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ORIGINAL CONTRIBUTION

Mechanical and Post-Cracking Performance of Recycled High Density Polyethylene Fiber Reinforced Concrete

Maheswara Marabathina Rao[1,2] · Sanjaya K. Patro[1] · Sunil S. Basarkar[3]

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Abstract UItilization of various plastic fibers to reinforce concrete panels and pathways provides major financial and ecological advantages over historically used steel fiber. However, introduction of plastic filaments by construction sectors has not been observed due to the lack of pertinent data on durability, mechanical characteristics, and their effects on concrete performance. An experimental program is initiated to study the impact on the recycled high-density polyethylene fiber reinforced concrete (rHDPE-FC) with the addition of rHDPE fiber at five mix variations from 0.3, 0.4, 0.5, 0.6, and 0.7% in concrete and relating the performance with control concrete after the 28, 90 days of curing. The experimental study is performed in the laboratory on the various mechanical attributes, Round Determinate Slab Test (RDST), and Crack Mouth Opening Displacement (CMOD) in the rHDPE-FC. With rHDPE fiber in concrete, splitting tensile and flexural strength performance is observed to increase while compression strength results are seen to vary marginally. The rHDPE fibers show outstanding performance in post-cracking, and significant improvement of ductility performance. Post-cracking performance is evaluated using the CMOD and RDST. It is concluded that the addition of 0.4 and 0.6% rHDPE fiber in concrete is considered optimum for splitting tensile and flexural strength, respectively. Usage of recycled plastic waste in new concrete manufacture is very tempting due to the small price of the raw resources, space-saving, environment protection, and concrete properties.

Keywords Fiber reinforced concrete · rHDPE fiber · CMOD · RDST · Energy absorption · Fracture energy

✉ Sanjaya K. Patro
litusanjay@yahoo.com

1 Department of Civil Engineering, Veer Surendra Sai University of Technology, Burla, Odisha 768018, India

2 Department of Civil Engineering, Aditya College of Engineering and Technology, Surampalem, Andhra Pradesh 533437, India

3 Afcons Infrastructure Limited, Mumbai, India

Introduction

Worldwide, waste plastics are unanimously considered a hazardous material, and the environment is disrupted due to the uncontrolled disposal of waste plastic. As the massive variety of modern-day activities like shopping, garbage bags, toys, clothing, housing, industries, packaging, cables, floor coverings, wrapping, containers, sheets, and pipes are increasingly produced, waste generation is unsurmountable [1]. Utilization of steel fiber reinforcement consumes substantial time and labor for placing and cut-off before pouring concrete. Furthermore, steel metal is susceptible to deterioration, and therefore, the performance of concrete structures can worsen due to steel corrosion when executed with the flaw. The manufacture of fiber from steel also generates substantial carbon traces. Plastic fibers, namely polypropylene (PP), HDPE, and polyethylene terephthalate (PET) fibers, thus, have progressively become a ravishing substitute to steel metal fiber. HDPE is a nonpolar, saturated, high molecular weight hydrocarbon. It has excellent resistance to chemicals, mild oxidants, and reducing agents. It hardly absorbs water. The main reason for selecting the rHDPE plastic fiber is its rampant use, disposal nuisance, and hence, a need to protect or safeguard the environment through their alternative use and prevent uncontrolled disposal. Utilization of plastic fibers in cement concrete has numerous benefits, like the comfort of construction, lower workforce time, and favorable cost economy. Fibers can efficiently enhance post-cracking performance and curb the contraction of cement concrete [2]. Fibers have an average tensile capacity of 450 MPa and a Modulus of elasticity in a range of 4–10 GPa [3]. Concrete reinforced commercially available steel or PP fibers have been a more resilient building material than bare concrete [4, 5]. Kim et al. [6] added 0.5% PP fiber and 1% steel fibers to examine fiber-reinforced concrete's durability achievement. Further, Ananthi and Karthikeyan [7] added PP fibers at 0, 0.1, 0.3, and 0.6% by the weight of the cement in M70 grade high-performance concrete. They reported optimum strength upon replacement of sand with 10% weld slag with further addition of 0.3% PP fiber to concrete. Raj et al. [8] report maximum energy absorption/cost ratio by adding 0.2% PP fiber, 0.75% steel fiber, and replacing 15% fine aggregate with crumb rubber. Marthong [9] studied different geometry PET fibers to enhance the bonding with the concrete. Furthermore, Alani et al. [4] investigated PET with silica fume and palm oil ash. Nibudey et al. [10] added 2 mm $\times$ 25 mm PET fiber in M30 concrete at 0.0 to 3.0% by weight of cement and noted 52.3 and 8% reduction in workability and density, respectively at 3% PET fiber in comparison to regular concrete. Kim and Lee [5] reported that the fibers have a mild effect on compression and splitting tensile strength but a considerable effect on the post-cracking aspect. Lin et al. [11] utilized hybrid fiber (polyethylene, polyvinyl alcohol, and steel fibers) on a masonry wall and observed significant improvement in the wall performance. Mohamadi [12] interestingly reports the effect of 1% polypropylene fibers to increase resistance to crack development significantly. Yoo et al. [13] reported that shrinkage and strains are considerably reduced in FRC with admixtures' addition. Babaie et al. [14] report that with the addition of plastics in concrete, tensile and flexural strength are improved, albeit accompanied by reduction of modulus, compressive and bond strengths. Plastics are given various shapes, treated with various chemicals to achieve desired results and engineering characteristics [15] and [16]. Naik et al.[16] added 0.5, 1.5, and 2% HDPE fiber in the concrete and indicated 2.5% increase and 86% decrease in compressive strength at 0.5 and 2% fiber contents, respectively. Pesic et al. [17] report that the addition of 0.40, 0.75, and 1.25% HDPE fiber in concrete increased the compressive strength by 3.3% at the aspect ratio of 92; whereas it is decreased by 7% with an aspect ratio of 75. However, an increase in flexural strength is observed at an aspect ratio of 75. In fact, available literatures reveal extensive investigation being done using PP plastic but not on HDPE plastic as fiber. Hence, it is strongly felt that plastic use should be encouraged as an alternate additive in concrete production and offer viable alternatives to their disposal problems. Jassiam [18] produced plastic cement with HDPE waste by utilizing 60% cement and 40% HDPE waste and achieved better ductility property of concrete. Plastic is not only used as fiber in concrete or mortar but also as a partial replacement of fine aggregate [19, 20], coarse aggregate [21, 22] in addition to their use in shotcrete [23]. Recycled plastic fibers have also been very useful in reinforcing concrete footpaths and precast panels [24]. Limited literatures are evident that lack of report on utilization of HDPE plastic as fiber in cement concrete.

Although some investigations are reported on the features and usage of plastic in concrete, the very few addressed on mechanical and longevity characteristics of concrete with rHDPE plastic fiber. As there is little literature on rHDPE-FC, a study is therefore proposed using rHDPE fiber as an additive in concrete to achieve low-cost, green, and ductile concrete.

Laboratory Program

Materials

Cement

The binder utilized in this study is 53 Grade cement (OPC) conforming to BIS specification IS-12269:2013 [19]. Physical, mechanical characteristics, and chemical composition are displayed in Tables 1 and 2.

Aggregates

Fine aggregate (Zone-II) derived from the local river Godavari bed in Rajahmundry, India, conforming to IS 383-1970 (reaffirmed in 1997) [25], and 12 mm size granitic stone aggregates from local quarry conforming to IS 383-1970 (reaffirmed in 1997) [25] are used. Sieve analysis of fine and coarse aggregates is carried out according to IS 2386-1963 (part 1) (reaffirmed in 2002) [26]. The outcome of physical and mechanical characteristics of aggregates are reported in Table 3, with particle distribution of aggregates indicated in Fig. 1.

Recycled HDPE Plastic Fibers

The recycled HDPE plastic (rHDPE) is available as 10 mm diameter commercial ropes in the market at an Indian rupees 20 per linear meter. This commercial rHDPE rope was bought and cut into 30 mm long fibers, with an aspect ratio of 75. The characteristics of rHDPE fiber are summarized in Table 4. Assistive photographs of rHDPE fiber before and after cutting are shown in Fig. 2.

Table 1 Physical and mechanical characteristics of OPC

Property	OPC	Test method
Specific gravity	3.12	[20]
Fineness (cm^2/g)	3190	[21]
Consistency (%)	31	[22]
Setting times		[23]
IST (min)	139	
FST (min)	300	
Compressive strength (MPa)	55.93	[19, 44]

IST initial setting time, *FST* final setting time

Table 2 Chemical characteristics of OPC

Contents (%)	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Loss of ignition (%)
OPC	19.10	8.59	1.78	64.41	1.61	2.11	1.6

Table 3 Characteristics of aggregate

Property	*CA	**FA	Test Standards	IS-383 limits [25]
Specific gravity	2.67	2.41	IS-2386 (part-3) [45]	–
Water absorption (%)	1.21		IS-2386 (part-3) [45, 46]	–
Impact value (%)	22.7	–	IS-2386 (part-4) [47]	45
Crushing value (%)	19.52	–	IS-2386 (part-4) [47]	45

*CA = Coarse aggregate

**FA = Fine aggregate

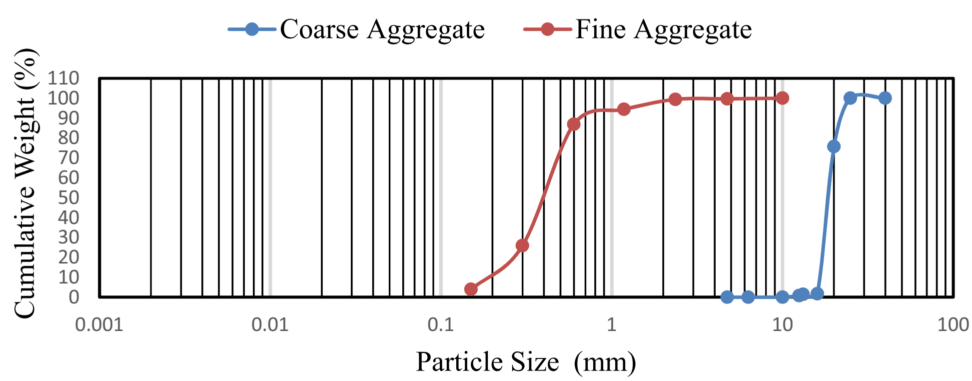


Fig. 1 Sieve analysis of aggregates

Literature review reveals that past researchers had adopted a range from 0.1 to 2% fiber and observed the optimum value at 0.4 to 0.5% by considering the medium range of aspect ratio. Fiber contents have been increased in smaller intervals in a range of 0.3 to 0.7% at a similar range of aspect ratio to fine-tune the investigations on variations near the optimum and thus to confirm the outcome reported in past studies.

Water

Potable water conforming to IS-10500:2012 [27] was used throughout the study while casting and curing the concrete specimen confirmed to IS 456-2000 (reaffirmed in 2005) [28].

Mix Proportions

M40 grade concrete mix design is prepared based on IS-10262:2009 [29] with cement quantity of 411.11 kg-m^{-3} with mix proportion of 1.41 parts fine aggregate and 2.05

parts coarse aggregate at 0.45 water-cement ratio. Study was undertaken with addition of rHDPE fiber by volume of concrete at six trials from 0% (MH-0), 0.3% (MH-3), 0.4% (MH-4), 0.5% (MH-5), 0.6% (MH-6) and 0.7% (MH-7). Mixing of rHDPE-FC resulted in ball formation at 0.7% and became stiffer for a given water-cement ratio, and hence further increase was discarded.

Test Specimens and Procedure

Detail of different types and their relevant standard codes of test specimens for each percentage of fiber reinforced concrete mix are summarized in Table 5.

Post cracking behaviour of fiber-reinforced concrete can be assessed effectively by conducting crack mouth opening displacement (CMOD) and round determinate slab test (RDST) [24]. The CMOD test assists in understanding the utility of fiber in bridging the cracks and arrest a sudden failure by associating a residual flexural strength. Further, RDST is necessary, since slab panels are subjected to combinations of stress behaviour that can reflect the in-situ behaviour of rHDPE-FC compared to other laboratory-based test specimens. The RDST specimen is chosen as it resembles the actual behaviour of structure with the addition of fibers. Among available proposals of slab testing specimen shapes, the RDST test appears to be a convenient and dependable procedure for the round determinate slab test (ASTM C1550-20). RDST also has added advantage of lower variability in the results compared to other tests [30]. The round determinate slab is a statically determinate test with three supports at a 120-degree interval that effectively determines crack pattern, toughness, and post-cracking behavior.

CMOD tests were conducted according to EN 14651–2005 (reaffirmed in 2007) [31] on concrete prisms with a notch cut to size 2 mm wide and 25 mm deep at the mid-length, as shown in Fig. 3. The CMOD test is done in the universal testing machine. The three-point bending test was used to determine the anticipated failure pattern of the notched prism. This test was extensively adopted to determine flexural characteristics of regular prism specimens.

Table 4 Physical attributes of rHDPE fiber

Attributes	rHDPE fiber
Specific gravity	0.97
Melting point (LC)	135
Young modulus (GPa)	0.8
Tensile strength (MPa)	45
Ignition point (LC)	490
Elongation at break (%)	104
Temperature at vaporization (^{o}C)	455
Water absoroption (%)	0.01

CMOD tests are executed on 0, 0.3, 0.4, 0.5, 0.6 and 0.7% rHDPE-FC admixed prisms to investigate the post-cracking efficiency conforming to EN 14651-2005 (reaffirmed in 2007) [31]. EN 14651-2005 (reaffirmed in 2007) [31] allows estimation of CMOD from the prism's central deflection (δ) using the following equation $\delta = 0.85\text{CMOD} + 0.04$, where δ = vertical deflection in mm, CMOD = horizontal deflection between the notch edges in mm. The outcome of results on load versus crack mouth opening displacement (CMOD) is discussed in detail in this work.

The RDST specimen of 0.7% rHDPE-FC admixed slabs were tested based on the ASTM C1550-20 [32]. The round determinate slab of thickness 75 mm and diameters of 800 mm, 600 mm, and 400 mm were cast with notches of 25 mm deep as per Ciancio [33] at 120° at the bottom of the round slab, as shown in Fig. 4a. These specimens were supported vertically at three equal distances along the perimeter, as shown in Fig. 4b. The testing load was applied at the center point of the slab. This load was applied using a 250 kN capacity hydraulic loading frame. Three pivoted support systems assured that load circulation was always determinate.

Results and Analysis

Compression Test Results

It is noted that some uncertainty is observed in compressive strength, which might be due to the orientation of fiber since fibers perpendicular to load result in low compressive strength, whereas fibers parallel to load gives higher compressive strength. Hence, an average of four specimens is taken for the analysis of the results. Also, worse workability and compaction cause heterogeneities in the concrete and thus, reducing its compressive strength [34]. Results of compression test of concrete mix—consisting of diverse proportions of rHDPE fiber at 28 days are furnished in Fig. 5. The compression test values of rHDPE-FC are marginally reduced compared to controlled concrete and decreased with increased concrete fiber content up to 0.4%. After that, it is found to increase with the highest strength achieved at 0.7% fiber. The compression test result of concrete containing 0.3% fiber is 52.71 MPa, which is, reduced by 3.40%. Thus, rHDPE fiber in concrete conclusively indicates a marginal reduction in compressive strength at the stated range of fiber, as Fig. 5 conveys. The compressive strength of rHDPE-FC relies on several factors like physical and mechanical characteristics, percentage of rHDPE fiber, and the water-cement proportion

[4, 9]. This reduction in compressive strength is probably because of the low modulus of plastic material. The influence of plastic fiber on the compressive strength of concrete had been a topic of intensive research in the past [21, 22]. The current tendency of fall in compression test values of concrete is consistent with the reported findings of the literature. However, the increase in compressive strength is 13% with plastic bag waste fiber as per Ghernouti et al. [35]. Naik et al. [16] have shown a drop in compression test values even after using treated and untreated fiber, a pattern which is also indicated in the current studies. This performance in compressive strength depends mainly on plastic content, aspect ratio, fiber length, orientation, and water-cement ratio, as previously described. There might be a reduction in compressive strength due to any of these parameters under a constant plastic content. rHDPE fiber performance is superior since PET and PP plastic have a low modulus of elasticity than HDPE plastic [17]. The 90-day compressive strength also follows the same pattern of 28 days.

Splitting Tensile Strength

The splitting tensile strength outcome of rHDPE-FC mixes with various percentages of rHDPE fiber at 28 days and 90 days of age are presented in Fig. 6. The splitting tensile strength of concrete mixes with rHDPE fiber primarily depends on the surface characteristics and mechanical strength of rHDPE fiber, fiber diameter [36], and filament type [38], as observed earlier. Pesic et al. [17] added 0, 0.4, 0.75, and 1.25% Vf of HDPE fiber in M30 grade concrete. They observed an increase by 10% in comparison to control concrete at optimum addition of 0.4% fiber. Figure 6 indicates that splitting tensile strength of the mix with supplement of various blending of rHDPE fiber increase from those of the control mix. The strength is increased by nearly 3, 36, 38, 39, and 38% in comparison to control concrete with addition of 0.3, 0.4, 0.5, 0.6 and 0.7% of fiber, respectively at 28 days. Moreover, similar trend is also observed at 90 days of curing. The gain in splitting tension test value was evident at 0.4 to 0.7% fiber addition compared to normal concrete. Song et al. [37] added Nylon fiber in concrete and reported an increase in splitting tensile strength by 17% in relation to control concrete at 0.06% addition. Yap et al. [38] used 0.25, 0.5, and 0.75% admixed Nylon fiber in M50 grade concrete, and reported increase in strength from 2.23 to 3.49 MPa at 0.75% addition with reference to control concrete.

With this background, it is worth mentioning that the current investigation using rHDPE fiber indicates better performance of modified concrete. The outcomes of concrete splitting tensile strength are compared well with previous studies, and a similar trend is displayed [17].

Fig. 2 Photographs of rHDPE: **a** rope before cutting, **b** after cutting as the fiber

Table 5 Test specimens

Specimen	Size	Relevant standard code	Name of test conducted
Cubes	150 × 150 × 150 mm^3	IS:516 [48]	Compression
Cylinders	150 mm diameter × 300 mm long	IS:5816 [46]	Splitting tension
Prisms	100 × 100 × 500 mm^3 with a 25 mm deep and 2 mm breadth cut	EN 14651 [31]	CMOD
Round slab	75 mm thick and diameters of 800 mm, 600 mm and 400 mm	ASTM C1550 [32]	RDST

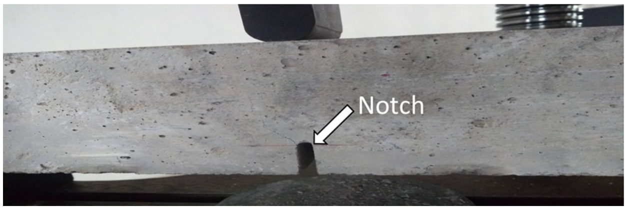


Fig. 3 Prism with Notch for CMOD test

Flexural Strength

Bending test of concrete results for different proportions of rHDPE fiber after curing of 28 days and 90 days are indicated in Fig. 7. Interestingly, Fig. 7 conveys that the bending test results pattern is the same as those of splitting tension tests. The bending test values of cement concrete mixes incorporating 0.3, 0.4, 0.5, 0.6 and 0.7% of rHDPE fiber increases by 28.12% (4 MPa), 36.22% (4.25 MPa), 34.6% (4.2 MPa), 29.0% (4.02 MPa) and 27.3% (3.97 MPa) respectively in sharp comparison with flexural strength of normal concrete (3.12 MPa). A similar trend of increase is observed at 90 days curing period, the flexural strength is observed to increase by 28.01, 35.05.16, 34.48, 28.9, and 27.19% in concrete mix MH-3, MH-4, MH-5, MH-6, and MH-7, respectively. At MH-4, rHDPE-FC has shown optimum flexural strength. This increased flexural strength of rHDPE-FC is attributed to the strong bonding between rHDPE fiber and concrete. There is slight reduction in flexural strength from 0.4 to 0.7% for rHDPE -FC.

A similar increase in flexural strength is reported using PET fiber [39] and PP fiber [40]. Borg et al. 2016 [39] used 30 mm and 50 mm length PET fiber at 0.5, 1, and 1.5% in concrete and conducted a three-point bending test on the notched rectangular prism of size 150 × 150 × 550 mm as per EN 14651-2005 (reaffirmed in 2007). They reported the highest flexural strength at 1% fiber fraction, with deformed fiber indicating higher strength than straight fiber; and better performance of long fiber (50 mm) than short fiber (30 mm). Alhozaimy et al. [40] reported a significant improvement in bending strength of 44, 271, and 386% at 0.1, 0.2, and 0.3% volume fraction of PP fibers in concrete, respectively. Pesic et al. [17] added 0.40, 0.75, and 1.25% HDPE fiber with an aspect ratio of 75 in unnotched concrete prism and reported an increase in flexural strength of 4.4% and 5.5% at 0.4% and 0.75%, respectively, in a similar trend as in the current study. A correlation is developed to examine the relation between compression test and flexure test results of the rHDPE-FC blends, as shown in Fig. 8. Compared to fiber-free concrete, the flexural strength increases at 0.3 to 0.7% of fiber

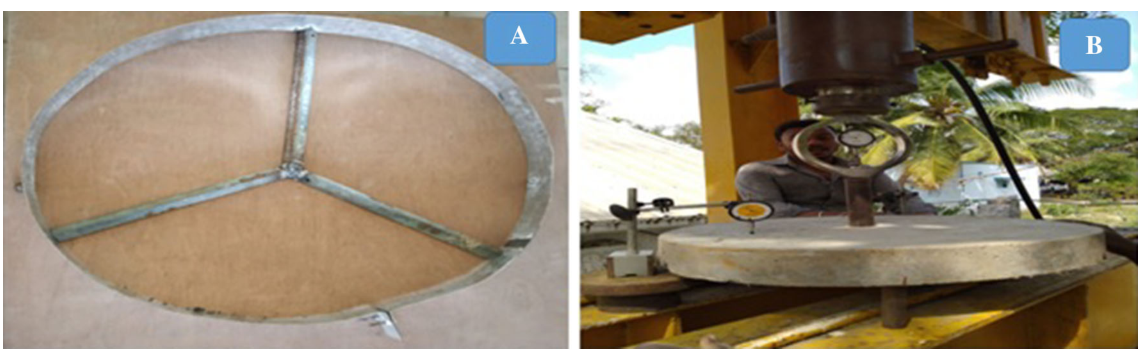
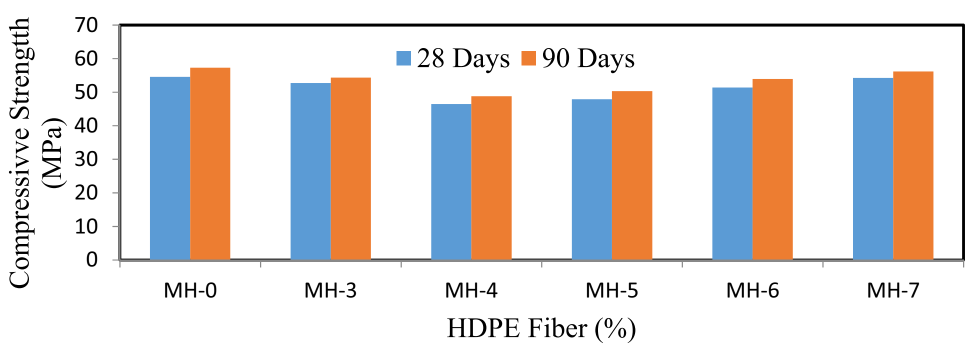


Fig. 4 Round determinate slab test: **a** Mould for round slab with notch; **b** Test setup

Fig. 5 Compressive strength of concrete mixes



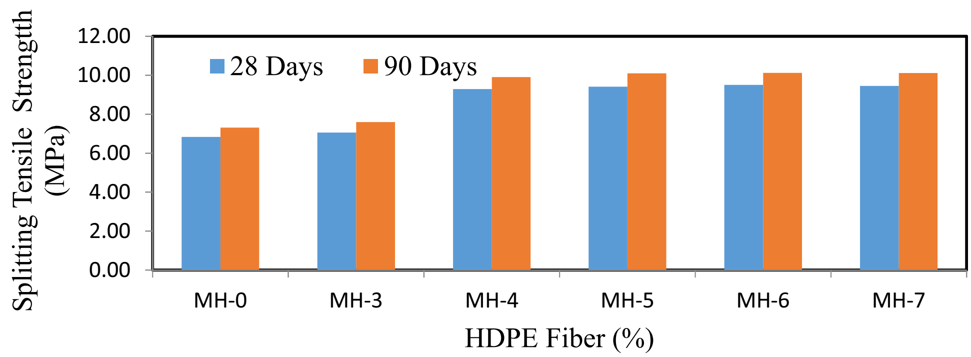


Fig. 6 Splitting tensile strength of concrete mixes

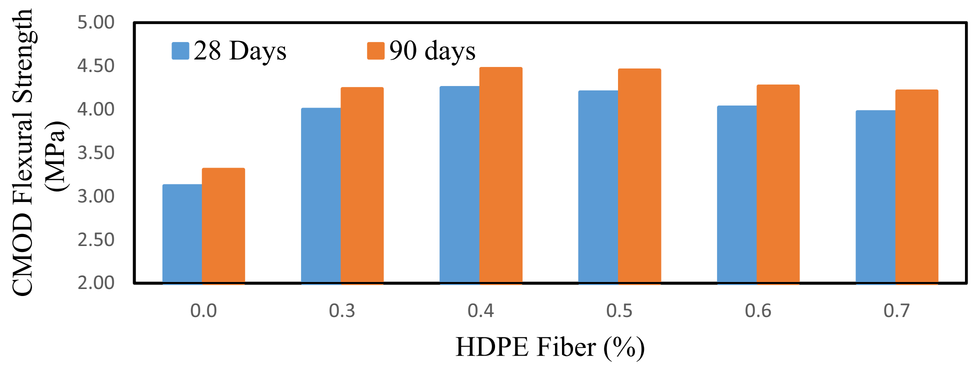


Fig. 7 Flexure strength of concrete mixes

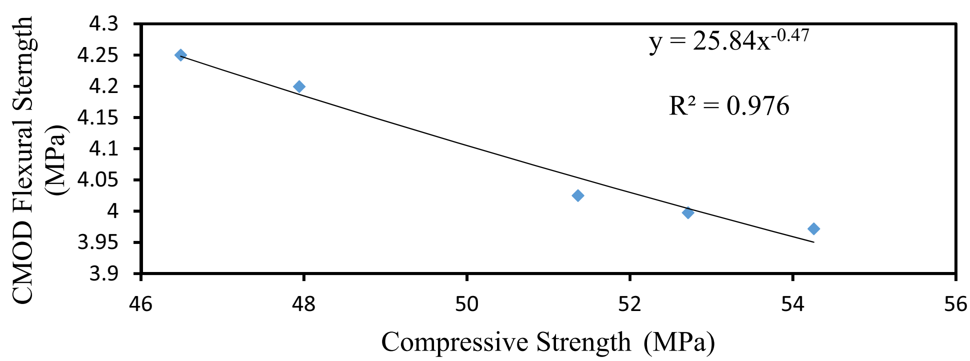


Fig. 8 Correlation between CMOD flexure and compression strength of concrete mixes

addition, as per Fig. 7. However, there is a marginal decrease in compressive strength compared with fiber-free concrete, as apparent in Fig. 5. So the trend line of correlation is observed downward, shown in Fig. 8. Thus, it is noticed from Fig. 8 that compressive strength is inversely proportional to the flexural strength. Regression analyses performed between flexural strength and compression test values indicated flexural strength = $25.84x^{-0.47}$, x being compressive strength, with a high correlation coefficient of 0.9762.

Flexural Strength with CMOD

CMOD tests (Fig. 9) are performed on 0, 0.3, 0.4, 0.5, 0.6 and 0.7% rHDPE-FC conforming to EN 14651-2005 (reaffirmed in 2007) [31] and results are presented in Fig. 10. The maximum loads attained for concrete mixes MH-0, MH-3, MH-4, MH-5, MH-6, and MH-7 are 7.24, 8.3, 8.38, 8.41, 9.02, and 8.82 kN, respectively, and interestingly, a sudden drop in loads are observed at CMOD values between 0.25 and 0.6 mm, beyond which a plateau load of 5–5.5 kN is observed. Significantly, the load is seen to drop to null for the controlled concrete prism once the maximum load is reached. All the percentages of rHDPE-FC indicated nearly the same trend. When

Fig. 9 CMOD flexure test: **a** Three-point load set up; **b** Fiber bridging action and failure pattern

Fig. 10 Load-CMOD curves for concrete mixes

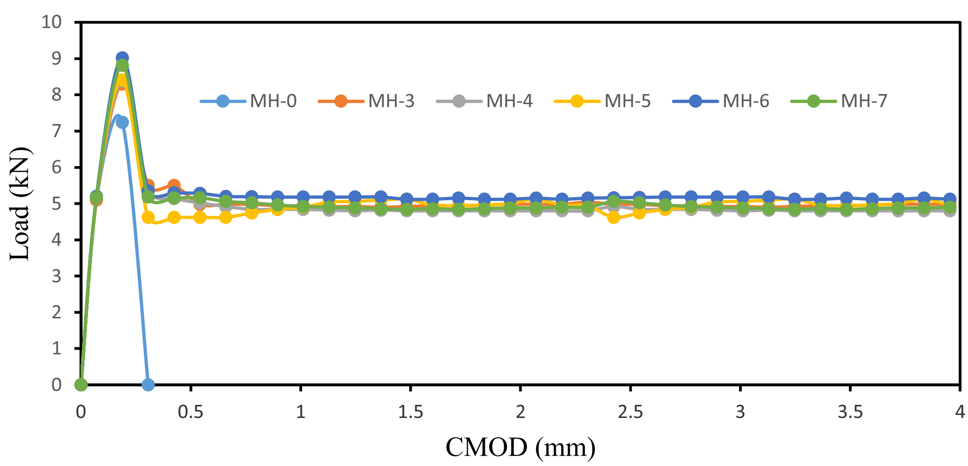


Table 6 Total fracture energy of CMOD prisms

Mix	MH-0	MH-3	MH-4	MH-5	MH-6	MH-7
W_r (Nm)	0.7	20	20.71	20	19.46	19.79
G_f (N/m)	93.335	2669	2763	2669	2597	2641

compared with MH-0, all other percentages indicated higher ductility properties. The above results conclusively indicate strong bridging effects due to the presence of rHDPE fibers. The Load–CMOD curves in Fig. 10 show that the elastic, peak load, and early post-peak load actions are akin for each beam when the CMOD is lesser than 0.2 mm. However, plain concrete specimens demonstrate complete failure at comparably crack opening widths, while the rHDPE-FC specimens can sustain a certain load level because of the fiber bridging zone. At the outset of this specific response, the fracture process zone can be divided into the aggregate and fiber bridging zones. Figure 9b shows the failure pattern of an rHDPE-FC sample, emphasizing that the linking influence displayed by rHDPE fibers is formidably sufficient to avoid the sample's complete and sudden detachment into two parts.

Peak crack potency is reached for CMOD values lesser than 0.6 mm (Fig. 10). CMOD results depend on rHDPE fiber dispersion, quantity, and direction on the notch-plane with the limited area even in the same batch of concrete prisms subjected to central point loading. As per Fig. 10, the ability of fiber to bridge the crack has been observed as the load can remain constant at large values of CMOD. These findings corroborate well with reported research and

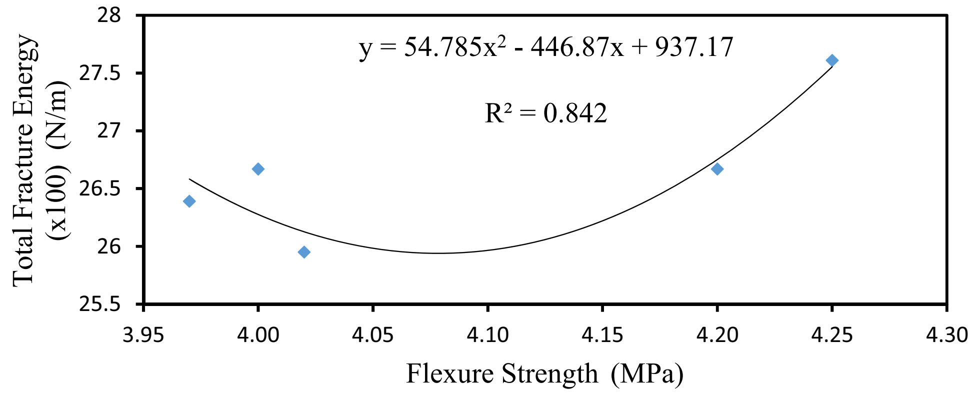


Fig. 11 Correlation between CMOD flexure and total fracture energy of concrete mixes

Fig. 12 Failure pattern of round determinate slab test (RDST)

conclusively suggest that PP fibers afford extra load carrying capacity at comparably bigger crack opening breadths [31]. A similar line of the behaviour is reported by Fraternali et al. [24], who investigated with PET fiber in 150 × 150 × 600 mm rectangular concrete prisms. They considered central 4 mm wide v-shaped notch as per Italian standards UNI 11039-1 and UNI 11039-2 and tested CMOD at the rate of 0.05 ± 0.01 mm/min and reported significantly higher ductility with PET fiber concrete compared to controlled concrete. Yin et al. [41] investigates on influence of PP fiber on M25 (0.45%) and M40 (0.6%) grade concrete, and reported improvement in ductility with the CMOD test for PP-FRC over the controlled concrete. Crack propagation is observed to be in line with the notch-plane, and the other parts of prisms indicate no significant plastic deformation.

Total fracture energy, defined as the amount of energy required to create a new crack under the unit fracture surface area of the concrete, is observed to improve with the addition of rHDPE-FC fibers compared to the contemporary use of concrete without fiber. The total fracture energy (G_f), determined based on the method suggested by Hillerborg [42], defines the proportion between the total energy ($Wr + 2Pw\delta_0$) and the concrete fracture surface area $(w - a0)t$. In the above relation, Wr is the area below the curve for the applied load versus the CMOD curve, Pw is the equivalent self-weight force, δ_0 is the CMOD displacement corresponding to peak applied load at failure, w is the depth of specimen, a_0 is the depth of notch and, t is the width of the specimen. The equivalent self-weight force is determined as $Pw = (s/2\ l)W_0$, where s is the span, l is the length of the prism, W_0 is the self-weight of the specimen. Total fracture energy was evaluated as $(Wr + 2Pw\delta_0)\ /((w - a_0)t)$, and their values are reported in Table 6. It is clear from Table 6 that the energy required to create crack is much less in normal concrete, whereas high energy is required in rHDPE-FC concrete for all fiber contents. The difference in fracture energy is insignificant for all rHDPE fiber reinforced concrete specimens and suggests a similar pattern [30, 43]. Figure 11 presents the correlation between flexural strength and total fracture energy of all concrete specimens. The coefficient of variation (R^2) is reasonably good, and the second-order approximation is quite consistent. It gives better agreement between both experimental observation and evaluated results.

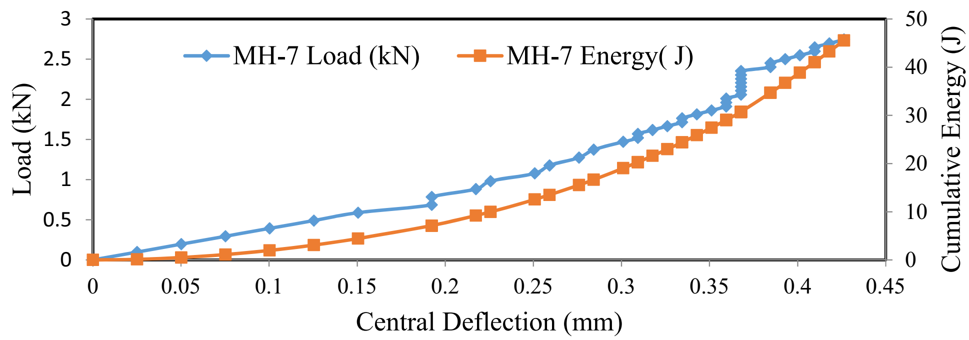


Fig. 13 Cumulative energy and load versus deflection curves from Round Determinate Slab Tests (RDST): 400 mm diameter and 75 mm thick (S4)

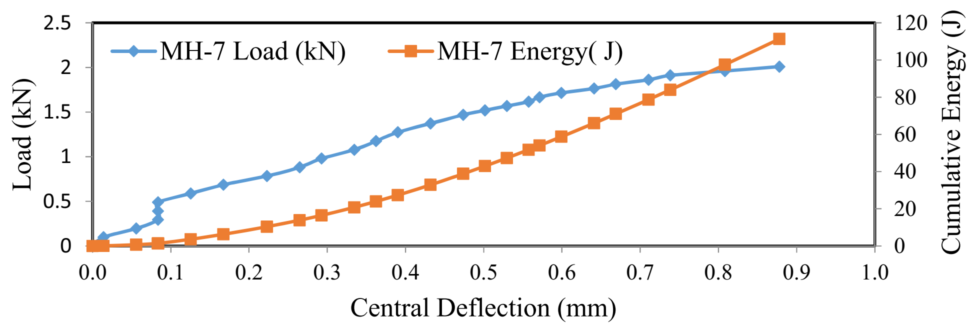


Fig. 14 Cumulative energy and load versus deflection curves from Round Determinate Slab Tests (RDST): 600 mm diameter and 75 mm thick (S6)

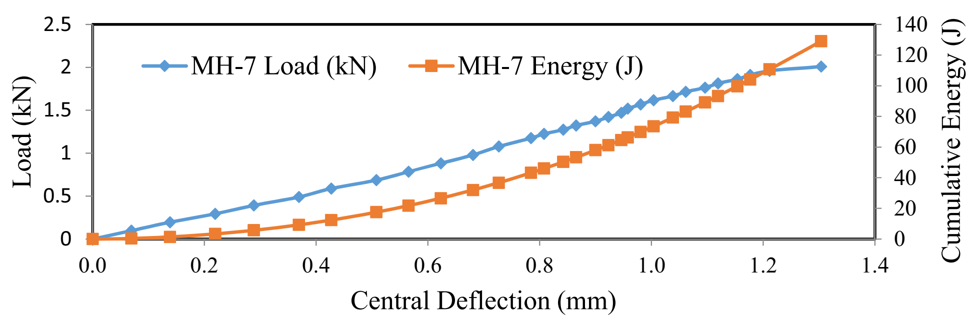


Fig. 15 Cumulative energy and load versus deflection curves from Round Determinate Slab Tests (RDST): 800 mm diameter and 75 mm thick (S8)

Table 7 Maximum deflection, peak load, and cumulative energy results of RDST

Round slab	Deflection (mm)	Peak load (kN)	Cumulative energy (Joules)
S4	0.43	2.74	45.54
S6	0.88	2.16	111.31
S8	1.30	2.01	129.06

Round Determinate Slab Test Results

Round slabs were cast and tested to know the performance of rHDPE fiber in concrete. The failure pattern during applied load at the central position is exhibited in Fig. 12. Results of energy absorption and load curves from 400 mm (S4), 600 mm (S6), and 800 mm (S8) diameter RDST of a concrete mix MH-7 are presented in Figs. 13, 14, and 15. Maximum deflection, peak load, and cumulative energy results of RDST are shown in Table 7.

All the slabs are associated with a failure, and cracks are observed equally along all three grooves. Further, MH-7 mix concrete round slab S8 shows more ductility than S4. The increase in cumulative energy is 183.39% and

144.42% for S8, and S6 respectively, compared to S4. The energy intake is the area below the load versus deflection curve, reflecting fiber reinforcement efficiency in absorbing energy. As evidenced in Fig. 15, S8 has shown a higher cumulative energy absorption than S4, indicating that S8 produces a higher post-cracking performance than S4. Figures 13, 14, and 15 show that an 800 mm diameter slab indicates higher ductility capacity and higher energy absorption than lower diameter slabs. This observation is significant and coherent with CMOD outcomes. Yin et al. [41] tested round slabs with 0.67% PP fiber in M40 and 0.45% PP in M25 using virgin and recycled PP. They reported a sudden drop in all the round slabs at a deflection of 1 mm. In contrast, the present study indicates 1.3 mm deflection before the sudden drop, which demonstrates that the reinforced concrete with recycled rHDPE fiber possesses better ductility than those reinforced with recycled PP**.**

Conclusions

The preceding sections presented the necessity and details of the utilization of plastic waste to develop sustainable waste management and preserve a safe environment through rHDPE plastic waste in concrete. Even today, widespread approval of recycled rHDPE fibers is still not permitted, a probable fallout due to low research emphasis. As an attempt to bridge the research gulf, mixes with varying proportions of recycled rHDPE plastic fibers have been prepared, and their impact on the characteristics of rHDPE-FC investigated. Based on the test findings, following closing remarks are summarized:

- The mechanical properties such as compression values of concrete mixes decrease marginally; splitting tensile and bending strength are observed to increase with the increase in rHDPE plastic fiber. It indicates optimum values of splitting tensile (39.14%, 9.5 MPa) and flexural strengths (36.22%, 4.25 MPa) of concrete at 28 days' respectively, at similar fiber content compared to those in control concrete (3.12 MPa).
- The mix with rHDPE fiber content less than 0.7% shows a marginal increase of 0.5% in compressive strength.
- The application of rHDPE fiber in a small amount (3.88 or 4.85 kg-m^{-3}) does not impact the compression results of concrete, but it considerably enhances the splitting tensile and flexure results of concrete which observed from the crack surfaces and energy quantity of CMOD and RDST experiments.
- Most of the fibers are breached instead of come out from the concrete matrix, implying high binding efficiency of rHDPE fibers with concrete.
- The findings of CMOD and RDST indicate that rHDPE fiber produced a better post-cracking and efficient fiber reinforced concrete. Hence, the preceding studies indicate a strong potential on use of recycled rHDPE fibers for concrete precast slabs.

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Declarations

Competing interest It is to say that authors declared no potential conflicts of interest with respect to the research, authorship, and publication of this article.

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