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Energy absorption behavior of reinforced concrete column consisting recycled aggregate, crumb rubber and polypropylene fiber under lateral impact

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ABSTRACT: Reinforced concrete columns are designed primarily to withstand gravity loads, but their vulnerability to transverse loads coming from extreme shock such as impact and explosion cannot be overlooked. This study is intended to investigate the impact energy response of rubberized recycled aggregate concrete structures. Reinforced concrete columns with 11 different combinations of Recycled Coarse Aggregate (RCA), Crumb Rubber (CR) and Polypropylene Fiber (PPF) were selected for testing. Lateral impact was provided at the mid height of the column with a hammer following the principle of simple pendulum. With increasing percentage of RCA energy absorption capacity decreased significantly. For fixed percentage of RCA with increasing proportion of CR and PPF, energy absorption capacity of the specimens increased significantly. Among all the specimens 30% RCA, 5% to 10% CR and 1% PPF showed the best energy absorption potential.

1 INTRODUCTION

The urban population of the world has grown rapidly from 751 million to 4.2 billion in the last 70 years. Currently 55% of the world population lives in urban areas and it is expected to rise to 68% by 2050(Revision of world urbanization prospect 2018). Due to rapid urbanization, cities are being rearranged by demolishing old and deteriorated buildings and traffic infrastructures, and substituting them with new construction. As a result, every year a huge amount of C&D (Construction and Demolition) wastes are being produced worldwide. At present, China is the largest producer of C&D waste amounting more than 1 billion tonnes each year (Akhter & Sarmah 2018). Unites States (US) generated 569 million tonnes of C&D waste in 2017, among which concrete constituted the largest portion at 69.7% followed by asphalt concrete at 15% (US EPA Report 2017). Overall, more than 3 billion tonnes of C&D debris is generated globally every year and concrete comprises a major portion of it (Akhter & Sarmah 2018). The disposal of such huge amount of C&D waste is often hazardous and creates negative impact on the environment. Additionally, the carbon footprint from C&D waste is also critical as it contributes 8.6% of the global anthropogenic CO2 emissions (Miller et al. 2018). On the other hand, the demand for concrete as a construction material is growing day by day making it the second most consumed material after water. Hence a balance needs to be drawn between the demand for concrete and the volume of demolished concrete waste. This balance can be established through recycling of demolished concrete waste. Aggregates, both fine and coarse can be recycled and used in place of natural aggregate. The major benefits of recycling include conservation of resources, reduction of carbon footprint, waste management and so on.

At present, recycled aggregates (RA) are more commonly used in backfills and road construction because of less stringent criteria (Ng & Engelsen 2018). But research on the use of RA in concrete in place of natural aggregate has generated growing interest in the recent past. The physical and mechanical properties of RCA in relation to NCA have already been found by various researchers. Limbachiya (Limbachiya et al. 2000) has shown that up to 30% RCA can be used in concrete mix design without significant reduction of concrete compressive strength. But more than 30% RCA replacement reduce the strength substantially. Etxeberria et al. 2007 has shown that the tensile strength of concrete increases up to 50% RCA replacement and then it starts to decrease with any further addition of RCA. On the other hand Alam (Alam et al. 2012) found that the tensile strength reaches its peak at 25% replacement level of RCA. Poon et al. 2002 and Alam et al. 2012 all have found that the flexural strength of concrete decreases for any replacement level of RCA which indicates its brittle nature. In case of dynamic impact loading it has been found that the compressive strength of RAC increases with increasing strain rate up to 50% replacement level of RCA but the tensile and flexural strength decreases with the increasing levels of RCA (Xiao et al. 2015).

The use of suitable proportion of crumb rubber derived from scrap tires in place of fine aggregate can increase the shock and energy absorption capacity of concrete and make the structure more resilient (Rubber statistical bulletin 2014). Every year around 1 billion of waste tires are generated of which the recycling industry processes only 100 million tires. As per 2017 U.S. scrap tire management summary, 249.4 million of scrap tires were generated in the U.S. of which only 8% were utilized for civil engineering construction (2017 US Scrap Tire Management Summary 2018). EU has already banned the dumping of old tires either whole or shredded in the landfills from 2006 (Torretta et al. 2015). Though burning tires as means of alternative fuel is a more popular approach to recycle old tires, it has huge negative environmental impact. Therefore, the use of scrap tire in civil engineering construction can help in waste management as well as conserve natural resources. Khatib and Bayomy (1999), Wong and Ting (2009), and Meherier (2016) have shown that the ductility or deformability of concrete structure increases whereas the compressive strength decreases significantly with the addition of increasing percentage of crumb rubber. A replacement level of up to 10% can be used without sacrificing the compressive strength substantially and increasing the resiliency of the structure at the same time (Humphrey & Blumenthal 1998). Khatib and Bayomy (1999) and Schimizze et al. (1994) suggested in their study that rubber should not exceed 17–20% of the total aggregate volume.

Concrete is considered to be a relatively brittle material and a small percentage of fiber can be used to overcome the additional brittleness imparted by RCA (Konig 1998). Fiber reinforced concrete first came in light back in 1960. Since then steel fibers have been commonly used in various concrete structures. The use of PPF in concrete has emerged recently which possess better durability as it does not rust compared to steel fiber. It is also easy to handle as it weighs about one-fifth of an equivalent steel fiber. Soroushian et al. (1992) found that with the use of 1% PPF the flexural and impact strength of concrete increases by 21% whereas the compressive strength increases by 23%. The fiber also prevents the crack formation in the structure (Banthia & Gupta 2006). Banthia et al 2006 showed that with addition of 0.5% PPF by volume, the crack formation in concrete reduces significantly. Konig et al. (1998) showed that the tensile strength and the ductility of concrete structure increases substantially with the introduction of PPF in the structure. Therefore a suitable combination of RCA, CR and PPF may overcome all types of negative effects of using RCA alone.

This study focuses on the investigating the energy absorption capacity of concrete columns consisting RCA, CR and PPF in place of NCA, sand and cement respectively. The compressive strength of the concrete were also determined on the day of testing to correlate between compressive strength and impact resistance as well as energy absorption capacity to find out the best combination.

2 RESEARCH SIGNIFICANCE

Bridge piers and piers of flyovers might be subjected to sudden impact from ships and vehicles respectively. Various researches on impact resistance of reinforced concrete columns and numerical simulations of barge impact on reinforced concrete piers have already been conducted. But no comprehensive study has yet been conducted to determine the impact resistance of piers made of Recycled Aggregate Concrete (RAC) with Crumb Rubber and polypropylene fiber. Since rubber has more energy absorption capacity than concrete hence application of suitable proportion of crumb rubber in combination with concrete should absorb more energy and should be more resilient against impact load theoretically compared to structure made with normal concrete while maintaining the same strength parameters. At the same time, the use of small amount of polypropylene fiber (1 - 2%) instead of cement increases the capacity of concrete against failure and also enhances the ductility of the member as a whole. Hence this research is designed to experiment the impact resistance behavior of concrete piers made with RAC and suitable proportions of crumb rubber and polypropylene fiber to determine the suitability of its use when structure comes under lateral impact loads like bridge piers and columns.

3 EXPERIMENTAL PROGRAM

3.1 *Mix Design*

Total 11 different concrete mixes were prepared with different proportions of RCA, CR and PPF for understanding the effect of each material. Design compressive strength was fixed 30 MPa. The cement content and water cement (w/c) ratio was fixed 430 kg/m3 and .39 respectively. 30% and 50% RCA was used in replacement of NCA by weight but the CR and PPF were replaced volumetrically. CR was used in replacement of sand by 5% and 10% and PPF was used in the replacement of cement by 1%. No water reducing admixture was used. For specimen identification, a simple code $R_XC_YF_Z$ is used throughout the study for easy understanding. Here R, C and F represent RCA, CR and PPF respectively whereas X, Y and Z represent their percent of replacement. For example, $R_{30}C_5F_1$ means 30% RCA, 5% CR and 1% PPF replacement in place of NCA, sand and cement respectively. The mix proportions of different materials are summarized in Table 1.

Table 1. Mix proportion for test specimens.

Serial	Batch Code	W/C Ratio	Coarse Aggregate		Fine Aggregate		Binder	
			NCA (kg/m3)	RCA (kg/m3)	Sand (kg/m3)	CR (kg/m3)	Cement (kg/m3)	PPF (kg/m3)
1	R0C0F0 (Control)	0.39	1059	-	763	-	430	-
2	R30C0F0		741.3	317.7	763	-	430	-
3	R30C5F0		741.3	317.7	662.08	17.15	430	-
4	R30C5F1		741.3	317.7	662.08	17.15	425.76	1.25
5	R30C10F1		741.3	317.7	645.47	34.3	425.76	1.25
6	R50C0F0		529.5	529.5	678.70	-	427.08	-
7	R50C5F0		529.5	529.5	662.08	17.15	427.08	-
8	R50C5F1		529.5	529.5	662.08	17.15	425.76	1.25
9	R50C10F1		529.5	529.5	645.47	34.3	425.76	1.25
10	R0C5F0		1059	0	662.08	17.15	427.08	-
11	R0C10F0		1059	0	645.47	34.3	427.08	-

3.2 *Specimen Design*

Total eleven different mix designs were prepared and tested for cylinders and columns for this study in order to have a comparative analysis of the results. All specimens used for this research were 10 inch x 10 inch in cross-section and 84 inch (7 ft) long with an effective length of 72 inch (6 ft). Four No.5 bars were used as longitudinal reinforcement (Figure2), resulting in a reinforcing ratio, ρ, of 1.24%. No.3 bars were used as stirrups with a spacing of 10 inch centre to centre. The only variable between specimens was the different proportions of RCA, CR and PPF used.

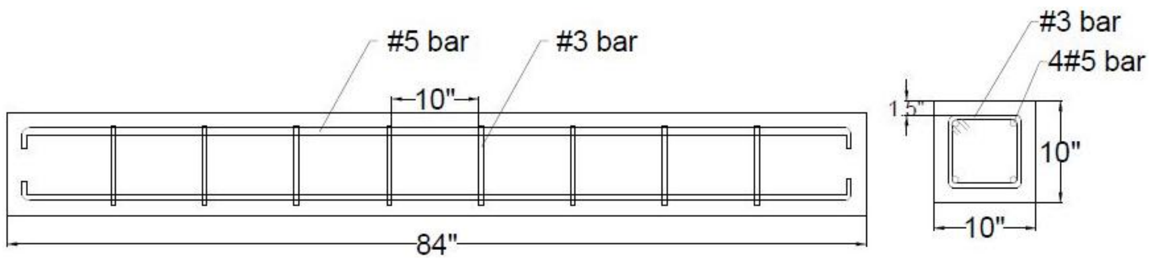


Figure 1. Reinforcement detailing of test specimens.

3.3 *Test Setup for Impact Load Application*

Dynamic impact loads for this testing program were applied by a customized steel frame built in a local workshop (Figure 3). The principle of simple pendulum was observed for applying the impact load. A rigid steel rod of 3.75 ft length and a steel sphere of 10 kg mass constituted the pendulum with a combined mass of 12.5 kg. The pendulum was released from an angle of 152^0 from a height of 2.115 m to impact the test columns at mid-height with an impact velocity of 6.5 m/s. The pendulum was fixed with the steel frame with a hinge. The frame is designed in such a way so that the pendulum strikes the test specimen at an angle of 11 degree with vertical to avoid secondary impact. The mass of the steel ball could be changed according to the strength and rigidity of the test specimens. The point of impact was also adjustable by changing the length of the steel rod. The hinge was properly greased before each experiment to reduce the effect of friction on the pendulum. Two load cells (top and bottom) and a displacement sensor (mid height) were attached at the back of the specimens to determine the impact load and displacements for each impact respectively.

(a) (b) (c)
Figure 2. Customized Dynamic Impact Testing Setup (a) Working principle (b) 3D modeling (c) Original setup.

3.4 *Testing Procedure*

Total 22 concrete columns (02 per trial mix) and 33 cylinders (03 per trial mix) were prepared for testing. All the specimens were tested after 56 days of casting and the concrete cylinder strength was also measured on the day of impact testing. Number of impact required for initial crack forming, peripheral crack and concrete crushing was observed. Since reinforcements were used in all the specimens, complete break of the columns were not possible. Peripheral cracks all around the column or crushing of concrete whichever occurred first was considered as ultimate failure state. The energy absorption capacity per impact was also determined using the following simple formula:

$E = mgh$

Where,

E = Impact energy in J g = Gravitational force (9.81 ms^{-2})

m = Mass of impactor (12.5 kg) h = Height of drop (2.155 m)

4 RESULTS AND DISCUSSIONS

4.1 *Energy Absorption Capacity*

The comparison between total energy absorbed (J) and energy absorbed per unit weight (J/Kg) is shown on table 2. Drop energy required to reach the failure state is considered as the total energy absorbed by each specimen. The compressive strength of each specimen was measured on the day of impact testing to understand the effect of each material on both compressive strength, energy response and finally to establish a relation between them. In general it is seen that both compressive strength and energy absorption capacity decreases with increasing % of RCA. Addition of CR increases the energy absorption capacity but substantially reduces the compressive strength. Addition of fiber increases both compressive strength and the energy absorption capacity up to an acceptable proportion of RCA and CR replacement level.

Table 2. Comparison of compressive strength and energy absorption capacity.

Batch code	Mean compressive strength (MPa)	Weight (Kg)	Energy per drop (J)	No of drop for failure	Total energy Absorbed	Energy absorbed per unit weight (J/Kg)
$R_0C_0F_0$	40.73	335	264.25	29	7663.25	22.88
$R_{30}C_0F_0$	37.96	336		25	6606.25	19.66
$R_{30}C_5F_0$	36.68	334		32	8456	25.32
$R_{30}C_5F_1$	38.02	334		37	9777.25	29.27
$R_{30}C_{10}F_1$	36.28	331		39	10305.75	31.14
$R_{50}C_0F_0$	32.36	337		22	5813.5	17.25
$R_{50}C_5F_0$	28.31	334		28	7399	22.15
$R_{50}C_5F_1$	33.69	334		31	8191.75	24.53
$R_{50}C_{10}F_1$	31.82	332		33	8720.25	26.276
$R_0C_5F_0$	30.9	332		31	8191.75	24.67
$R_0C_{10}F_0$	29.82	330		34	8984.5	27.23

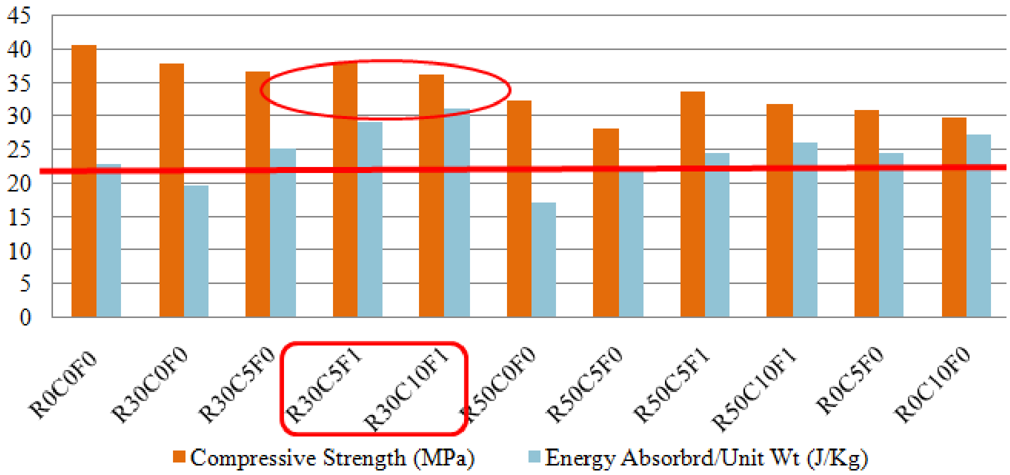


Figure 2. Comparison of compressive strength and energy absorption capacity.

4.1.1 *Effect of RCA on energy absorption capacity*

With the increasing proportion of RCA without the addition of CR and PPF both the compressive strength and the energy absorption capacity decreased substantially. For 30% replacement level the compressive strength reduced by 6.8% while energy absorption capacity per unit weight reduced by about 14%. For 50% replacement level the compressive strength reduced by 20% while energy absorption capacity per unit weight reduced by about 25%. Since the traditional role of concrete column is to resist the gravity load hence 50% replacement level of RCA may be deemed unsuitable.

Table 2a. Effect of RCA on energy absorption capacity.

Item	$R_0C_0F_0$ (Control)	$R_{30}C_0F_0$	$R_{50}C_0F_0$
Mean Compressive Strength (MPa)	40.73	37.96 (- 6.8%)	32.36 (- 20%)
Total Energy Absorbed (J)	7663.25	6606.25 (-13.8%)	5813.5 (- 24.14%)
Energy Absorbed per Unit Weight (J/Kg)	22.88	19.66 (- 14.07%)	17.25 (- 24.6%)

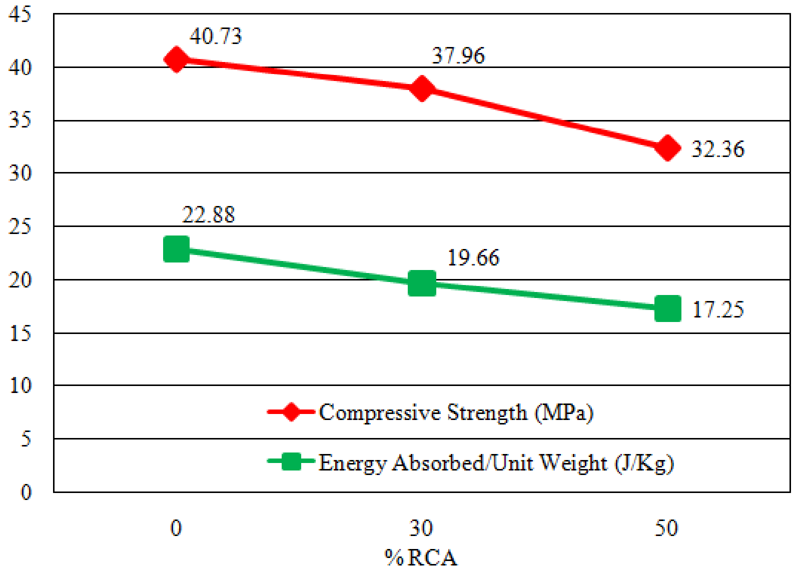


Figure 3. Effect of RCA on compressive strength and energy absorption capacity.

4.1.2 *Effect of crumb rubber on energy absorption capacity*

The comparison of compressive strength and energy absorption capacity at a fixed RCA and fiber with different replacement levels of crumb rubber are shown in Table 3. For a fixed RCA and fiber replacement, it is seen than the compressive strength decreases but energy absorption capacity increases with the increasing proportion of CR. Without the addition of RCA and fiber (R_0F_0), for addition of 5% CR compressive strength reduced by 24% while energy absorption capacity per unit weight increased by about 7%. For addition of 10%

CR with the same combination compressive strength reduced by 26.8% while energy absorption capacity per unit weight increased by 17.24%. The same trend is observed in case of 50% RCA replacement level. It is observed that for all the combinations addition of CR decreases the compressive strength significantly. Since concrete columns are designed primarily for resisting axial loads hence application of CR alone may not be feasible.

Table 3. Effect of CR on compressive strength and energy absorption capacity.

Item	0% RCA + 0% Fiber			30% RCA + 0% Fiber		50% RCA + 0% Fiber	
	$R_0C_0F_0$ (Control)	$R_0C_5F_0$	$R_0C_{10}F_0$	$R_{30}C_0F_0$	$R_{30}C_5F_0$	$R_{50}C_0F_0$	$R_{50}C_5F_0$
Mean compressive strength (MPa)	40.73	30.9 (- 24.13%)	29.82 (- 26.79%)	37.96	36.68 (- 3.37%)	32.36	28.31 (- 12.52%)
Total energy absorbed (J)	7663.25	8191.75 (6.9%)	8984.5 (17.24%)	6606.25	8456 (28%)	5813.5	7399 (27.27%)
Energy absorbed per unit weight (J/Kg)	22.88	24.67 (7.82%)	27.23 (19%)	19.66	25.32 (28.79%)	17.25	22.15 (28.4%)

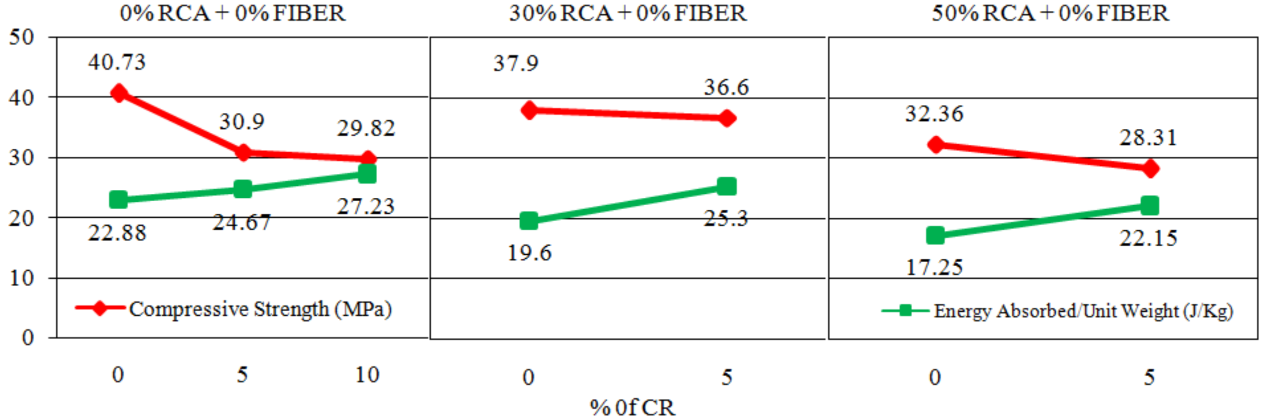


Figure 4. Effect of CR on compressive strength and energy absorption capacity.

4.1.3 *Effect of polypropylene fiber on energy absorption capacity*

The comparison of compressive strength and energy absorption capacity at a fixed RCA and CR with different replacement level of fiber is shown in Table 4. Keeping the percentage of RCA and CR fixed, as the percentage of fiber is increased both compressive strength and energy absorption capacity of the specimen increases. For 30% RCA and 5% CR with the addition of 1% fiber the compressive strength increased by 3.65% while energy absorption capacity per unit weight increased by 16%. For 50% RCA and 5% CR with the addition of 1% fiber the compressive strength increased by 19% while energy absorption capacity per unit weight increased by 10.75%. So, by the addition of suitable proportion of fiber the effect of CR in reducing compressive strength can be mitigated and the energy absorption capacity can also be increased at the same time.

Table 4. Effect of fiber on compressive strength and energy absorption capacity.

Item	30% RCA + 5% CR		50% RCA + 5% CR	
	$R_{30}C_5F_0$	$R_{30}C_5F_1$	$R_{50}C_5F_0$	$R_{50}C_5F_1$
Mean compressive strength (MPa)	36.68	38.02 (3.65%)	28.31	33.69 (19%)
Total energy absorbed (J)	8456	9777.25 (15.5%)	7399	8191.75 (10.71%)
Energy absorbed per unit weight (J/Kg)	25.32	29.27 (16%)	22.15	24.53 (10.75%)

4.2 *Failure Pattern*

Almost all the specimens have similar initial crack pattern. The initial crack formed diagonally from the point of impact towards all direction in the impact face. Afterwards with each impact the crack propagated along the periphery of the specimens. Only combinations $R_0C_5F_0$ and $R_0C_{10}F_0$ failed due to concrete crushing before peripheral crack could occur. For these two combinations, the initial crack developed diagonally on one side only. An in depth analysis was conducted about the crack pattern and crack width upon failure of various specimens. It was found that the crack width with only RCA was minimum and less than the control upon failure. With the addition of CR, the crack width increases but the impact face of the specimens cracked before peripheral crack could generate. It indicates weaker bonding and less cohesion between CR and concrete. Specimens with combination of RCA, CR and PPF show a slightly increased crack width than the control. Table 10 shows the average initial and peripheral crack width upon failure and figure 06 represents the failure pattern of various specimens.

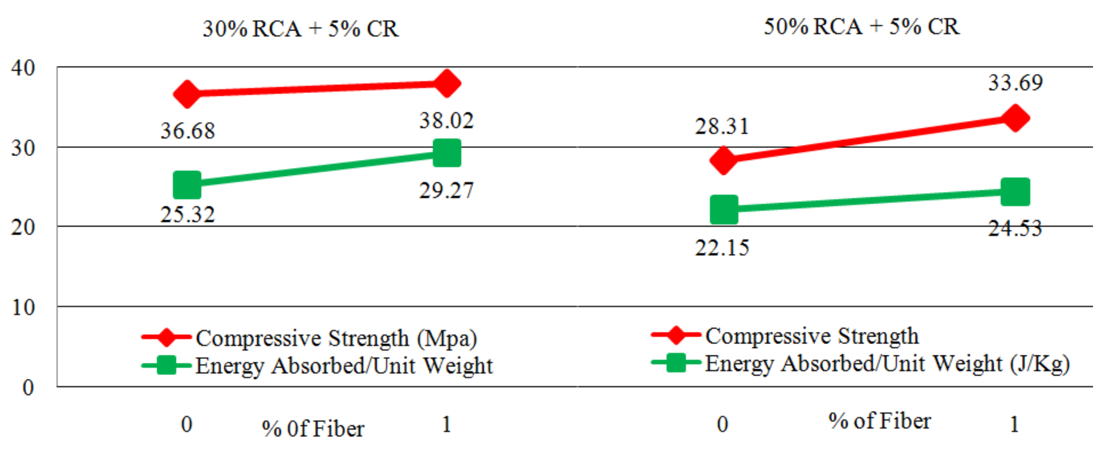
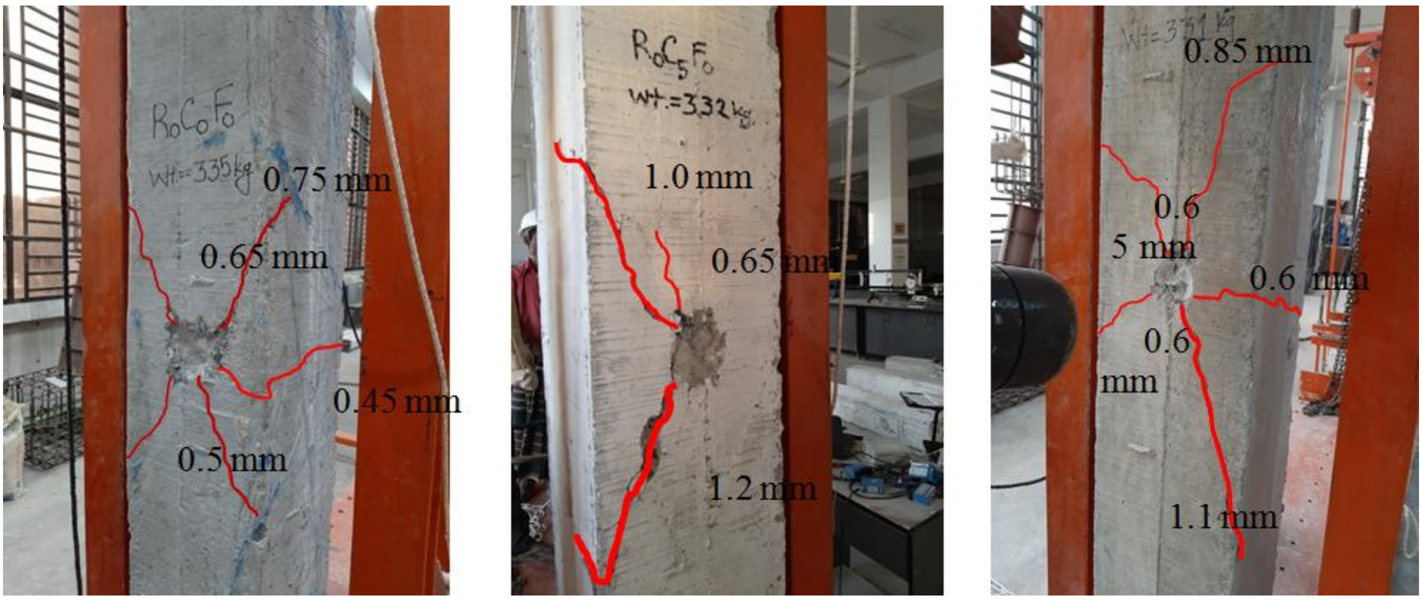


Figure 5. Effect of fiber on compressive strength and energy absorption capacity.

Table 5. Average initial and peripheral crack width upon failure for all the specimens.

Batch code	$R_0C_0F_0$	$R_{30}C_0F_0$	$R_{30}C_5F_0$	$R_{30}C_5F_1$	$R_{30}C_{10}F_1$	$R_0C_5F_0$	$R_0C_{10}F_0$
Average initial crack width (mm)	0.6	.55	.65	.75	0.8	.95	1.1
Average peripheral crack width (mm)	0.45	0.4	0.5	0.55	0.6	No crack	No crack

Batch code	$R_0C_0F_0$	$R_{50}C_0F_0$	$R_{50}C_5F_0$	$R_{50}C_5F_1$	$R_{50}C_{10}F_1$
Average initial crack width (mm)	0.6	0.5	0.6	0.7	0.7
Average peripheral crack width (mm)	0.45	0.4	0.45	0.55	0.6



(a) (b) (c)

Figure 6. Failure pattern of test specimens (a) Control (b) Specimens with only CR (c) Specimens with combination of RCA, CR and PPF.

5 CONCLUSIONS

This study thoroughly investigates energy absorption capacity of RAC columns containing CR and PPF. Based on experimental programs carried out in this research the following conclusions can be drawn:

- CR based concrete shows better performance in terms of energy absorption capacity. Addition of fiber further increases the energy absorption capacity and also compensates the reduction of compressive strength. The combination containing 30% RCA, 10% CR and 1% fiber showed the best energy absorption potential among all the specimens.
- Addition of RCA and PPF decreases the crack width while addition of CR increases it upon failure. But rubberized concrete fails due to concrete crushing before peripheral cracking because of less compressive strength and less cohesion.
- Overall the combination of 30% RCA, 5% to 10% CR and 1% PPF showed the best performance among all the specimens in terms of higher energy absorption potential without significant reduction of compressive strength.

In addition to the gravity loads, modern day structures are also vulnerable to out of plane impact loads. As the application of recycled aggregate in construction is relatively a new field, therefore more research may be undertaken for determining design codes, specifications and procedure for practical assignment of rubberized concrete in the structural domain. Future study may investigate the fire resistance and durability of rubberized concrete under different conditions such as polluted and saline environment to determine its resilience against lateral impact loads.

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