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Flexural behavior of reinforced concrete beams containing hybrid fiber and recycled tire rubber

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ABSTRACT

One of the main goals of sustainable waste management is to maximize recycling and reuse. Environmental sustainability and trash management are aided by the reuse of tire rubber waste, such as crumb rubber (CR), as aggregate in concrete. On the other hand, mechanical characteristics are significantly reduced by integrating (CR). In this study, rubber concrete reinforced with polyvinyl alcohol fiber (PVA), polypropylene fibers (PP), and steel fiber (SF) were used to improve the flexural behavior of concrete beams. The concrete mix contains crumb rubber 10% and 20% (1-2 mm in size) by volume as a substitute for fine aggregate. The bonding efficiency of crumb rubber and concrete was analyzed by testing the compressive strength and studying the flexural behavior of beams with different contents of crumb rubber and other types of fibers added to the mixtures used to enhance the properties of the beams. The ductility index properties of the produced beams have been investigated as well. The experimental results indicated an improvement in the strength of the produced beams after reinforcing them with fibers. The concrete mix with hybrid fibers (0.5% PP + 0.5% SF) and 10% (CR) had higher ultimate strength of 95.43 kN compared to other concrete mixes containing (CR). The concrete mixture with 20% crumb rubber had the highest ductility index measuring 4.75. A successful combination of (CR) and hybrid fibers was achieved when replacing the fine raw materials with (CR).

Keywords: Crumb rubber; Fiber; Polyvinyl alcohol; Polypropylene; Steel fiber; Flexural behavior; Recycled rubber

1. INTRODUCTION

Recycling provides opportunities for long-term diversion of significant volumes of waste from landfills and for developing lower-cost and energy-efficient products. Reusing garbage is significant from several angles. It supports and preserves natural resources. Environmental preservation and effective utilization of resources lead to interest in using recycled materials derived from construction and demolition waste growing worldwide. In recent years, the focus has been turning to natural and industrial waste and byproducts that have previously received little or no attention. In construction projects, industrial solid waste can be utilized in place of some aggregates, saving land and reducing the need to collect natural raw materials.

Rubber waste is readily available in huge quantities, making its application in concrete an intriguing issue. Research on applications of rubber waste in concrete has increased since 2003. Many studies have been carried out to investigate the performance of concrete using different ratios of rubber as a replacement for fine or coarse aggregate; rubber wastes from scrapped have been added as fiber to concrete; and to study the flexural behavior of concrete beams and the mechanical properties of concrete and the workability of concrete mixtures (Al-Azzawi et al., 2018). To guarantee that future generations have enough resources, it is essential to preserve natural aggregates as part of sustainable development (Rakshvir and Barai, 2006).

Concrete is a material that frequently used in buildings. The present construction criteria are recommended to further improve the durability, flexibility, impact resistance, and energy absorption of concrete (Topcu, 1995; Wang et al., 2000). In the meantime, the problem of abandoned garbage has grown to be a major environmental concern globally due to health concerns and difficult disposal. Approximately 1000 million are withdrawn every year. In 2030, the number is expected to reach 1.2 billion, representing nearly 5.0 billion discarded as stockpiling or junk (Pacheco-Torgal et al., 2012). Significant scientific studies address the issue of how to properly dispose of this waste in an environmentally friendly manner.

Like fiber-reinforced concrete, plain concrete (PC) gains hardness and ductility when rubber aggregate from used is added. Nonetheless, the quick development of cracks in the cement mixture is connected to the tension around the rubber aggregate (Carroll and Helminger, 2016). Therefore, utilizing waste in concrete decreases the mechanical properties (density, elastic modulus, and compressive, tensile, and flexural strengths) (Reda-Taha et al., 2008; Ozbay et al., 2011). On the contrary, other mechanical properties of concrete, such as crack resistance, ductility, and energy absorption, increase due to the incorporation of recycled rubber aggregate (Reda-Taha et al., 2008; Al-Tayeb et al., 2012; Atahan and Yücel, 2012).

The recycled rubber mixture is classified into four foremost types: Slit, shredded, crumb rubber (CR), and floor rubber (Siddique and Naik, 2004). Different types of recycled rubber from waste as a replacement for fine aggregate were studied in (Al-Tayeb et al., 2012; Al-Tayeb et al., 2013; Noaman et al., 2015). Adding fibers to concrete can improve the mechanical qualities of rubberized concrete (Xie et al., 2019). Adding fibers of varying lengths and widths is a practical way to prevent concrete fractures that emerge (Yang, 2011; Mobasher and Li, 1996).

According to Bentur and Mindess, (1990), the advantages of hybrid-fiber systems include improving the first crack stress and ultimate strength of the sample, enhancing the toughness and strain capacity of the post-cracking zone, which helps arrest propagating macro cracks and improving the fracture toughness of the composite. The small size of the fiber and its smooth surface help bridge micro-cracks, control growth, and increase the tensile strength of the composite. Due to the limited flexural behavior and increased drying shrinkage, the application of rubberized concrete is still very restricted.

These concerns should be resolved to promote the market of rubberized concrete (Wang et al., 2018). Therefore, this research presents studies on improving the flexural behavior of rubberized concrete beams reinforced with (PVA), (PP), and (SF) fiber. The results verified that (PVA), (PP), and (SF) fiber reinforcement could be considered as a novel method to improve the flexural behavior of rubberized concrete. Additionally, integrating (CR) from used vehicle into concrete is a viable solution to the waste problem, supporting sustainable construction and an environmentally beneficial approach.

2. MATERIALS AND METHOD

Raw materials

The materials used in this study included the sulfate-resisting pozzolanic cement [CEM IV /A (P) (42.5 N- SR)] which complies with the requirements of Egyptian Standard Specifications. Natural siliceous sand was chosen as a fine aggregate with a specific gravity of 2.6, and a fineness modulus of 2.91. Coarse aggregate (C.A) from crushed stone with a specific gravity of 2.6. One type of tire-rubber particle was used as a partial replacement for sand. Tire rubber, which is a fine material with grading close to that of the sand produced by mechanical shredding with an aggraded size of 1–2 mm, and a density of 1.14 g/cm3 as displayed in (Figure 1).

The availability of high range water reducing admixture has facilitated the use of silica -fume, a part of the cementing material in concrete to produce high-strength concrete. The used Silica fume has a specific gravity of 2.2. A high-range water-reducing (HRWR) admixture (Sikament 163 M) produced concrete with high workability. The used Superplasticizer (S.P) has a density of 1.2 kg/lit.

Figure 1 Tire-rubber sample

The hybrid fibers in this study included three types of fibers: (SF) fibers (length = 50 mm and aspect ratio = 50) with a tensile strength of 1000 MPa and (PP) fibers (length = 18 mm) with a tensile strength of 600MPa and (PVA) fibers (length = 8 mm) with a tensile strength of 1620MPa. The appearances of (SF) (PP) and (PVA) fibers are displayed in (Figure 2 and Figure 3). 10 mm and 12 mm diameter steel bars. The stirrups were made of 8mm mild steel bars.

Figure 2 Steel fiber used

Figure 3 Appearances of PP and PVA fibers

Mix Proportioning

One controlled mix (B1) and six concrete mixes were prepared with various fiber combinations, as presented in (Table 1).

Table 1 Fiber percentage in different concrete mixes

Mix	Crumb Rubber (CR)	Percentage of fiber (by volume)			Total volume
		PVA	PP	SF	
B1(Control)	0	0	0	0	0%
B2	0	0.5%	0.5%	0.5%	1.5%
B3	0	0.75%	0	0.75%	1.5%
B4	0	0.5%	0	0.5%	1%
B5	10%	0	0	0	0%
B6	10%	0	0.5%	0.5%	1%
B7	20%	0.5%	0.5%	0.5%	1.5%

The fiber combinations were (PVA - PP - SF) hybrid fiber. The volume fraction of 1.5% and 1% used. The mixes divided into two categories, namely, with or without (CR) at a replacement ratio of 10% and 20% (by volume) by fine aggregate. Each mix used the same water/cement (W/C) ratio of 0.45. The details of the concrete mix proportions are summarized in (Table 2). These mixes were used in casting the reinforced beam.

Table 2 Details of the concrete mix proportions

Mix	Cement (kg/m3)	Silica fume %	S.P %	W/C ratio	C.A/ Sand ratio	Coarse aggregate (kg/m3)	Fine aggregate (kg/m3)		Mix Proportions (unit weight: kg/m3)		
							Sand	CR	PVA	PP	SF
B1 Control	400	10	1.5	0.45	1.5:1	1003.5	669	0	0	0	0
B2	400	10	1.5	0.45	1.5:1	1003.5	669	0	6	4.55	39.25
B3	400	10	1.5	0.45	1.5:1	1003.5	669	0	9	0	58.875
B4	400	10	1.5	0.45	1.5:1	1003.5	669	0	6	0	39.25
B5	400	10	1.5	0.45	1.5:1	909.9	606.6	66.8	0	0	0
B6	400	10	1.5	0.45	1.5:1	909.9	606.6	66.8	0	4.55	39.25
B7	400	10	1.5	0.45	1.5:1	802.8	535.2	133.8	6	4.55	39.25

Specimen Preparation (Mixing, Casting, and Curing Procedure)

Cubes were used to measure compressive strength with 150 mm sides. Seven beams' specimens with dimensions of (120 * 250 * 2000) mm (width * depth * length) were used. The laboratory was the site of the concrete mixture preparation. The rubber was dry mixed in a container with cement, and sand using a mixer (in the case of mortar containing rubber and fiber). After that water was added to the dry mixture mixed. The mortar was placed in molds and compacted. Wood forms were used in casting the beams. The curing phase, which lasted for 28 days, began after the beams and cubes were removed from the formwork.

Figure 4 Compressive test machine

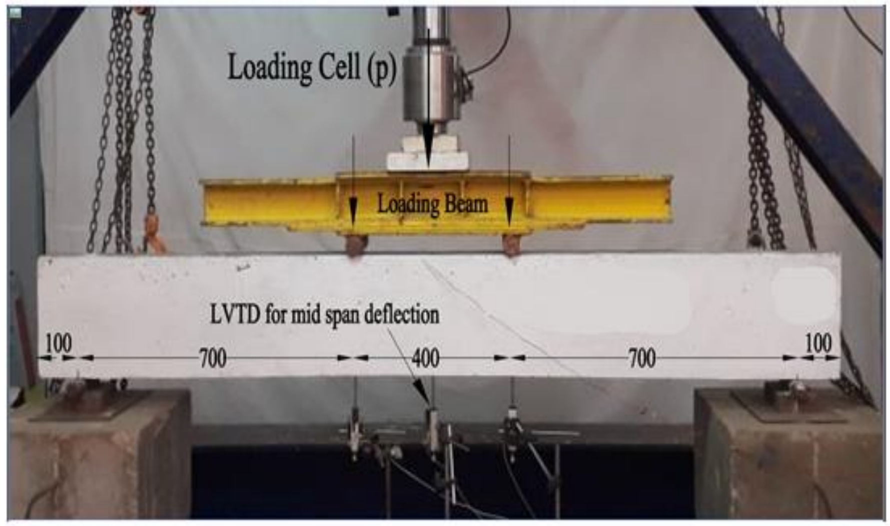

Figure 5 Configurations of test setup

Compressive strength tests were conducted by Testing Concrete, (1986), and cubes with a length of 150 mm were utilized, the test is displayed in (Figure 4). All beams were painted with white plastic paint to help in crack detection during the testing process. The load was applied using the universal testing machine of capacity 200 kN in uniform ramping increments failure. Specimens were loaded in flexure under a two-point loading system with a simple supporting condition. Figure 5 displays the test's setup. The steps involved in getting a specimen ready are displayed in (Figure 6).

Figure 6 Procedures for preparing a specimen.

3. RESULTS AND DISCUSSION

Compressive Strength

Properties preliminary Concrete Mixtures such as compressive strength. The compressive strength values for each combination at 28 days are displayed in (Figure 7). The experimental compressive strength values for various combinations are displayed and compiled in (Table 3).

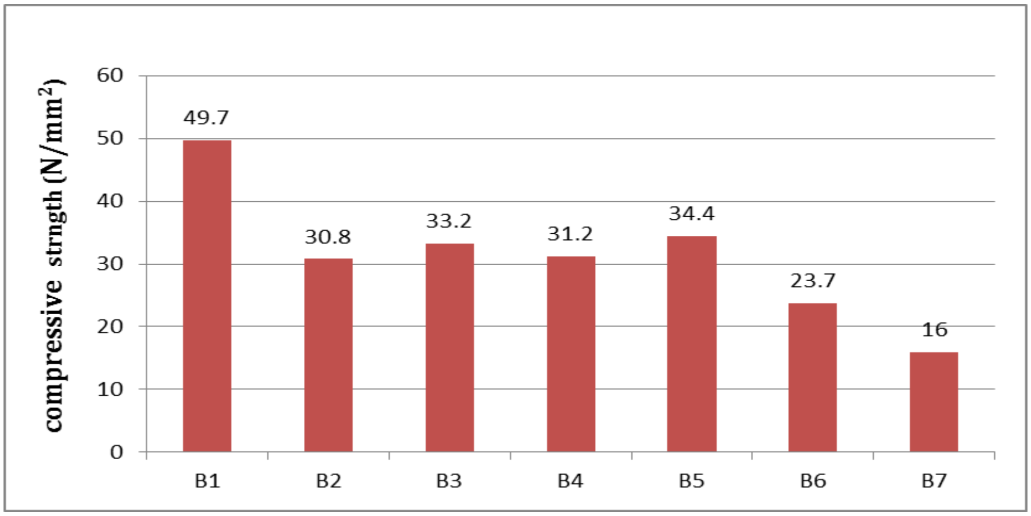

Figure 7 Compressive strength of all mixes

Table 3 Experimental results

Mix	Compressive Strength (N/mm2)	First Crack Load Pcr (KN)	Ultimate Load Pu (KN)	Ductility Index (Δu/Δy)
B1 Control	49.7	20	94.52	1.54
B2	30.8	17	99.14	2.10
B3	33.2	30	102.78	1.81
B4	31.2	20	97.14	1.87
B5	34.4	18	89.84	1.66
B6	23.7	27	95.43	1.41
B7	16	17	90.34	4.75

The compressive strength decreased when (SF + PVA + PP) fibers without (CR) were used. The compressive strength of the control mix (B1) was 49.7 MPa. The reason is that the decrease in compressive strength is due to the increase in (SF) fiber content, which increases air content in the mix, which in turn reduces the density of concrete specimens (Alwesabi et al., 2020; Iqbal et al., 2015). The compressive strength decreased when rubber fibers were used.

The severe decline in compressive strength and strain capacity is mostly attributable to the large deformability of Waste tire rubber particles caused by their high Poisson's ratio (around 0.5 for Waste tire rubber compared to 0.2 for the replaced conventional aggregates). The large deformability of Waste tire rubber particles under compressive loading causes stress concentrations and premature micro-cracks in the geopolymer concrete binder, thus facilitating the creation and propagation of cracks and eventual failure at a considerably lower load than the control mix (Alsaif and Albidah, 2022).

Analysis of Beams Subjected to Flexural Loading

First Crack Loads and Ultimate Loads

The experimental results for the first cracking load and ultimate load are displayed in (Table 3). Load values were recorded for all beam specimens. Figure 8 represents the first cracking load and ultimate load values for all the tested beams. It is clear from Figure 8 that, as expected, the ultimate load capacity of the beam (B5) decreased with waste rubber percentage; it decreased by 5% with a replacement percentage of 10%. The beam (B3) recorded a maximum ultimate load of 102.78 kN because it does not contain (CR) and has a high percentage of fibers that enhance its strength, while (B5) recorded the lowest ultimate load of 89.84 kN.

Adding (CR) to concrete mixes decreases the strength due to the poor bonding between (CR) and cement mortar. The beam (B6) recorded a maximum ultimate load of 95.43 kN with 10% (CR) and (0.5% PP + 0.5% SF) fiber, while (B7) recorded an ultimate load of 90.34 kN with 20% (CR) and (0.5% PVA + 0.5% PP + 0.5% SF) fiber. Beam (B6) recorded a maximum first cracking load of 27 kN, while beams (B2) and (B7) recorded a minimum first cracking load of 17 kN. The beam (B6) best recorded an ultimate load of 95.43 kN with a replacement percentage of 10% of (CR) compared to other concrete mixes containing (CR).

This may be related to the low ratio of crumb rubber and the addition of (SF) fibers, which have a high elastic modulus and tensile strength. Plus (PP) fibers can bridge microcracks. Overall, the effects of combining (PVA), (PP), and (SF) in rubberized concrete mixes result in materials with superior mechanical properties. These enhanced properties include increased flexural properties of rubberized concrete. Such improvements are crucial for developing durable and resilient concrete structures capable of withstanding the challenges of modern construction environments.

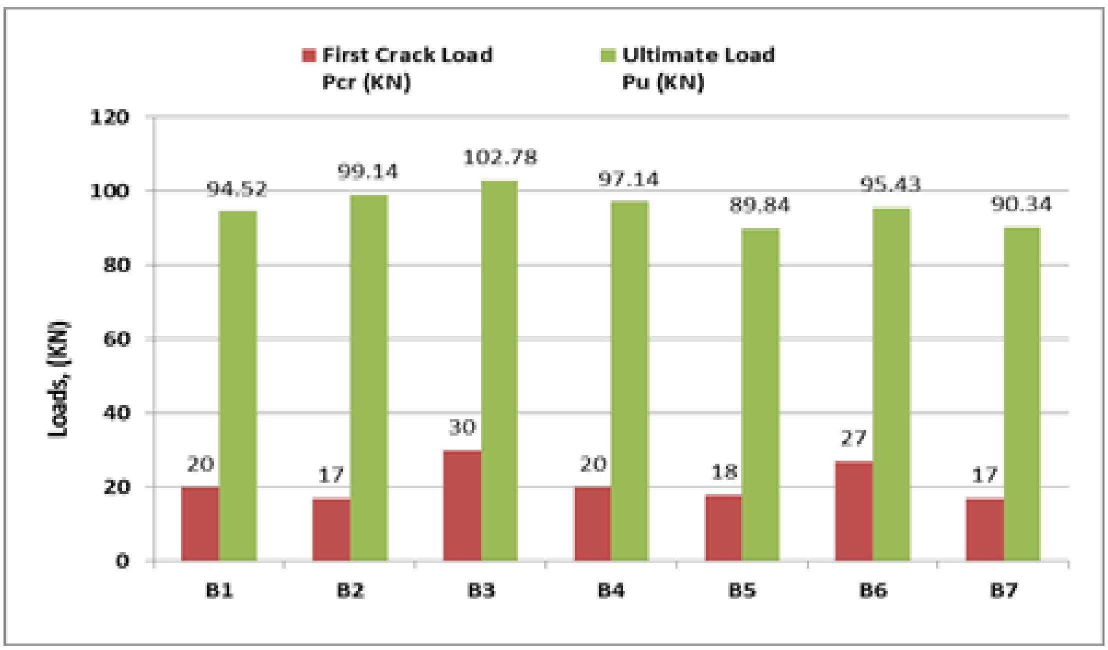

Figure 8 First cracking loads and ultimate loads values of all tested beams

Load Versus Deflection Relationship

It was observed that there is no noticeable difference in cracking pattern depending on the usage of rubber aggregates or hybrid fiber (PVA), (PP), and (SF). The failure of the seven beams is a classical flexural failure. The cracks started at the bottom fibers of all beams. When the weight improved, cracks at mid-span improved in number, widened, and prolonged toward the compression sector till failure. Figure 9 shows the relationship between the applied load and deflection at mid-span for all beams.

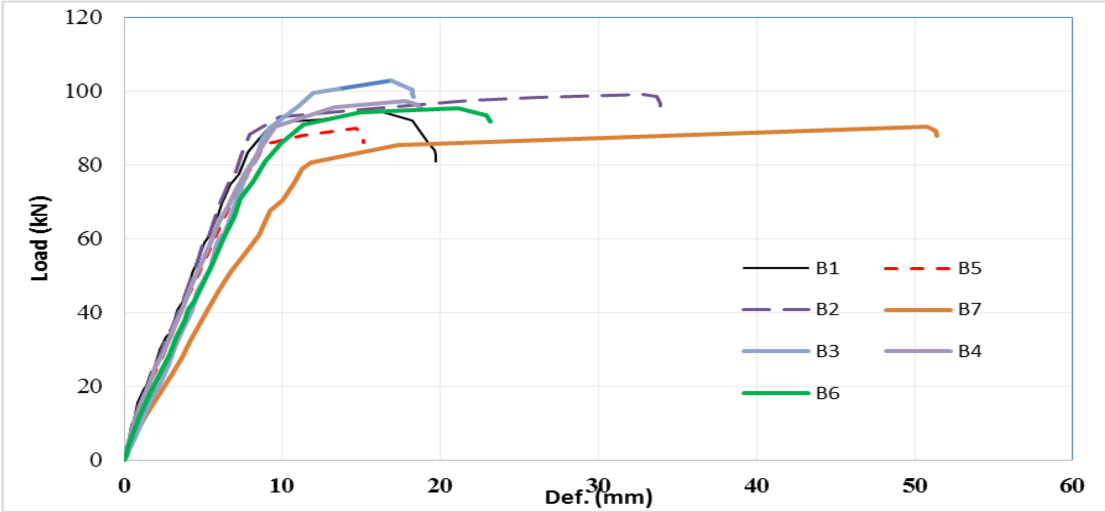

Figure 9 Load-deflection relationship of all beams.

Cracks Patterns

Figures 10 display the cracking patterns for each beam specimen. According to Table 3, the first crack load varied depending on the type of material used. The type of material impacted the number of cracks that occurred. Generally, bending failure was the domina.

Ductility Index

A ductility index analysis was conducted to quantify the ductility of each specimen. The ductility index is calculated as the ratio of the mid-span deflection at the ultimate load to that at the yielding load ($\Delta u/\Delta y$) (Shaheen et al., 2012). Specimens with larger ductility index values are more ductile. Table 3 lists the ductility index values for all tested beams and represented in (Figure 11). According to Figure 11, beam (B7) recorded the maximum ductility index among all the tested beams with 3 times better ductility than the (B1) control beam.

This may be related to the higher maximum deflection than the maximum deflection of the other beam specimens. Also, the deflection at yield loads was close to the deflection at yield loads of the other beams. For beam (B7) with a rubber aggregate percentage of 20% of fine aggregates and (0.5 PP + 0.5 PVA + 0.5 SF) reinforcement, it showed a significant improvement in the value of the ductility index.

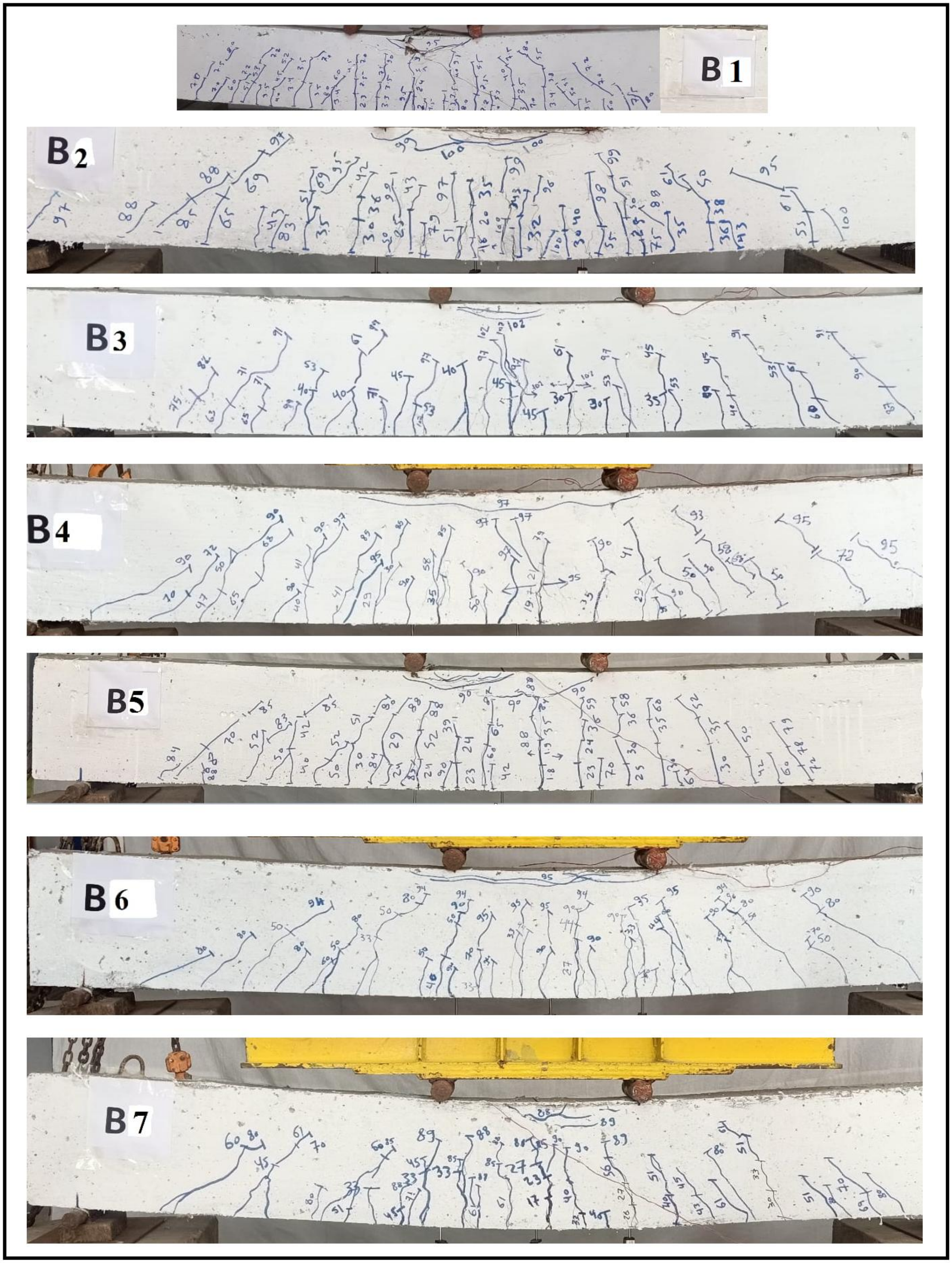

Figure 10 Cracks patterns of B1 to B7 specimen.

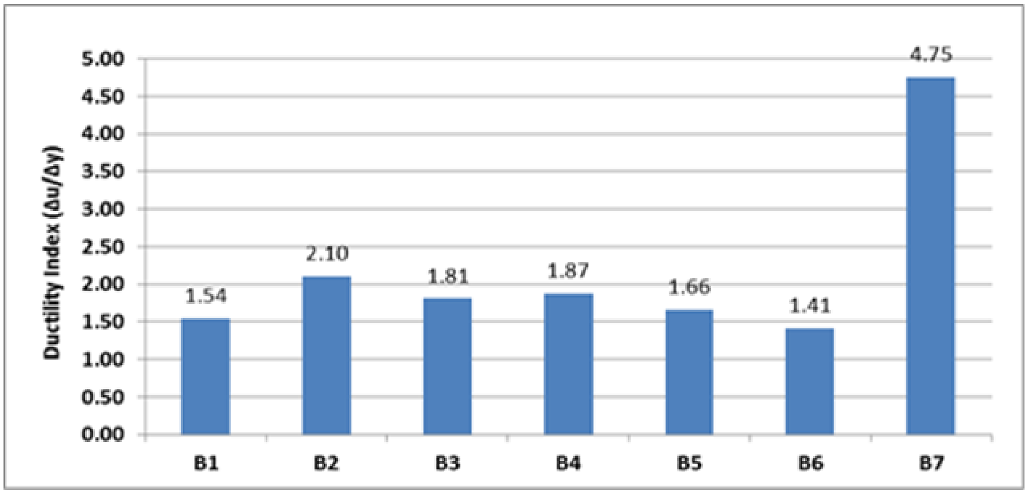

Figure 11 Ductility Index of all beams.

4. CONCLUSION

The flexural behavior of reinforced concrete beams was examined experimentally to get essential knowledge about improving the mechanical characteristics and performance of fiber-reinforced concrete, with or without (CR). From the results, the compressive strength is reduced when fine aggregates are substituted with 10% and 20% (CR). Also, A 10% (CR) replacement value results in a drop in ultimate strength. However, when fractures are formed, including (SF+PP) fiber and then hybrid fiber can increase the final strength. Furthermore, the ultimate strength and the ductility index value are significantly increased by adding (0.5% PVA, 0.5% PP) and (0.5% SF) fibers to the (B7) mix. Compressive strength is adversely affected when (CR) is used instead of fine aggregates in all combinations.

Post-cracking behavior can be improved by (PVA), (PP), and (SF) fiber reinforcement. The research conducted that using polyvinyl alcohol (PVA), polypropylene (PP) fibers and steel fibers (SF) offer notable improvements in crack resistance when added to rubberized concrete mixes. Their compatibility with cementitious matrices contributes to the formation of a robust network of reinforcement within the concrete matrix. This network of reinforcement efficiently fills up microcracks, improving the beams' flexural performance. Making improvements is essential to creating robust and long-lasting concrete buildings that can endure the difficulties of contemporary construction sites. Rubberized concrete is therefore important economically and offers enough environmental advantages.

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Author Contributions

Conceptualization, Mohamed Said: Investigation; Ayman Khalil and Mohamed Said: Methodology; Noha Zaki, Mohamed Makhlouf and Mohamed Said: Software; Noha Zaki: Supervision; Ayman Khalil: Validation; Mohamed Said, Noha Zaki, and Mohamed Makhlouf: Visualization; Mohamed Makhlouf, and Mohamed Said: Writing—original draft; Mohamed Makhlouf: Writing—review & editing, Noha Zaki, Ayman Khalil, and Mohamed Makhlouf. All authors have read and agreed to the published version of the manuscript.

Informed consent

Not applicable.

Ethical approval

Not applicable.

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Conflict of Interest

The author declares that there are no conflicts of interests.

Data and materials availability

All data associated with this study are present in the paper.

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