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EXPERIMENTAL STUDY ON THE MECHANICAL PROPERTIES OF RECYCLED AGGREGATE CONCRETE USING CRUMB RUBBER AND POLYPROPYLENE FIBER

Shahjalal, Md.[1], Hossain, F.M. Z.[2], Islam, K.[3,4], Tiznobaik, M.[2] and Alam, S.[2]
[1] Military Institute of Science and Technology, Bangladesh
[2] University of British Columbia, Canada
[3] Ecole Polytechnique de Montreal, Canada
[4] kamrul.islam@polymtl.ca

Abstract: A huge amount of concrete waste is produced every year all over the world due to demolishing old infrastructure resulted in great concern for the disposal of this concrete waste. In addition, waste rubber derived from end-of-life discarded tires also contribute to environmental degradation while using them partly as a replacement of natural aggregate is one of the methods for constructing sustainable concrete. This study is focused on the improvement of strength and toughness of concrete having recycle coarse aggregate (RCA) and crumb rubber (CR) as a partial replacement of natural coarse aggregate (NCA) and natural fine aggregate (NFA). Level of RCA replacement is 30%, CR 5% and 10%, and the addition of polypropylene fiber are 1% and 2% in the concrete mixture. Eight different mixtures are considered for this study and the results of the mechanical properties are presented in terms of compressive strength, flexural responses and repetitive drop-weight impact responses of various rubberized concrete with RCA and fiber in comparison with control mixture. The result indicates that compressive strength, flexural strength increase with increasing fiber content but decrease with increasing rubber content. Moreover, the rubberized concrete with RCA and polypropylene fiber shows more toughness and ductility which indicates that rubberized concrete provides more warning before failure and shows better energy absorption capacity compared to the control concrete mixture.

1. INTRODUCTION

Sustainable construction and infrastructure management largely depend on the recycling and reuse of waste material. For demolishing old buildings, offices and bridges a huge amount of concrete waste is produced every year all over the world. In British Columbia, Ontario and Alberta, the amount of Construction and Demolition (C & D) waste is almost 27.5%, 29% and 7.5 % of total municipal solid waste, respectively (Canada Statistics 2008). Nowadays it is getting a great matter of concern for the disposal of this huge concrete waste. On the other hand, it is estimated that Canada's national municipal infrastructure deficit is about $123 billion which is annually growing by $2 billion (Mirza 2007). J. T. Smith (Smith 2010) showed that almost 10 to 12 billion tons of aggregates are being used throughout the world every year to cope up with this demand. So, the use of concrete waste as a recycled coarse aggregate can provide a viable solution to meet the increasing demand for natural aggregate. Many research has been conducted by replacing a percentage of natural aggregate with Recycled Granulated Steel, Poly-Ethylene Terephthalate (PET), Recycled Coarse Aggregate etc. (Quadir 2016., Islam 2016, Alam 2013).

To improve the shock absorption capacity a more popular approach is to use crumb rubber (CR) as a partial replacement of fine aggregate (Liu 2012, Bindiganavilea 2013). It is also an alternative way to use waste material. It is found that about 70% of produced rubber is consumed by the tire-manufactured companies globally (M. S. Meherier 2015) and almost 1000 million tires are generated as scrap tires from bicycle/rickshaw, motorcycle, bus and truck etc., all over the world every year (Thomas 2014). In 2010, more than 380 thousand metric tons of scrap tires were collected from all the provinces of Canada (M. S. Meherier 2016). A significant portion of this waste is used as landfill as they do not naturally decompose. So the reuse of these waste rubber can make the environment free from pollution and minimize material handling cost as well as their disposal and transportation cost.

As concrete is a brittle material, so it is prone to cracking and for preventing this crack development in concrete and increasing the ductility and toughness fiber can be used in concrete which also improves its tensile capacity (Najimi. M. 2009, Soroushian 1992). The polypropylene fibers are relatively inexpensive, easy to split into finer sizes and durable.

However, studies indicate that the use of recycled coarse aggregate (RCA) shows slightly lower slump value than control because of the attached mortar on the surface of the RCA which increases its workability and absorption capacity but decreases its specific gravity (Alam 2013, Salem 2003, Huda 2015). In a study of RCA concrete by Limbachiya et al. (Limbachiya 2000) it was found that there was no significant effect on the compressive strength for 30% RCA replacement, while RCA replacement exceeding 30% reduced the strength. Another study found that the compressive strength of recycled concrete was very close to the control mixture for RCA replacement level of 25 % to 50% (Alam 2013). This study also found that the flexural strength decreased by 16% and 32.4% for 25% and 50 % RCA replacement respectively. There was no significant effect occurred on the modulus of elasticity and Poisson’s ratio of recycled concrete up to 50% which was comparable to regular concrete (Huda 2015). For CR and fiber content, the slump value also decreased with the increased amount of them (M. S. Meherier 2016, Najimi. M. 2009, Mastali 2017). It was also observed that, the compressive strength decreased significantly when crumb rubber was more than 20% but up to 20% it was more than the desired compressive strength of 35 MPa (M. S. Meherier 2016). Another study found that the optimum replacement level of rubber content was 10% of fine aggregate (K. P. Tamanna 2017). Using polypropylene fiber in concrete decreases the compressive strength and modulus of elasticity but increases the flexural strength (Najimi. M. 2009, Soroushian 1992, Mastali 2017). It is also seen that adding fiber to concrete increased the impact strength and prevented the crack development. Under both quasi-static and impact loading, the modulus of rupture was increased by adding polypropylene microfibers (Mamun 2010). Another study found that the energy absorption capacity of the rubber-reinforced concrete increased with the increasing of rubber contents up to 10% and then decreased (Liu 2012) and due to the lighter density of CR, they are attractive as shock absorbing composites (Bindiganavilea 2013).

Limited studies have been conducted on the combination of recycled coarse aggregate, CR, and fibre (Jian-he 2015, K. Tamanna 2018), hence, this study investigates possible correlations in the mechanical properties of different mixtures of RCA, CR, and fiber to optimize the composition of this mixed aggregate for future construction projects.

2 EXPERIMENTAL INVESTIGATION

The experimental study constitutes of determination of hardened mechanical properties of the concrete mixtures like compressive strength, flexural responses and impact responses of concrete.

2.1 Materials

Materials for concrete mixtures include natural coarse aggregate, recycled coarse aggregate, natural fine aggregate, CR, PCC (Portland Composite Cement) and polypropylene fiber. PCC is the most widely used cement in Bangladesh. A locally available well graded natural sand and coarse aggregate are used in this study. The maximum grain size of natural coarse aggregate (NCA) and natural fine aggregate (NFA) are 19 and 4.75 mm respectively. The recycled concrete used in this study is collected from a demolished building. From that recycled concrete RCA was prepared with a maximum size of 19 mm. The gradation curve of NCA and RCA, presented in Figure 1(a), shows a well-fitting curve within the ASTM range (ASTM International 2014). A maximum CR size of 4.75 mm is used as a fine aggregate. The gradation curve of rubber and NFA are presented in Figure 1(b). From the figure, it is clear that NFA particles fit within ASTM range but rubber does not fit. It means that NAF particles are well-graded and CR is gap-graded. It happens because CR is commercially produced and supplied by a company, However, because of using CR as NFA replacement, the combined gradation of both the materials are considered to fit within the standard specified. To determine the physical properties of aggregate ASTM standards are followed. The physical properties of the aggregates are summarized in Table 1. A Japanese private company provided the polypropylene fiber for this study. The specifications for the polypropylene fiber are presented in Table 2.

Table 1: Physical properties of aggregates

Variables	Cement	NCA	RCA	NFA	CR
Bulk Specific Gravity (SSD)	-	2.71	2.51	2.41	1.18
Bulk Specific Gravity (OD)	2.95	2.70	2.44	2.36	-
Absorption Capacity (%)	-	0.48	3.23	1.8	1.3
Fineness Modulus	-	2.51	2.45	2.39	3.49
Normal Consistency (%)	26.7	-	-	-	-
Initial Setting Time (min)	130	-	-	-	-
Final Setting Time (min)	180	-	-	-	-

Table 2: Specifications for polypropylene fiber

Variables	Polypropylene fiber
No of Denier	03
Specific gravity (g/cm^3)	0.91
Fiber Length (mm)	12
Tensile Strength (MPa)	480
Elastic Modulus (GPa)	7.0

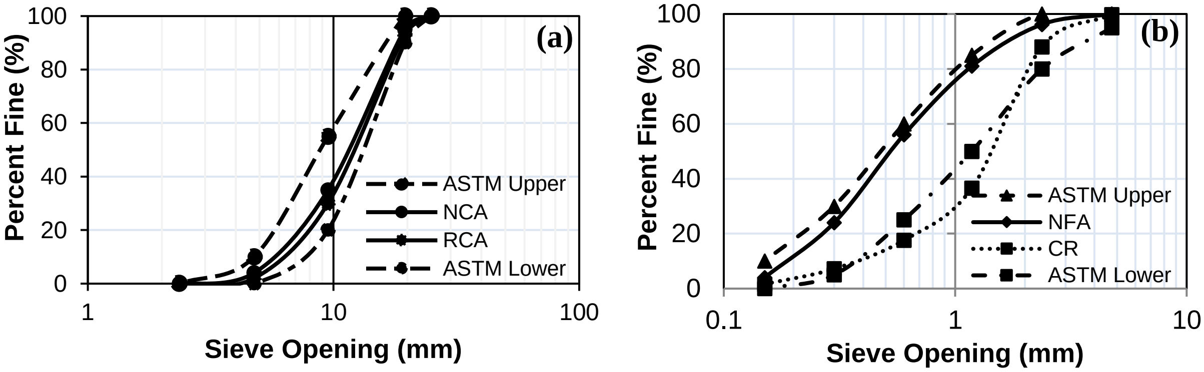


Figure 1: The gradation curve: (a) NCA & RCA, and (b) NFA & CR

1.1 Mixture proportions

In total eight concrete mixtures are prepared including the control mixture (0% RCA, 0% CR and 0% polypropylene fiber) for this study. Level of RCA replacement is kept constant at 30% for all batches and the variations are in the percentage of NFA, CR, cement, and polypropylene fiber. CR is used in the replacement of sand in 5% and 10% proportions, and polypropylene fiber is used in the concrete mixture at 1% and 2% proportions. As the specific gravity of CR and fiber are low compared to NFA and cement, they are replaced in volume basis but RCA is replaced by weight basis. The design compressive strength is fixed as 30 MPa and the effective water-cement ratio is fixed as 0.38 throughout the mix design to eliminate the effects of water on concrete properties. The coarse aggregate and fine aggregates used in the concrete are in saturated surface dry (SSD) condition. No water-reducing admixture is used. Table 3 summarizes the mixture proportions of different materials in the concrete cylinders. Each mix design is designated with a unique name for ease in referencing within the text. For example, Batch name $R_{30}C_{10}F_2$ indicates that this mixture consists 30% recycled coarse aggregate (R), 10% crumb rubber (C) and 2% polypropylene fiber (F). Therefore, 70% NCA and 90% NFA were used in this mixture. The other batches are named in the same manner.

Table 3: Proportions of concrete mixtures (kg/m^3)

Batch No.	Batch Name	Water	Cement	NCA	NFA	RCA	CR
1	$R_0C_0F_0$	163.8	427.1	990.2	678.7	0.0	0.0
2	$R_{30}C_0F_0$	163.8	427.1	693.1	678.7	297.0	0.0
3	$R_{30}C_0F_1$	163.8	427.1	693.1	678.7	297.0	0.0
4	$R_{30}C_0F_2$	163.8	427.1	693.1	678.7	297.0	0.0
5	$R_{30}C_5F_1$	163.8	427.1	693.1	662.1	297.0	16.6
6	$R_{30}C_5F_2$	163.8	427.1	693.1	662.1	297.0	16.6
7	$R_{30}C_{10}F_1$	163.8	427.1	693.1	645.5	297.0	33.2
8	$R_{30}C_{10}F_2$	163.8	427.1	693.1	645.5	297.0	33.2

Note: R=RCA; C=CR; F=Polypropylene fiber

1.2 Specimens

A total of 72 cylinders (100 mm diameter × 200 mm height) are cast for the compressive strength test at 7, 28, and 56 days. Moreover, for eight different concrete mixtures, a total of 48 beams with a mold size of 100 mm × 100 mm × 500 mm are cast to quantify the flexural strength at 28 days and impact strength at 120 days. After casting the specimens are initially cured for 24 hours within the mold in a moist room and then demolded and kept at a controlled temperature in a constant condition under fresh water for 28 days.

1.3 Testing Procedure

All tests are performed according to ASTM standards. The compressive strength test is performed according to ASTM C39-18 (ASTM International 2018) . The rate of the load is 0.25 ± 0.05 MPa/s. For 56 days concrete cylinders two strain gauges were attached to the specimen in both longitudinal and transverse directions at the mid-height of the cylinders. Before testing, the upper and lower surface of each cylinder is levelled with sulfur capping to eliminate the eccentricity of loading. A Universal Testing Machine with a capacity of 1000KN is used to perform the third point loading flexural strength test according to ASTM C1609/C1609M-12 (ASTM International 2012) using a displacement rate of 0.15 mm/min. The peak load for each test is determined and flexural strength is calculated from these load values. To perform the drop-weight impact test a drop weight machine is used shown in a Figure 2. It's basically a frame made of both steel and wood. The wooden horizontal frame can slide up and down. A vertical post is firmly connected with the horizontal frame at the middle which actually helps to releases the weight from a variable height with the help of a trigger. A weight of 0.988 kg is being dropped from a height of 0.893 meter creating an energy of 8.66 J. To reduce the vibration made by the sudden drop of weight on the beam a rubber pad is placed beneath the beam support. After that a steel baseplate is used under the rubber pad which is connected with Load cells. From there the data will be transmitted to the data acquisition system through an amplifier. After dropping the weight, the number of drops that is required to break the beam are counted with a stop watch. The deflection of the beam is measured by using Displacement Transducer named NS-WY02, which is an electromechanical device used to convert mechanical motion or vibrations, specifically rectilinear motion, into a variable electrical current, voltage or electric signals, and the reverse. 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 data acquisition system from the amplifier.

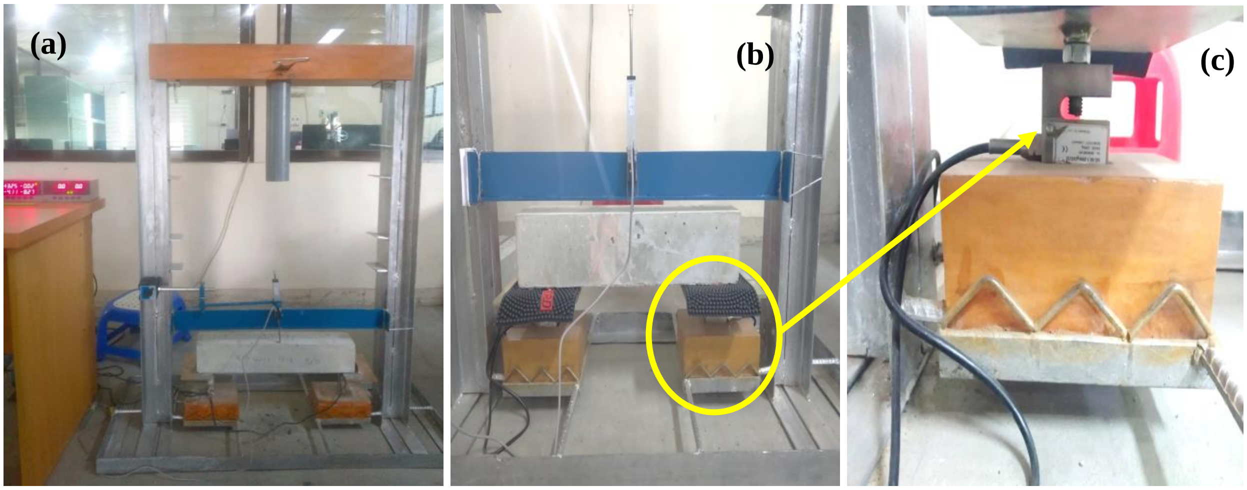


Figure 2: Test set up; (a) impact testing frame, (b) set up of beam and (c) Set up of load cell.

2 RESULTS AND DISCUSSIONS

The effects of using RCA, CR and polypropylene fiber, on compressive strength, splitting tensile strength and flexural strength of concrete are presented in this section.

2.1 COMPRESSIVE STRENGTH

The results obtained from the hardened concrete compressive strength test after 7, 28, and 56 days are presented in Figure 3.

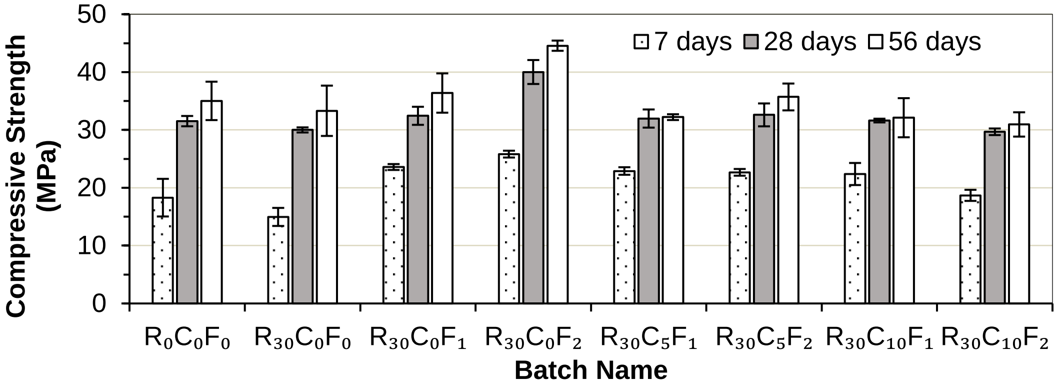


Figure 3: Results of compressive strength of concrete cylinders

It is seen that all the specimens achieve the designed compressive strength of 30 MPa expect Batch-8 ($R_{30}C_{10}F_2$). At a fixed fiber content with the incremental replacement of CR, the compressive strength decreases (Batch-3, Batch-5, Batch-7 and Batch-4, Batch-6, Batch-8), as shown in Figure 4 (a). It is observed with the incremental replacement of crumb rubber, the compressive strength decreases. This may attribute to the weaken transition zone between CR and cement paste. In addition, various deleterious materials (i.e., sulfur and zinc) are present on the surface of rubber, which results in a poor bonding capacity (M. S. Meherier 2016). On the contrary, it is seen that, for a fixed CR replacement level, the compressive strength increases with an increasing replacement level of fiber (Batch-3 & Batch-4, Batch-5 & Batch-6). But from Figure 4 (b) we see that Batch-7 ($R_{30}C_{10}F_1$) and Batch-8 ($R_{30}C_{10}F_2$) do not follow this trend. This may attribute to the fact that in these combinations the RCA replacement level and CR replacement level is both relatively high, and for a large amount of rubber replacement level, the effect of fiber is less significant. From Batch-6 ($R_{30}C_5F_2$) and Batch-7 ($R_{30}C_{10}F_1$), it is seen that compressive strength decreases more for Batch-7 than for Batch-6 because, for Batch-7, the rubber percentage increases while the fiber content decreases. Same trend is seen for Batch-4 ($R_{30}C_0F_2$), Batch-5 ($R_{30}C_5F_1$). Batch-4 ($R_{30}C_0F_2$) shows the highest compressive strength because in this combination there is no CR and at the same time the fiber percentage is higher.

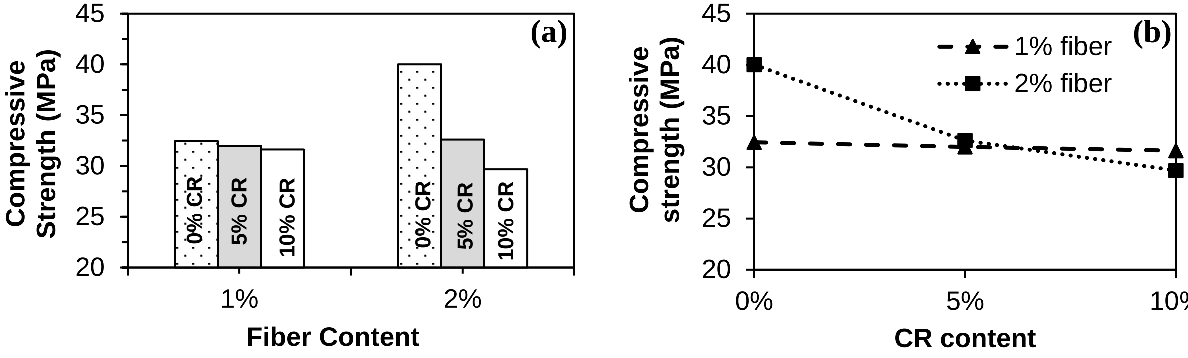


Figure 4: Variation of compressive strength (28 days) (a) with different replacement level of CR and (b) with different replacement level of fiber.

From Table 4 it is observed that rubber-based concrete shows high Poisson's ratios because of its soft material property and higher energy absorption capacity. The Poisson's ratio increases with the increasing replacement level of rubber, which signifies better deformability and energy absorption capacity. On the contrary, it is seen that the Poisson's ratio decreases with the incremental increase of fiber percentage, which implies the contribution of fiber in resistance against deformation.

Table 4: Mechanical properties of different concrete mixes 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
$R_{30}C_0F_0$	33.31	2.642	6.600	3.100	0.250
$R_{30}C_0F_1$	36.38	5.850	18.250	6.190	0.312
$R_{30}C_0F_2$	44.56	2.384	5.080	2.700	0.213
$R_{30}C_5F_1$	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
$R_{30}C_{10}F_1$	32.11	3.402	11.400	3.820	0.335
$R_{30}C_{10}F_2$	30.95	5.188	12.420	5.420	0.240

2.2 FLEXURAL STRENGTH

The summary of the quasi-static flexural strength test results is presented in Figure 5. Most of the concrete mixtures show lower flexural strength than the control mixture. At a fixed fiber replacement with incremental increases in CR replacement level, the flexural strength decreases (Batch-3, Batch-5, Batch-7 & Batch-4, Batch-6, Batch-8), as shown in Figure 4(a). This occurs because of the lower modulus of elasticity of rubber aggregate compared to hardened cement paste and the poor adhesion between the rubber particles and surrounding mortar. Thus, it can be concluded that the flexural strength decreases with incremental increases in the replacement level of CR. On the contrary, it is seen that, for a fixed CR replacement level, the flexural strength increases due to increasing replacement level of fiber (Batch-3 & Batch-4, Batch-5 & Batch-6 and Batch-7 & Batch-8), as shown in Figure 6(b). This occurs because fiber creates a good bridge between the aggregate and cement paste. After the beam was broken, it is seen that the bridging fibers are projecting outward and perpendicular to the cross section. Batch-4 ($R_{30}C_0F_2$) shows the highest flexural strength at 8.6% more than the control. In this combination, there is a high percentage of fiber which produces a strong bond between aggregate and cement paste, and there is no CR present.

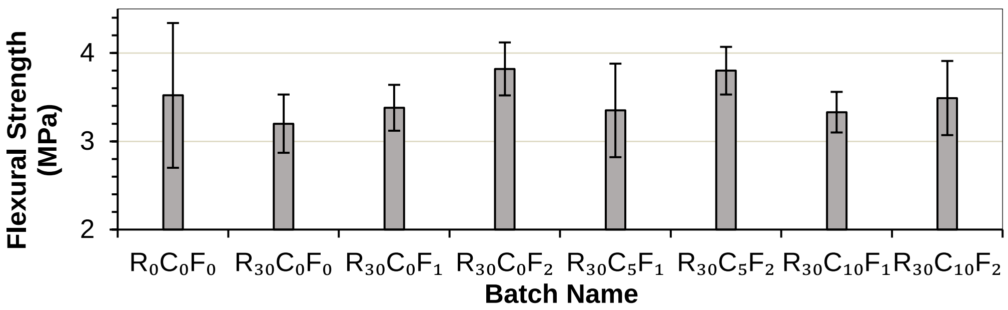


Figure 5: Result of flexural strength of concrete beam

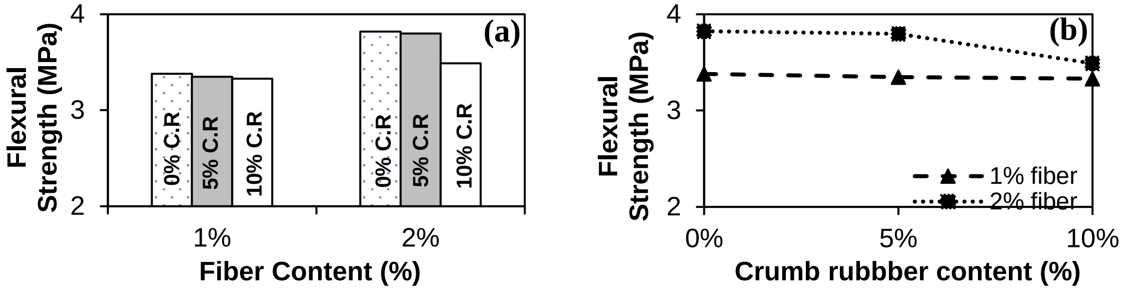


Figure 6: Variation of flexural strength with different replacement level of (a) CR and (b) fiber.

From Table 5 it is seen that for all batches, the toughness value is more than the control. The toughness value increases due to the increasing replacement level of fiber because fiber can form bridges between aggregate and cement paste on either side of the crack and is able to resist load against a long-term deflection after it has reached its ultimate point which is shown in Figure 8. On the contrary, it is seen that toughness value increases with an increasing replacement level of CR up to 5% and then decreases for 10% CR shown in Figure 7(a) (Batch-3, Batch-5, Batch-7; Batch-4, Batch-6, Batch-8). Batch $R_{30}C_5F_2$ shows the highest toughness value. Same trend is also observed for ductility value. A summary of the quasi-static flexural response and ductility is provided in Table 5.

Table 5: Summary of flexural response

Flexural response	$R_0C_0F_0$ (Control)	$R_{30}C_0F_0$ (B-2)	$R_{30}C_0F_1$ (B-3)	$R_{30}C_0F_2$ (B-4)	$R_{30}C_5F_1$ (B-5)	$R_{30}C_5F_2$ (B-6)	$R_{30}C_{10}F_1$ (B-7)	$R_{30}C_{10}F_2$ (B-8)
Toughness, T^D_{150} (N-mm)	1827	3477 (90.3%)	5689 (211.3%)	9688 (430%)	6277 (243.5%)	10179 (457%)	5242 (186.9%)	5640 (208.7%)
Ductility	2.30	1.15	1.21	1.29	2.43	2.80	1.27	1.31

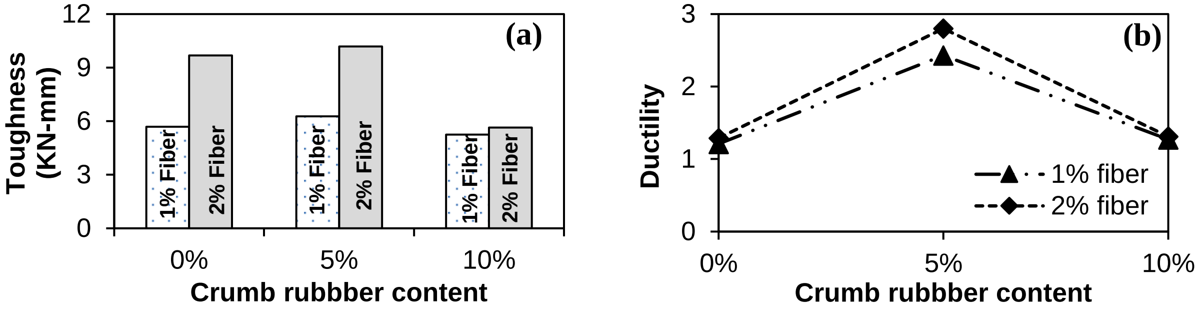


Figure 7: Variation of (a) toughness and (b) ductility of different batches with the replacement level of fiber

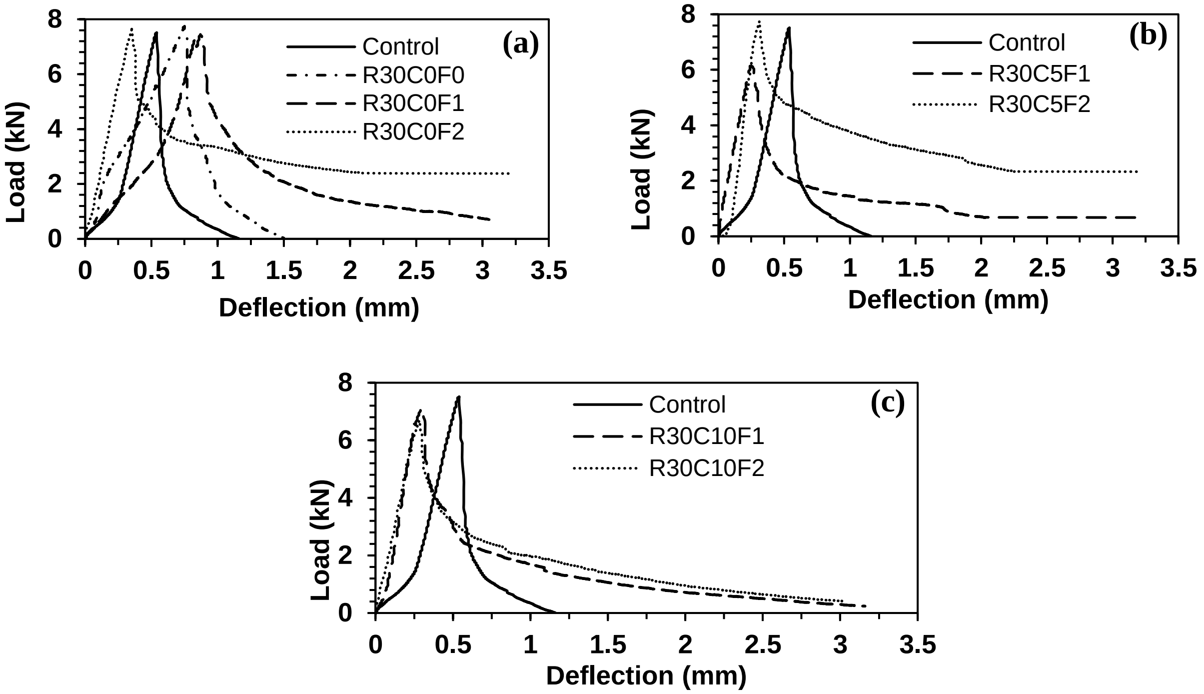
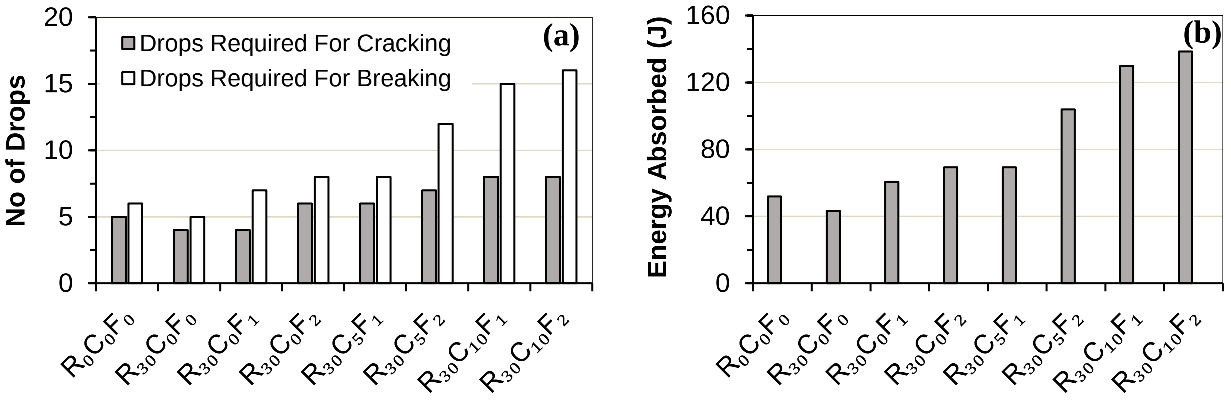


Figure 8: Load vs deflection response of beams under various replacement level of fiber for (a) 0% CR, (b) 5% CR, and (c) 10% CR combinations.

2.3 REPETITIVE DROP-WEIGHT IMPACT TEST

From Figure 9 it is seen that, no of drops required to form crack and break is increased with increasing replacement level of CR and fiber content, thus increases the energy absorption capacity. This occurs because of their lower modulus of elasticity and lower density. At the same time the maximum deflection that occurred before failure is also increased thus improves the deformation capacity. Batch-8 ($R_{30}C_{10}F_2$) shows maximum energy absorption capacity which is 2.5 times more than the control specimens because in this combination the percentage of CR and fiber is more.



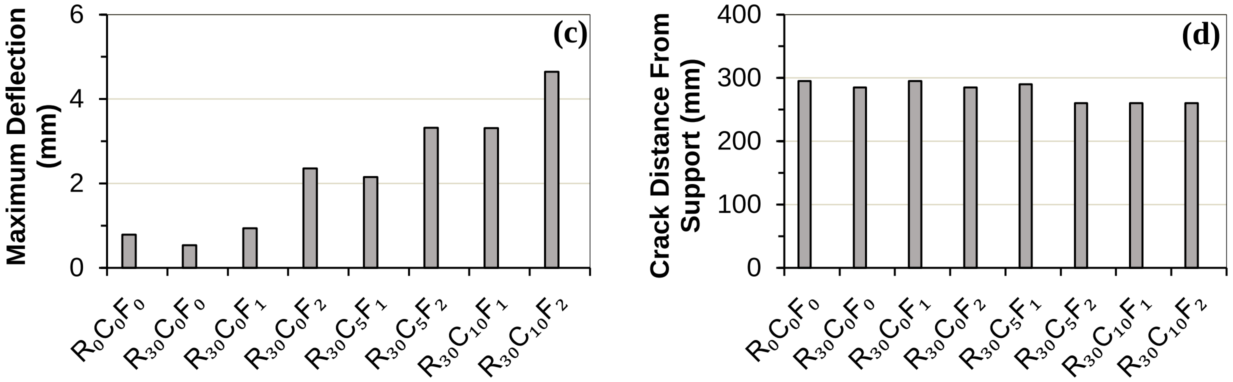


Figure 9: (a) No of drops required for forming first crack and breaking, (b) energy absorption capacity, (c) maximum deflection, and (d) distance of crack formed from support of different concrete beam specimens

3 CONCLUSION

Based on the experimental findings, the following conclusions can be drawn:

- The compressive strength and flexural strength decrease as the CR content increases, but increase with increasing fiber content. However, when the percentage of RCA and CR are higher (30% RCA and 10% CR), the effect of fiber is less pronounced and the compressive strength decreases instead of increasing. $R_{30}C_0F_2$ shows the highest compressive strength and flexural strength which is 26.9% and 8.6% higher than the control, respectively.
- The Poisson’s ratio increases with an increase in the level of CR but decreases with incremental increases in fiber percentage.
- The effect of fiber on toughness and ductility is more pronounced than those of RCA and CR. This study shows that 30% RCA, 5% CR and 2% fiber combination show the best performance with regard to toughness and ductility.
- It is also observed that the energy absorption capacity is increased with increasing amount of rubber and fiber content thus improve beam's deformation capacity.

This study investigates the mechanical properties of recycled aggregate concrete with CR and fiber. Since this is a new concept, further research is required before this product can be established as a safe and viable alternative to natural aggregate-based concrete. Short-and long-time exposure should be considered in order to evaluate its durability performance. Bond strength between concrete and reinforcing bar, earthquake resistance capacity and blast effect should also be investigated.

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