetitive drop-weight impact test (a) impact testing frame, (b) set up of beam, and (c) set up of load cell.

2.3.3 *Four-point bending test of RC beam*

The RC beam detailing and experimental set up for four-point static bending test is shown in Figure 5. The length of each beam is 1500 mm having an effective length of 1200 mm with a 150 mm × 200 mm cross-section. For beams having a low reinforcement ratio (0.59%), two 10 mm MS rebars are used at the bottom. Beams with a high reinforcement ratio (1.60%) are reinforced with five 10 mm MS rebars placed in two layers at the bottom. 4.5 mm MS rebars are used as stirrups with a center to center spacing of 75 mm and 100 mm in the shear span and the mid-span regions, respectively. The test is performed at a displacement controlled rate of 5 mm/min. Three additional LVDTs are used to measure the deflections at two mid shear span and mid-span of the RC beam. The data is recorded through an automatic data logger system at regular intervals. A high-resolution camera is used to observe and capture the crack propagation as well as the failure pattern of each of the corresponding beams.

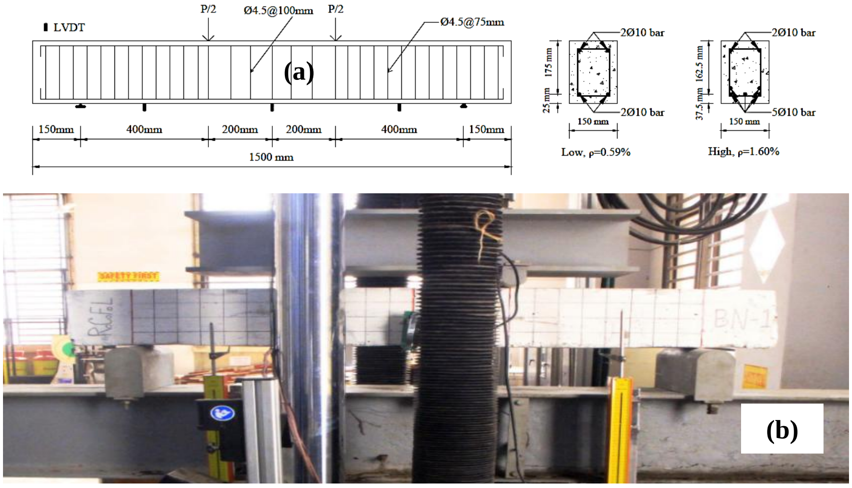


Figure 5. (a) RC beam specimen details, and (b) experimental set-up for four-point static bending test.

3 RESULTS AND DISCUSSIONS

3.1 *Compressive, splitting tensile and quasi-static flexural strength*

The compressive, splitting tensile, and flexural strength of different concrete mixtures are presented in Figure 6. From Figure 6a it is seen that the compressive strength is increased for RFRRAC compared to that of the control mixture due irregular surface texture of RCA and a better bonding between RCA and mortar. The test results of 2% fiber combination shows better strength compared to 1% fiber combination. On the contrary, the splitting tensile strength is decreased for RFRRAC. Though fiber can increase the tensile strength, the inclusion of CR and RCA reduces the tensile strength due to fragile nature of CR in tension (Hossain et al. 2019, Tamanna et al. 2020). For the combination of 2% fiber, it decreases only 5% compared to the control mixture. In terms of flexural strength, though it decreases slightly (4.8%) for RFRRAC containing 1% fiber, using 2% fiber content can ultimately increase the flexural strength of about 8%. The Poisson's ratio decreases with in-creasing the fiber content into the concrete mixture (Table 5). It can be concluded that using RCA and CR with 2% fiber content can exhibit better mechanical properties, even superior to control.

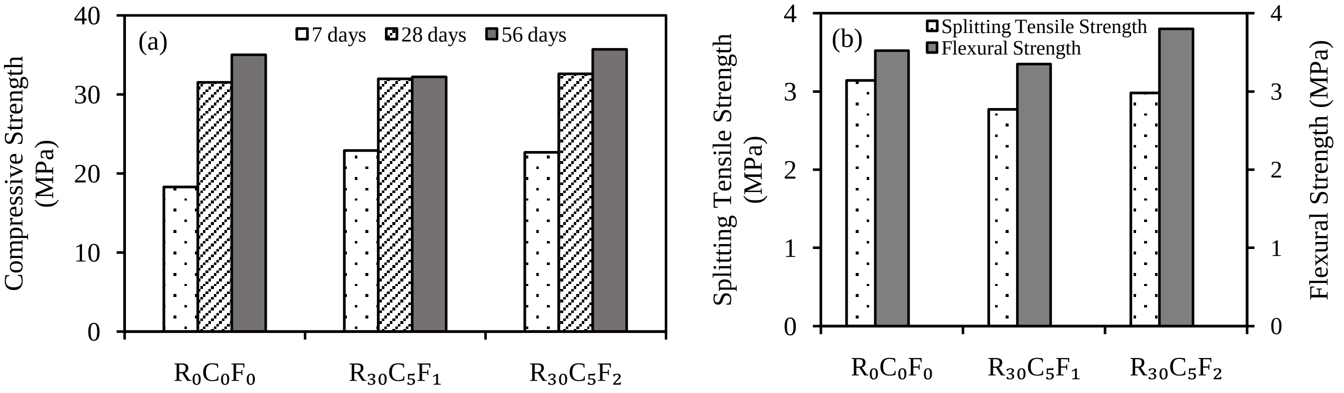


Figure 6. Mechanical properties of concrete: (a) compressive strength and (b) splitting tensile strength & quasi-static flexural strength.

Table 5. Mechanical properties of the different concrete mix under compression at 56 days.

Batch Name	Peak Stress (MPa)	Axial Strain at Peak Stress×10^{-3}	Transverse Strain at Peak Stress×10^{-4}	Ultimate strain×10^{-3}	Poisson's Ratio
$R_0C_0F_0$	35.02	2.780	6.840	2.940	0.246
$R_{30}C_5F_1$	35.21	4.082	13.400	4.270	0.328
$R_{30}C_5F_2$	35.70	4.442	10.100	4.630	0.227

3.2 *Repetitive Drop Weight Impact Resistance*

From Figure 7 it is seen that number of drops required to form crack and break is increased for RFRRAC and it increases with increasing the fiber content, thus provides more the energy absorption capacity than that of the control mixture. This occurs because of the lower modulus of elasticity and lower density of CR and fiber can also resist crack propagation due to its bridging phenomena between the aggregates of the concrete. At the same time, the maximum deflection that occurred before failure is also increased for RFRRAC demonstrating the improved deformation capacity of concrete.

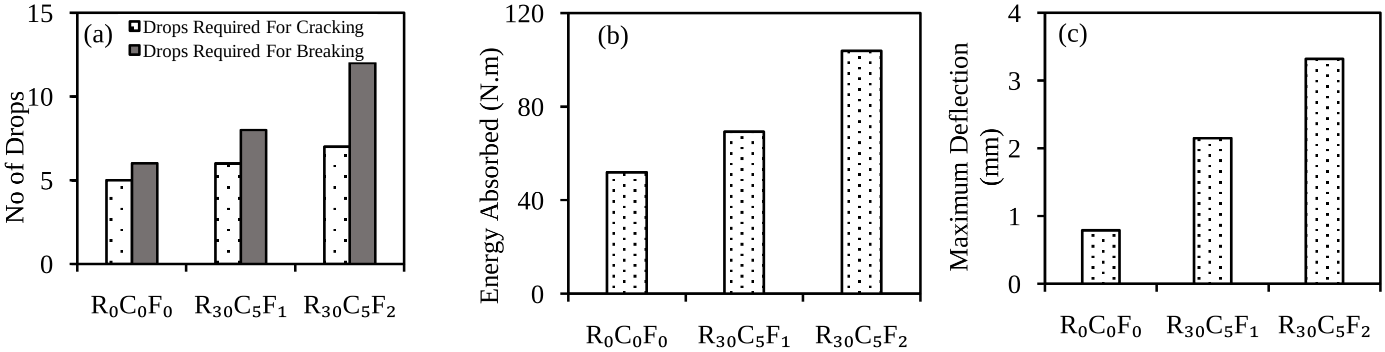
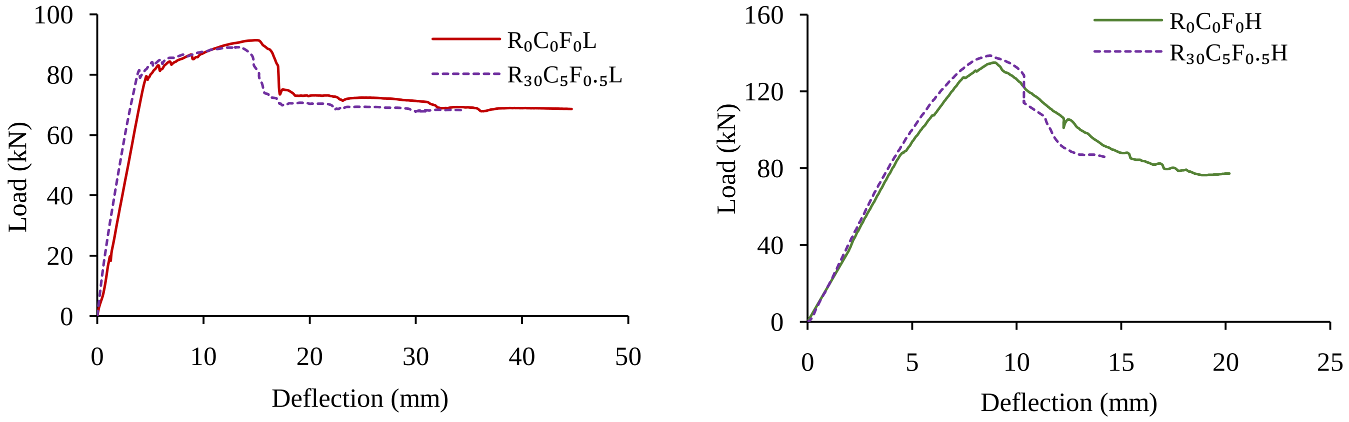


Figure 7. (a) No of drops required for forming first crack and breaking (b) energy absorption capacity (c) maximum deflection.

3.3 *Flexural Responses of RC Beam*

The load vs. deflection responses at mid-point of the tested RC beams is represented in Figure 8. It is observed from Table 6 that the ultimate deflection and the ultimate moment capacity of RFRRAC and normal concrete beams are almost close to each other. Thus, the inclusion of RCA and CR cannot reduce the moment capacity abruptly if fiber is incorporated into it. Besides, the inclusion of fiber along with CR content can also increase the toughness and ductility value which is much more than that of the control beam (Figure 9a). Fiber can create a strong bridging between the aggregates of concrete, thus can take additional load after yielding occurred. To observe the configuration of fiber the beams are broken manually after the test and the briding-phenomea was clearly observed which is shown in Figure 10. The ultimate moment is compared with available design guide-lines which are presented in Figure 9b. For LR (low reinforcement ratio) beams the design guidelines under-estimate the moment capacity whereas for HR beams they can over-estimate. The LR beams exhibit flexural failure whereas HR beams exhibit shear failure due to higher reinforcement ratio in the beam.



(a) (b)

Figure 8. Experimental load vs. deflection responses of different RC beams at mid-point; (a) low reinforcement ratio, and (b) high reinforcement ratio.

Table 6. Results of the flexure test of RC beams.

Beam Name	Moment Capacity (kN-m)	Deflection at Mid-Point (mm)	Ductility	Toughness (kN-m)	Failure Type
	Ultimate	Ultimate			
$R_0C_0F_0L$	18.28	14.91	3.11	1.07	Flexural
$R_{30}C_5F_{0.5}L$	17.82	13.42	3.28	1.00	Shear/Flexural
$R_0C_0F_0H$	26.98	8.91	1.88	0.71	Shear
$R_{30}C_5F_{0.5}H$	27.74	8.72	2.87	0.78	Shear

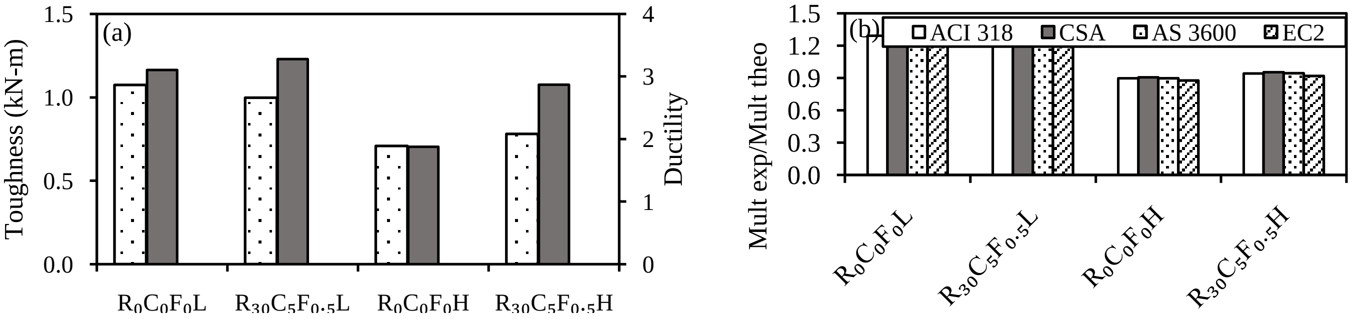


Figure 9. (a) Variation in toughness and ductility of different RC beams and (b) ratio between the experimental and the theoretical values of ultimate moment capacity using available design codes.

3.4 *Cost Analysis*

The economy index and cost analysis of materials for different concrete mixtures have been calculated and presented in Table 7. For estimating the total cost of a particular batch, the cost of cement, NCA, NFA, CR, and PP fiber are taken into consideration, whereas RCA and water are not considered. RCA is considered to not affect this cost estimation as it is obtained from CDW and used as a better approach rather than just a pileup on landfills. From Table 7, it is seen that when PP fiber is incorporated into the concrete mixture, the cost is relatively increased compared to the control mixture. The cost is increased by 17.6%, 40.9%, and 87.1% for PP fiber content of 0.5%, 1% and 2%, respectively. Results of the experiments and economy index suggest that concrete containing 0.5% fiber content might be the optimum limit. Therefore, concrete made using waste materials will help recycle construction and demolition wastes, reducing the cost, and improving the sustainability in concrete industry.

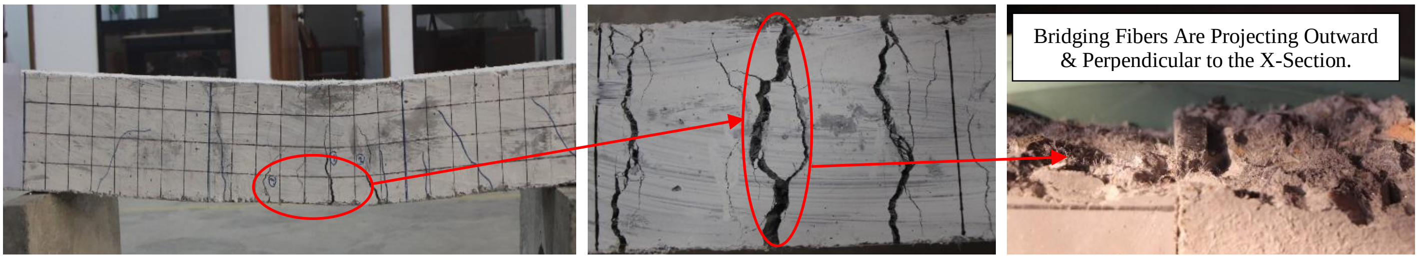

Bridging Fibers Are Projecting Outward & Perpendicular to the X-Section.

Figure 10. Failure pattern of RC beams containing crumb rubber and PP fiber.

Table 7. Economy index for different concrete mixtures.

Batch Code	Cement (kg)	NCA (kg)	NFA (kg)	CR (kg)	PP Fiber (kg)	Total cost of Concrete/m^3 (USD)	Compressive Strength (MPa)	Economy Index (Strength/Cost)
$R_0C_0F_0$	427.1 USD 46.98	990.2 USD 27.36	678.7 USD 7.06	-	-	81.40	35.02	0.43
$R_{30}C_5F_{0.5}$	428.0 USD 47.08	710.5 USD 19.63	622.4 USD 6.48	15.62 USD 3.75	4.55 USD 18.84	95.77	30.02	0.31
$R_{30}C_5F_1$	427.1 USD 46.98	693.1 USD 19.15	662.1 USD 6.89	16.6 USD 3.98	9.1 USD 37.67	114.68	35.21	0.31
$R_{30}C_5F_2$	427.1 USD 46.98	693.1 USD 19.15	662.1 USD 6.89	16.6 USD 3.98	18.2 USD 75.35	152.35	35.70	0.23

4 FUTURE TEST PROGRAMS

This study did not consider the durability properties and bond behavior of RFRRAC with reinforcement which needs to be further investigated before using this new type of sustainable green concrete in the bridge barriers. Future research should consider long-term environmental exposure to assess the durability properties, corrosion, and creep behavior of RFRRAC. Moreover, further studies should investigate the small-scale impact test on bridge barriers incorporating fiber and crumb rubber. Besides, a numerical study using ABAQUS should be performed to further substantiate the experimental test results.

5 CONCLUSIONS

This study explored the mechanical characterization of rubberized fiber reinforced recycled aggregate concrete (RFRRAC) for bridge barriers where 30% RCA and 5% CR content was used along with the different percentages of PP fiber content. Results indicate that RCA and CR with 2% fiber content can exhibit better mechanical properties and flexural resistance compared to the other mix ratios. The inclusion of fiber along with CR content can increase the toughness and ductility of RC beams. This is mainly attributed to the higher tensile capacity of PP fibers which create a strong bridging between the aggregates, thus help resist additional load even after the yielding of reinforcement. The available design equations developed for normal aggregate concrete under predict the ultimate capacity of LR concrete beams and tend to overestimate the capacity of the HR beams. The LR beams exhibit flexural failure mode, and the HR beams exhibit shear failure due to the higher reinforcement ratio. The RFRRAC requires more drop to break compared to the control concrete, and this number increases with the increasing percentage of the fiber content within the concrete mixture. Moreover, the PP fiber and CR content improve the deformation capacity of the concrete beams. Thus, the efficient and optimized material composition of RFRRAC in barriers of road-side highways or bridges can absorb more shock/impact, thereby reducing the damage due to accidents in highways.

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