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Flexural Behavior of Portland Cement Mortars Reinforced with Hybrid Blends of Recycled Waste Fibers

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Abstract: Laboratory tests were performed for evaluating the flexural performance of Portland cement mortars reinforced with recycled fibers. The objective was to find the best blend of unsorted recycled post-consumer tire steel fibers (RTSF), and recycled plastic fibers (RPF) for enhancing the flexural behavior and ductility of cement-based composites. Ten mortar mixes containing various blends of RTSF and RPF were cast and tested under a displacement-controlled four-point bending ASTM test. Test results indicate that the mortar mixes reinforced with recycled fibers satisfied the ASTM flow requirements and achieved a flexural response and toughness comparable to the response of similar mixes, containing manufactured steel fibers (MSF) only, at the same fiber dosage. Among the recycled fiber blends investigated, the mix containing 0.5% RTSF and 0.5% RPF (on volume basis) exhibited relatively superior flexural characteristics compared to the mixes reinforced with the same dosage of MSF only. Moreover, the positive synergetic effect of fiber blends on the post-cracking strength and flexural toughness was pronounced at 0.5% RTSF and 0.5% RPF (on volume basis). Hence, as an echo-friendly material, recycled fiber blends of RTSF and RPF could be recommended for enhancing the flexural performance of cement-based composites at a lesser cost.

Keywords: recycled tires steel fibers; recycled plastic fibers; steel fiber-reinforced mortar; hybrid steel fiber reinforcement; flexural pot-peak behavior; flexural toughness

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1. Introduction

Identifying strategies for reducing the environmental impact of concrete is essential for greening the building industry sector and meeting the sustainability goals set by the United Nations. Millions of tons of post-consumer tires, and plastic beverage containers are discarded annually worldwide. Since landfill areas are depleting rapidly, and the cost of solid waste disposal is increasing, it is crucial to find proper means for minimizing their effect on the environment. Recycling holds a great promise for turning the waste materials into valuable products. Recently, there began a growing interest in exploring the potential of recycled waste materials in replacing manufactured fibers for producing fiber-reinforced concrete (FRC). Since concrete is the most consumed building material in the world, the feasibility of using industrial waste products for enhancing its performance attracted practitioners' attention in developed and developing countries as well. Many researchers proved that the fibers recovered from waste materials are appropriate for use in reinforced concrete, and are less costly than non-recycled fibers [1–8].

Fiber-reinforced cement-based composites offer the engineer an outstanding combination of properties, including strength, ductility, and durability. Several types of fibers, including metallic and non-metallic, can be blended together in specific proportions for further enhancement in the performance of cement-based composites. Randjbaran, E. et al. [9] investigated the flexural strength of reinforced carbon–Kevlar hybrid fabrics affected by impact damage and compared it to the strength of the intact specimen. The test results indicate that for the samples of the neat epoxy composite laminates, the flexural strength and toughness increased compared to the system reinforced with 1.5% carbon

nano tubes, CNT. Moreover, after ballistic impact damage and fiber fracture, within a range of 0 to 40 degrees, the flexural properties for the reinforced carbon–Kevlar hybrid fabrics laminate reinforced with 1.5% CNT by volume, exhibited a reduction in the flexural modulus and the maximum flexural stress. Attari, N. et al. [10] examined the efficiency of external strengthening systems for reinforced concrete beams using fiber-reinforced polymer (FRP) fabric (glass–carbon). They proposed different strengthening schemes, including use of separate unidirectional glass and carbon fibers with some U-anchorages or bidirectional glass–carbon fiber hybrid fabric for strengthening reinforced concrete beams in flexure. Among the schemes investigated, the use of twin layer glass–carbon FRP fabric was the most effective as a strengthening configuration for reinforced concrete structures. Farooq et al. [2] attempted to develop a fiber-reinforced geopolymer mortar using 1%, 2%, and 3% volume fractions of fibers with adequate mixing time and high workability, with natural river sand as a filler. The fibers investigated are polyvinyl alcohol (PVA), polypropylene (PP), high strength steel (HSS), and chopped steel wool (CSW). The parameters evaluated include the effect of fiber type, solution concentration, and sand content on tension performance of eco-friendly ductile geopolymer composites (EDGC). They observed a pseudo-strain hardening response with both PVA and HSS fibers in all cases. With PP fibers, a low post-crack bridging tensile strength was observed, whereas the tensile strain capacity was very high (>4%) due to the large elongation of PP fibers before fracture.

The methods of combining different types and sizes of discreet fibers to provide improvements on multiple properties of fiber-reinforced concrete were proven to be successful [5–8,11–15]. Sivakumar and Santhanam [13] investigated the mechanical properties of high-strength concrete reinforced with steel fibers and non-metallic fibers, such as micro polypropylene fibers, polyester fibers, and glass fibers. Their test results indicate that a steel and polypropylene fiber combination performed better than the same fibers when used separately. Naser et al. [14] combined short copper fibers, recycled from wastes of electrical connection wires, and long steel fibers recycled from galvanized binding wires. They observed that the highest flexural and tensile strengths can be obtained by combining 0.45% copper fibers with 0.1% steel fibers. Moreover, they observed that hybridization not only saved costs, but improved flexural and tensile strengths as well. Caggiano et al. [15] found that the combination of recycled and commercial metallic fibers increased the first crack strength by 20% in comparison with a single-fiber composite containing an equal amount of commercial fibers. Moreover, the highest first crack strength was obtained when the proportion (recycled fibers: industrial fibers) was equal to 70:30 for a fiber volume fraction of 1.25%. Graeff [16] studied the feasibility of using recycled tire steel fibers (RTSF) and manufactured steel fibers (MSFs) for reinforcing steel fiber-reinforced concrete (SFRC), and roller-compacted concrete (RCC) pavements. Their study showed that the RTSF concrete reacted well against accelerated corrosion and freeze–thaw of RCC. Moreover, RTSF delayed the propagation of micro cracks, whereas MSFs were more effective in controlling the macro cracks. Hu et al. [17] studied the mechanical behavior of different hybrid fiber mixes, including MSF and sorted RTSF blends. They concluded that, for the same fiber dosage, mixes with hybrid fibers exhibited better performance compared to mixes reinforced with one type of fibers only. Younis et al. [18] found that the mixes containing hybrid fibers of crimped type MSF and sorted RTSF exhibited higher flexural strength and toughness than the mixes containing MSF only.

AL-kamyani et al. [19] investigated the effects of manufactured steel fibers (MSFs), and sorted recycled steel fibers from end-of-life tires (RTSF) on the mechanical properties of steel fiber-reinforced concrete (SFRC). Their test results indicate that the mechanical properties of hybrid mixes containing RTSF were comparable to those containing similar dosages of MSF only. Moreover, test results display a positive synergetic effect for the hybrid mixes containing 10 kg/m^3 of RTSF only. Hu et al. [5] studied the flexural behavior of steel fiber-reinforced concrete (SFRC) containing hybrid blends of sorted recycled tire steel fibers (RTSF) and recycled tire steel cords (RTSC). Their test results indicate that for the same

dosage of fibers, the post-cracking strength of recycled-fiber mixes was approximately two times larger than the mixes containing MSF only. In addition, further improvements in the flexural behavior of concretes reinforced with larger contents of RTSC were observed. Alsaif and Alharbi [6] carried out an experimental investigation on the effects of a hybrid system of steel fibers on the strength, durability, and shrinkage of rubberized concrete. Their test results reveal the possibility of producing rubberized concrete with comparable properties to ordinary concrete by using 40 kg/m^3 of steel fibers in conjunction with 20% of ground rubber. Al-Tulian et al. [8], as well as Alhuzaimy and Alshannag [11], conducted laboratory experiments on the effects of recycled plastic fibers on the flexural behavior and plastic shrinkage of Portland cement mortar. Their test results show significant improvements in flexural behavior and considerable reduction in plastic shrinkage cracks of the mortar reinforced with recycled plastic fibers.

Limited experimental data exists in the literature on the hybridization of recycled fibers with a volume fraction less than 1.5% in the concrete industry [20,21]. Some researchers indicated that the significant improvement in the mechanical behavior of cement-based composites can be achieved by adding different types of fibers simultaneously. This is mainly due to the role of the combined fibers in enhancing the performance of the composite at the micro, meso, and macro structural levels. This investigation aims at finding an eco-friendly fiber–concrete mixture that satisfies the workability, strength, and ductility requirements of cement based mortar. The main objective of the current investigation is to develop a hybrid system of recycled fibers in which one type possesses high strength and stiffness for improving the first crack and ultimate strengths, and the second type possesses high ductility for improving toughness and post-cracking strength. The novelty of the present approach relies on combining the strength and stiffness of echo-friendly recycled tire steel fibers (RTSF), and the high strain capacity and flexibility of recycled plastic fibers (RPF) for enhancing the performance of cement-based composites. To the authors' knowledge, the test results of the hybrid system proposed in the current investigation are reported for the first time. No study exists in the literature that addresses the combined effects of recycled plastic strands and tire steel wastes on the behavior of cement-based composites. RTSF, RPF, and manufactured steel fibers (MSF) will be used at volume fractions ranging between 0.25% and 1.0%. Parameters investigated include flow, compressive and flexural strengths, and ductility.

2. Experimental Program

The experimental program was designed to study the effects of various types of recycled fibers on the compressive and the flexural strengths of high-strength Portland cement mortar. A total of 30 prisms of 100 × 100 × 500 mm were cast to determine the flexural strength, and 40 cube specimens of 100 × 100 × 100 mm were cast to determine the compressive strength, in addition to 10 semi cone specimens for determining the flow of fresh mortar.

2.1. Materials Properties

The materials used included Portland cement, type I, complying with ASTM C150 standards [22], white silica sand with a specific gravity of 2.65, and tap water. Table 1 shows the chemical properties of the cement. Table 2 presents the physical properties of the white sand, obtained through conducting the following procedures: (a) particle density and water absorption according to EN 1097-6 [23] and (b) loose bulk density according to EN 1097-3 [24]. Figure 1 shows the particle size distribution of the white sand, acquired in accordance with ASTM C136 [25].

Table 1. Chemical properties of cement.

CaO	SiO_2	Al_2O_3	Fe_2O_3	SO_3	K_2O	TiO_2	P_2O_5	MgO	Na_2O
64.00%	20.21%	5.33%	4.52%	2.86%	0.45%	0.31%	0.03%	0.74%	0.09%

Table 2. Physical properties of white sand.

Physical Properties	White Sand
Specific gravity (oven-dried basis)	2.57
Specific gravity (saturated surface-dried basis)	2.58
Absolute specific gravity	2.59
Water absorption after 24h, %	0.30
Loose bulk density, kg/m^3	1543

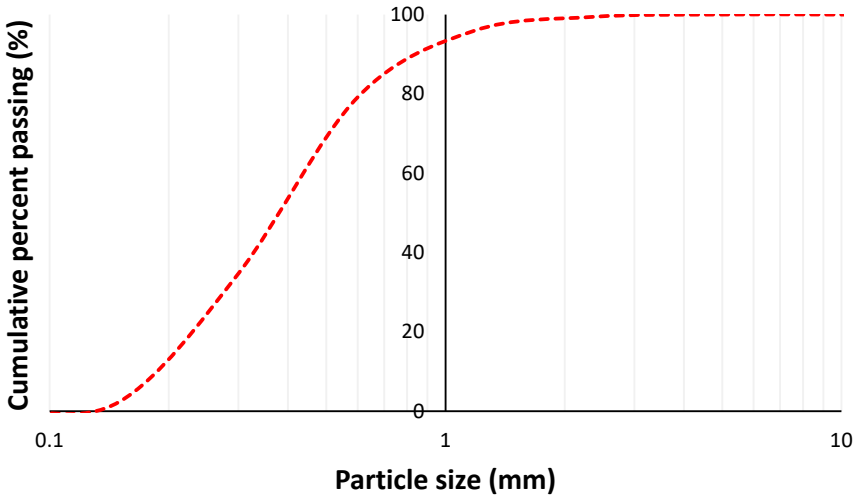


Figure 1. Particle size distribution for the white sand.

The fibers used included commercially available manufactured hooked-end steel fibers (MSF), unsorted recycled post-consumer tire steel fibers (RTSFs), and unsorted recycled plastic fibers (RPFs). The RPFs were obtained by slitting deformed plastic sheets into thin strands and cutting it to the desired lengths. The properties of the MSF, RTSF, and RPF fibers used in this investigation are listed in Table 3. The RTSFs were obtained from post-consumer tires by mechanical shredding techniques followed by separating the steel fibers using electromagnets. The various types of fibers used in this investigation are demonstrated in Figure 2.

Table 3. Mechanical properties of MSF, RTSF, and RPF.

Fiber Type	Length (mm)	Diameter (mm)	Width (mm)	Density (g/cm^3)	Tensile Strength (MPa)	Young's Modulus (MPa)
MSF [26]	60	0.75	-	7.8	1800	200,000
RTSF [17,27]	10–60	<0.3	-	7.8	≈2570	200,000
RPF (flat) [11]	50	0.5	2.0	1.38	310	10,200

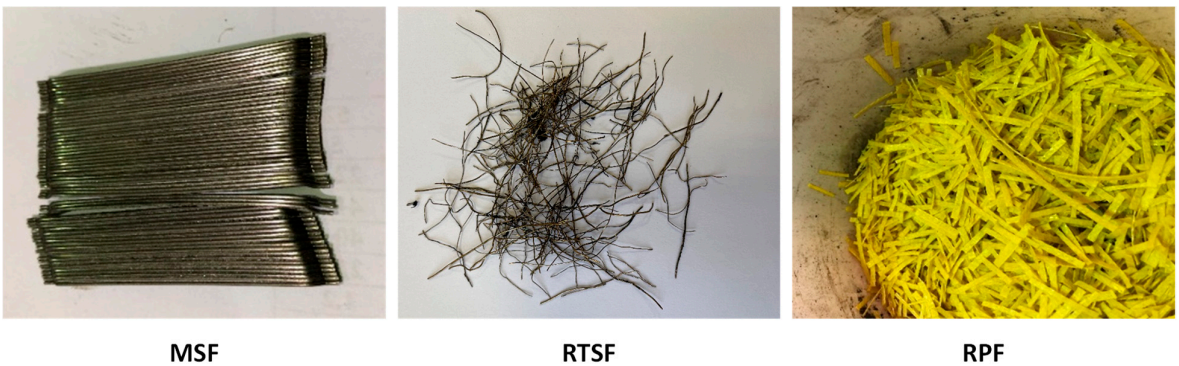


Figure 2. Types of fibers used in this investigation.

2.2. Mortar Matrix

A total of ten mortar mixes were designed following ASTM C109 [28] standards to achieve 28-day compressive strength of 50 MPa, as well as a standard flow of 110 ± 5%, as specified in ASTM C1437-20 [29]. The mix proportions were 0.5:1.0:2.0 (water, cement, and white silica sand) by weight of cement. A tilting drum mixer with a capacity of 0.15 m^3 was used for mixing the mortar. Various types and contents of fibers, including manufactured and post-consumer steel fibers and recycled plastic fibers, were added gradually to the mortar mixtures during mixing. This was to ensure random distribution of the fibers within the matrix, and thus avoid fiber lumping. The details of the mortar mixes and the types of fibers used are presented in Tables 4 and 5.

Table 4. Proportions of control mortar mix.

Material	Weight	Unit
Cement Type 1	637	kg/m^3
White sand 0/1 mm	1274	kg/m^3
Water	319	L/m^3

Table 5. Volume fractions of different types of fibers used.

Mix #	Fibers Volumes			Fibers Quantity in kg		
	MSF	RTSF	RPF	MSF	RTSF	RPF
M1	-	-	-	0.00	0.00	0.00
M2	0.50%	-	-	1.18	0.00	0.00
M3	-	0.50%	-	0.00	1.18	0.00
M4	-	-	0.50%	0.00	0.00	0.21
M5	-	0.25%	0.25%	0.00	0.59	0.10
M6	0.75%	-	-	1.78	0.00	0.00
M7	-	0.25%	0.50%	0.00	0.59	0.21
M8	-	0.50%	0.25%	0.00	1.18	0.10
M9	1.00%	-	-	2.37	0.00	0.00
M10	-	0.50%	0.50%	0.00	1.18	0.21

MSF: manufactured steel fibers, RTSF: recycled tire steel fibers, and RPF: recycled plastic fibers.

2.3. Casting and Curing

The prism and cube specimens were cast in two layers and compacted using a vibrating table. All specimens were covered with wet burlap and kept in the laboratory environment for 24 h. They were then demolded, cured in water for 28 days, and prepared for testing. Figure 3 shows mixing, casting, and curing of the mortar mixes investigated.

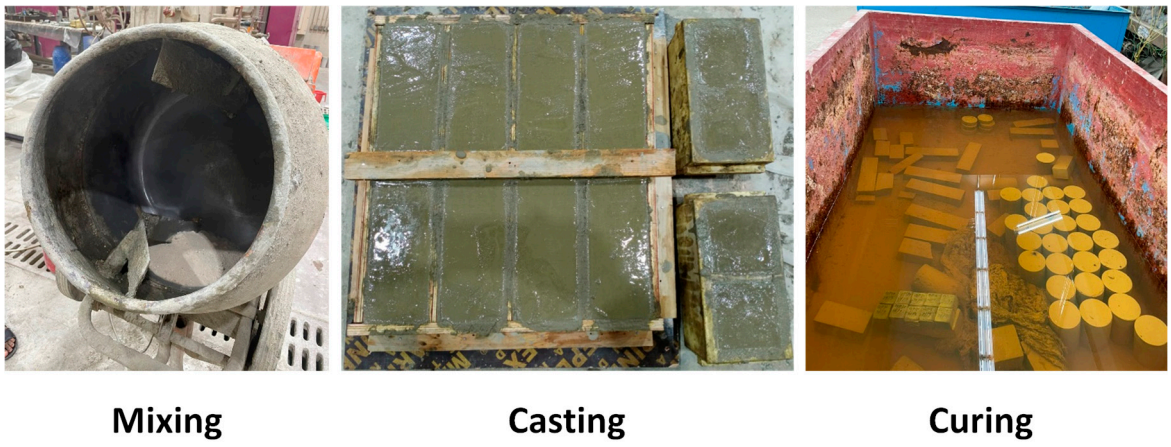


Figure 3. Mixing, casting, and curing of the mortar mixes investigated.

2.4. Test Methods

The tests performed in this study included the flow of fresh mortar, compressive strength, flexural strength, and flexural toughness. The flow was measured as the percentage increase in the average base diameter of the table as specified in ASTM C1437-20 [29]. For each mix, the average of four diameter measurements at approximately equi-spaced intervals was determined following the procedure prescribed in the ASTM C1437-20 standard. The compressive strength at 28 days was measured on 100 mm cubes following the BS EN 12390–3 [30] standard. The tests were performed using a 3000 Kn capacity compression machine at a rate of 0.4 Mpa/s. The results are reported as an average of four specimens for each mix. The flexural strength was measured at 28 days, using 100 mm × 100 mm × 500 mm prisms following the standard procedure prescribed in ASTM C1609 [31]. A four-point bending test was carried out using a displacement control servo-hydraulic actuator with a capacity of 3000 Kn at a rate of 0.075 mm/min. Mid-span deflections were measured using two linear variable differential transducers (LVDT) placed at each side of the yoke. The average value of three prisms was recorded for each mix. The toughness was calculated following the procedure prescribed in ASTM C1609 [31] standards.

2.5. Assumptions and Limitations

The experimental test results and related discussions are based on the following assumptions; (1) random orientation of the recycled fibers within the mortar matrix; (2) uniform geometrical properties of the fibers investigated including length, diameter, width, and thickness; (3) uniform surface characteristics of the fibers investigated; and (4) adequate workability of the cement mortar mixtures, regardless of the type and dosage of fibers added. The limitations of the current laboratory investigation include; (1) availability of factories for processing post-consumer tire steel and recycled plastic wastes on a large scale; (2) producing recycled waste fibers with uniform geometrical properties (i.e., desired dimensions) using a specially designed apparatus; (3) producing recycled waste fibers with the desired surface characteristics using a specially designed apparatus; (4) availability of truck mixers for a large-scale production of concrete with adequate workability; and (5) the availability of an experienced technician for supervising mixing and casting operations of fiber-reinforced concrete mixtures.

3. Discussion of Test Results

The experimental test results and the effects of the recycled waste fibers on the flow, compressive, and flexural strengths of mortars are presented and discussed in the subsequent sections.

3.1. Flow of Mortar

Several trial mixes were performed to achieve a standard ASTM C1437-20 [29] flow for the control mix, M1 of 110 ± 5% (i.e., 5 to 15 % increase in the average base dimeter of the flow table). The flow diameters of the fiber-reinforced mortar mixes investigated are shown in Figure 4 and the measurements are presented in Figure 5. Each flow value represents the average of four diameter measurements. It can be seen that the flow of most of the fiber-reinforced mortar mixes satisfied the flow range prescribed by the ASTM C1437-20 standard and were almost the same as that of the control mix. This is because of the uniform properties of the cement mortar mixture, in addition to the lower dosages of fibers used per unit volume. Moreover, the mixes reinforced with hybrid blends of RTSF and RPF (i.e., M5, M7, and M10) exhibited similar flow to the mixes reinforced with MSF, except M8, which showed a decrease in flow of about 2%. This reduction is very small and within the range of testing error (2%) of the flow table apparatus reported in ASTM C1437-20 standard.

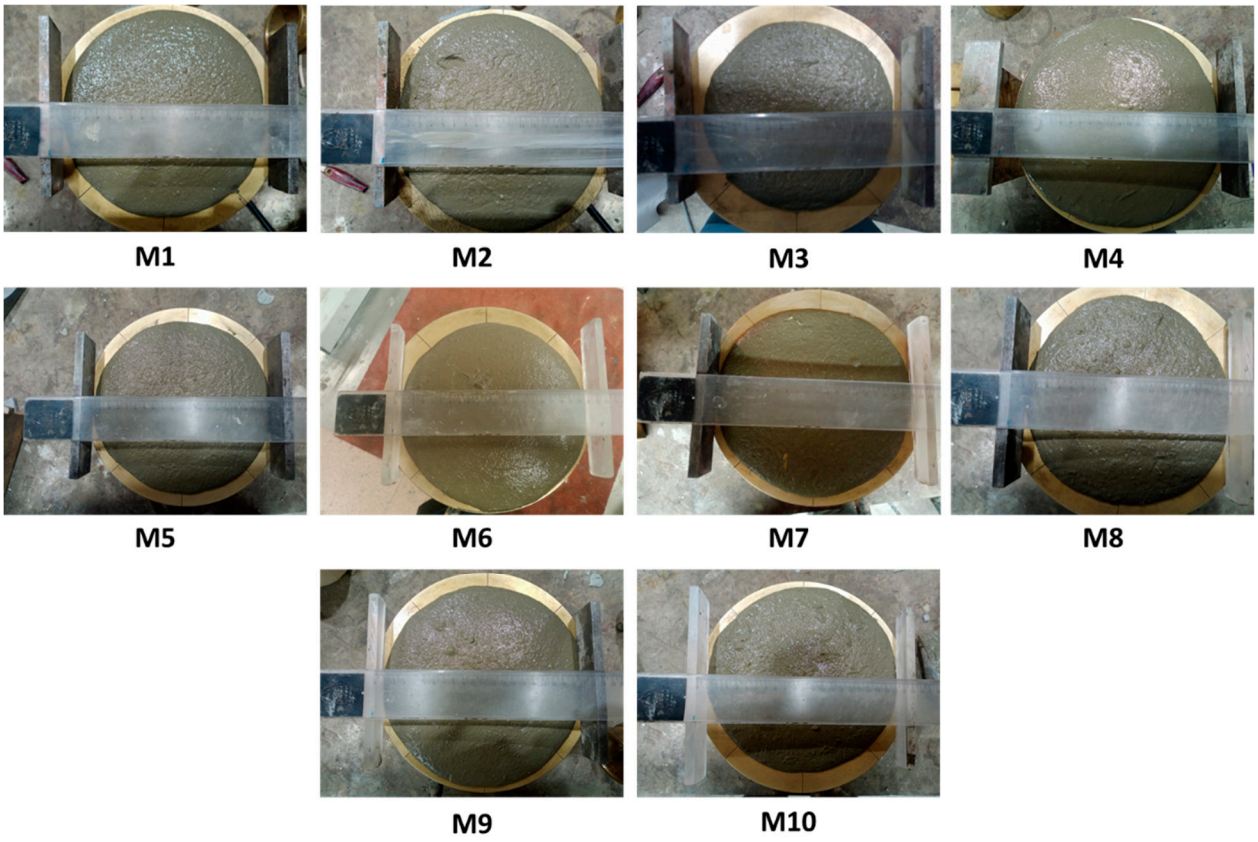


Figure 4. Flow table test dimeters of the mortar mixes.

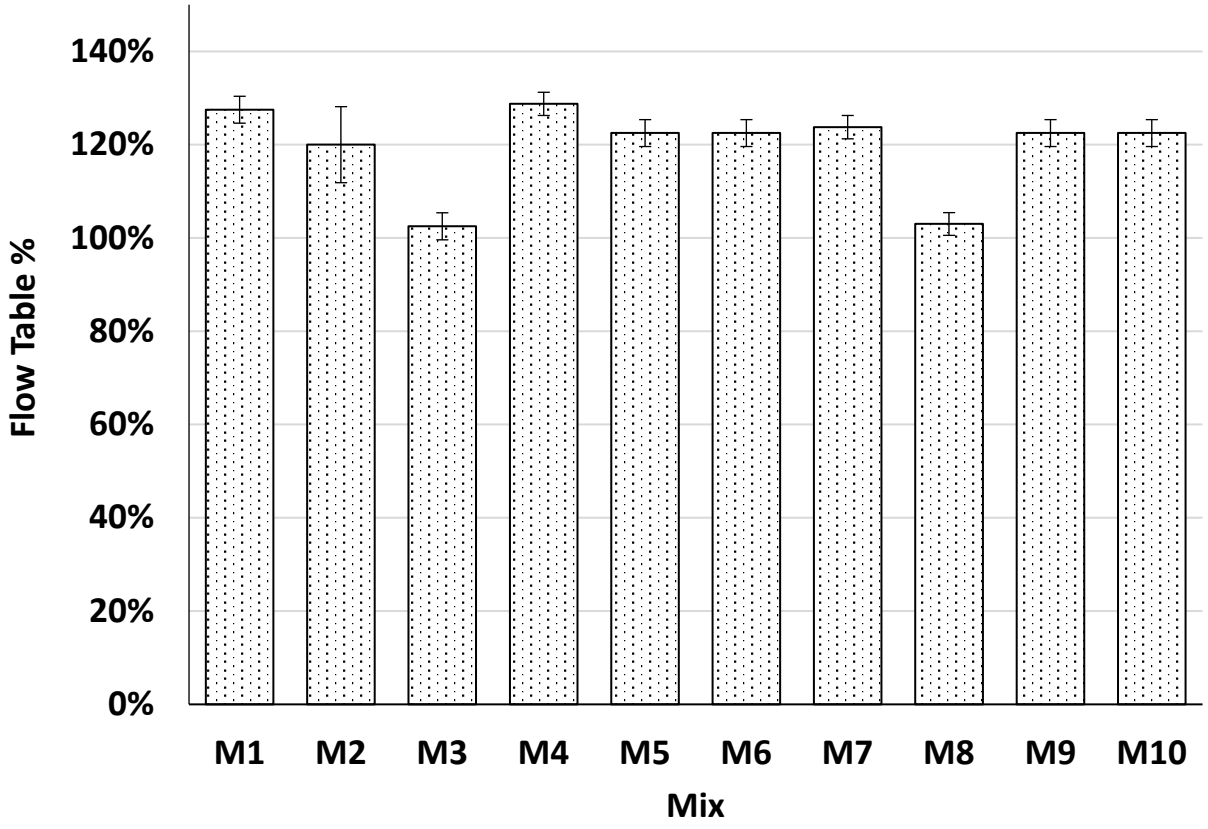


Figure 5. Flow table measurements of the mortar mixes investigated.

3.2. Compressive Strength of Mortar

The compressive strength tests were performed for quality control purposes. The test results shown in Figure 6 represent the average ultimate compressive strength of four cube specimens at 28 days. It can be observed that the mortar mixes reinforced with hybrid blends of recycled fibers, M5, M7, M8, and M10 showed more or less similar compressive strengths to the mixes reinforced with manufactured steel fibers, M2, M6, and M9. However, some of the fiber-reinforced mixes, M2, M3, M8, M9, and M10, showed about a 3% to 10% decrease in compressive strength compared to control mix M1. This could be due to fiber lumping caused by non-uniform distribution of the recycled fibers within these mixes. Despite the small decrease in the compressive strength of some mixes, their ultimate compressive strengths remained within the range of high-strength mortar. Furthermore, among all the mixes investigated, the mix containing a hybrid blend of 0.25% of RTSF and 0.50% of RPF on a volume basis, M7, had the highest compressive strength compared to all mixes. As expected, the effects of the fibers on compressive strength are expected to be less significant compared to flexural and tensile strengths. This is in conformity with the test results reported in the literature by some other researchers [1,8,32].

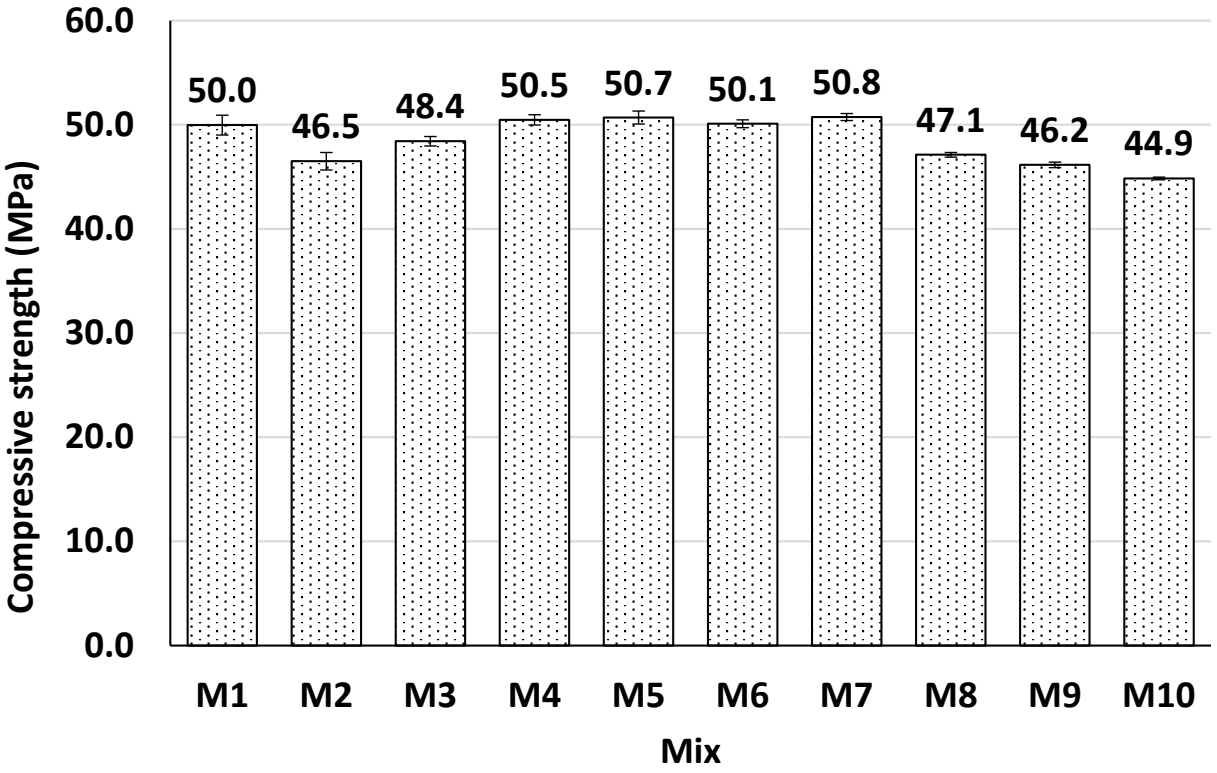
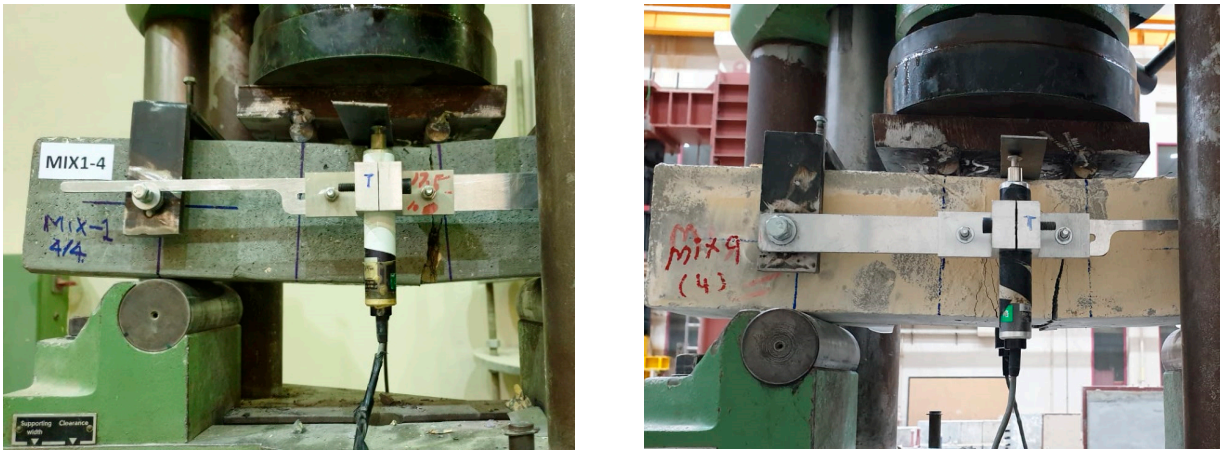


Figure 6. Compressive strength test results of the mortar mixes investigated.

3.3. Flexural Behavior of Mortar

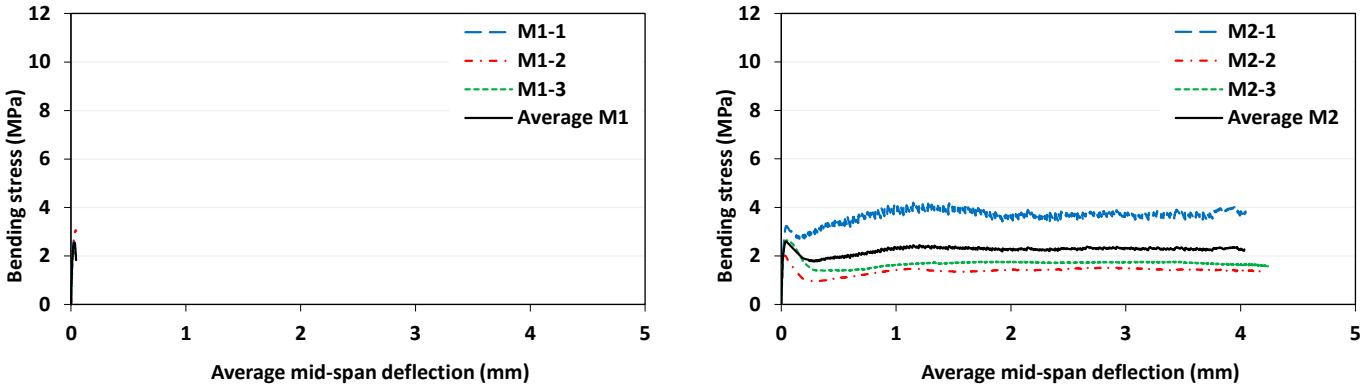
Figure 7 shows the typical failure mode for the tested concrete prisms. The plain mortar specimens exhibited a sudden and brittle failure characterized by the occurrence of a single major crack only, see Figure 7a. On the other hand, all the FRCM specimens tested failed in a ductile flexural mode characterized by the occurrence of numerous fine cracks within the middle third part of the prisms, followed by the formation of a major flexural crack at failure, as illustrated in Figure 7b.



(**a**) (**b**)

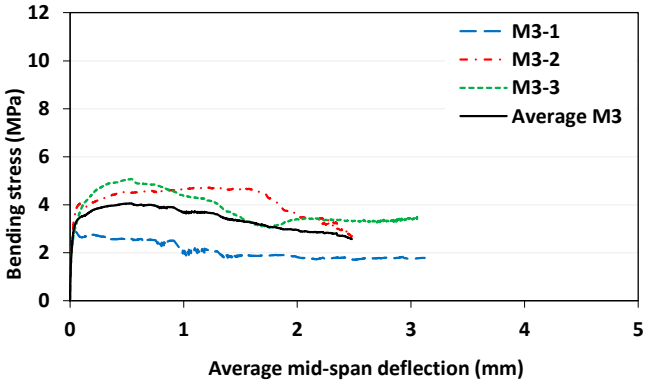
Figure 7. Typical failure mode of; (**a**) plain mortar specimens, and (**b**) fiber-reinforced mortar specimens.

The flexural behavior of the fiber-reinforced mortar mixes was investigated in terms of the flexural strength, flexural toughness, and cracking pattern. The complete bending stress deflection response of all the mixes investigated is presented in Figure 8a through (j). The average flexural response of the prisms tested was also determined using a specially designed software and plotted on the same graphs for comparison purposes. Moreover, the averages of the flexural characteristics, along with the corresponding standard deviations of all the specimens tested, are presented in Table 6. The averages of the peak flexural stresses are illustrated in Figure 9 and the residual flexural stresses at 0.5 mm and 2.0 mm deflections are shown in Figure 10. The flexural toughness was also computed at 2 mm deflection following the method prescribed in ASTM C1609 standards, as shown in Figure 11.

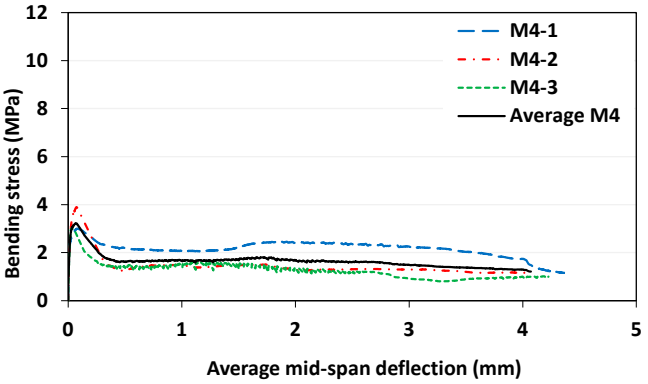


(**a**) M1 (**b**) M2

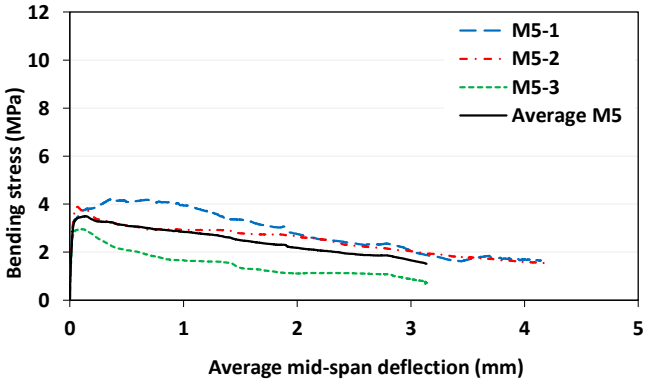
Figure 8. *Cont.*



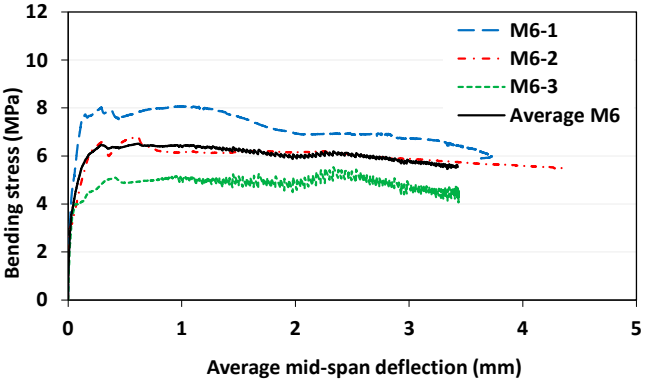
(**c**) M3



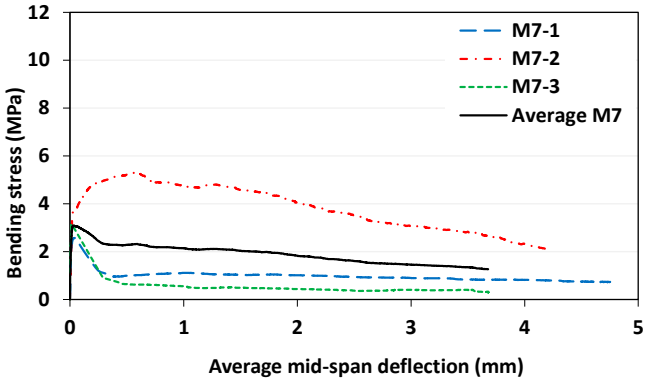
(**d**) M4



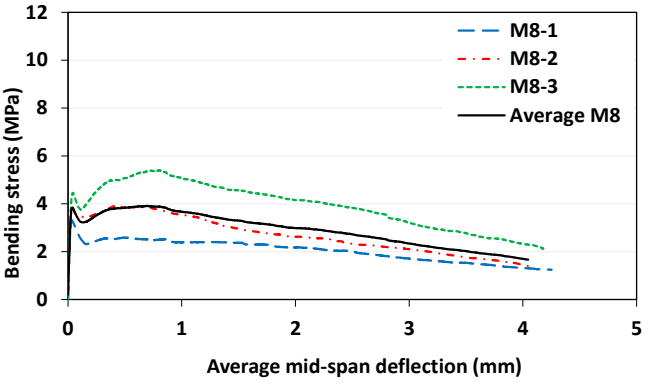
(**e**) M5



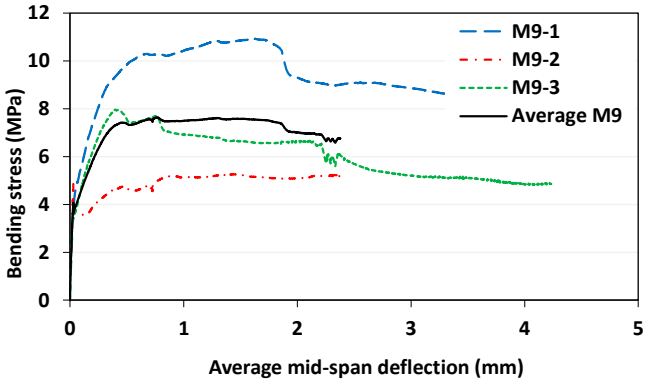
(**f**) M6



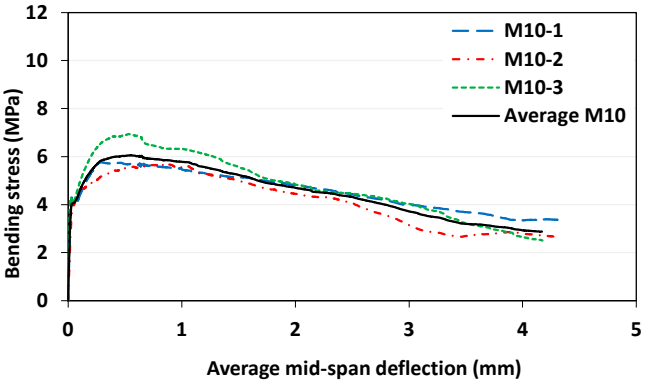
(**g**) M7



(**h**) M8



(**i**) M9



(**j**) M10

Figure 8. Flexural stress versus average mid-span deflection of all mixes: (**a**) M1; (**b**) M2 FR; (**c**) M3; (**d**) M4; (**e**) M5; (**f**) M6; (**g**) M7; (**h**) M8; (**i**) M9; and (**j**) M10.

Table 6. Average flexural characteristics and the standard deviations of the mortar mixes.

Mix	P_p (Kn)	f_p (Mpa)	P_{600}^D (Kn)	f_{600}^D (Mpa)	P_{150}^D (Kn)	f_{150}^D (Mpa)	T_{150}^D (J)
M1	8.7	2.6					
(Stdev.) *	(1.5)	(0.4)					
M2	9.8	2.9	6.6	2.0	7.6	2.3	14.6
(Stdev.)	(3.7)	(1.1)	(4.3)	(1.3)	(4.1)	(1.2)	(8.2)
M3	14.0	4.2	13.5	4.0	9.8	3.0	23.8
(Stdev.)	(4.1)	(1.2)	(4.3)	(1.3)	(3.3)	(1.0)	(7.8)
M4	11.0	3.3	5.5	1.6	5.7	1.7	12.1
(Stdev.)	(1.7)	(0.5)	(1.6)	(0.5)	(2.1)	(0.6)	(2.6)
M5	15.3	4.6	12.8	3.8	9.0	2.7	22.8
(Stdev.)	(6.1)	(1.8)	(5.7)	(1.7)	(4.3)	(1.3)	(9.6)
M6	22.7	6.8	21.3	6.4	20.2	6.1	40.9
(Stdev.)	(4.2)	(1.3)	(4.7)	(1.4)	(3.1)	(0.9)	(9.3)
M7	12.3	3.7	7.6	2.3	6.1	1.8	14.7
(Stdev.)	(4.8)	(1.5)	(8.5)	(2.5)	(6.5)	(1.9)	(14.3)
M8	14.0	4.2	12.8	3.8	10.0	3.0	23.3
(Stdev.)	(3.6)	(1.1)	(4.2)	(1.3)	(3.5)	(1.0)	(7.6)
M9	26.8	8.1	24.6	7.4	23.4	7.0	47.3
(Stdev.)	(9.4)	(2.8)	(8.6)	(2.6)	(7.1)	(2.1)	(16.4)
M10	20.4	6.1	20.1	6.0	15.7	4.7	36.0
(Stdev.)	(2.3)	(0.7)	(2.5)	(0.7)	(0.8)	(0.2)	(2.8)

P_p = peak load; f_p = peak strength; P_{600}^D = residual load at net deflection L/600; f_{600}^D = residual strength at net deflection L/600; P_{150}^D = residual load at net deflection L/150; f_{150}^D = residual strength at net deflection L/150; and T_{150}^D = area under stress vs. net deflection L/150; * Numbers in brackets represent the standard deviation of three measurements.

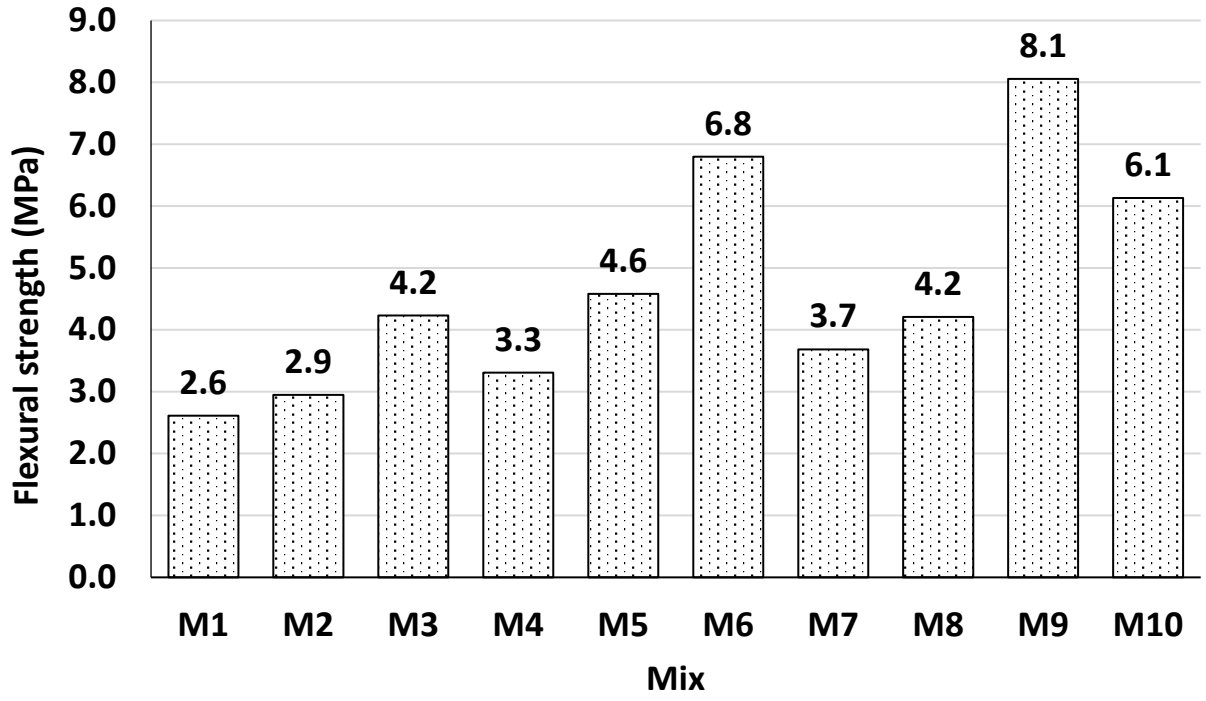


Figure 9. Peak flexural strength of the mortar mixes investigated.

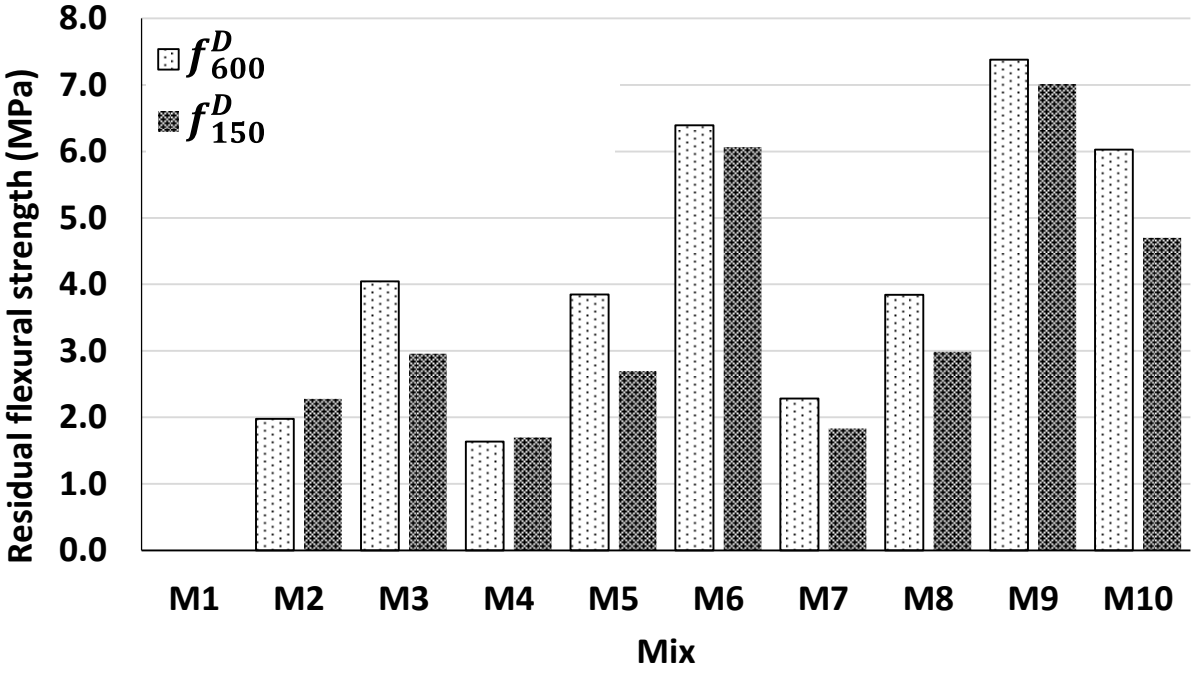


Figure 10. Residual flexural strength at 0.5 mm and 2.0 mm deflection of the mortar mixes investigated.

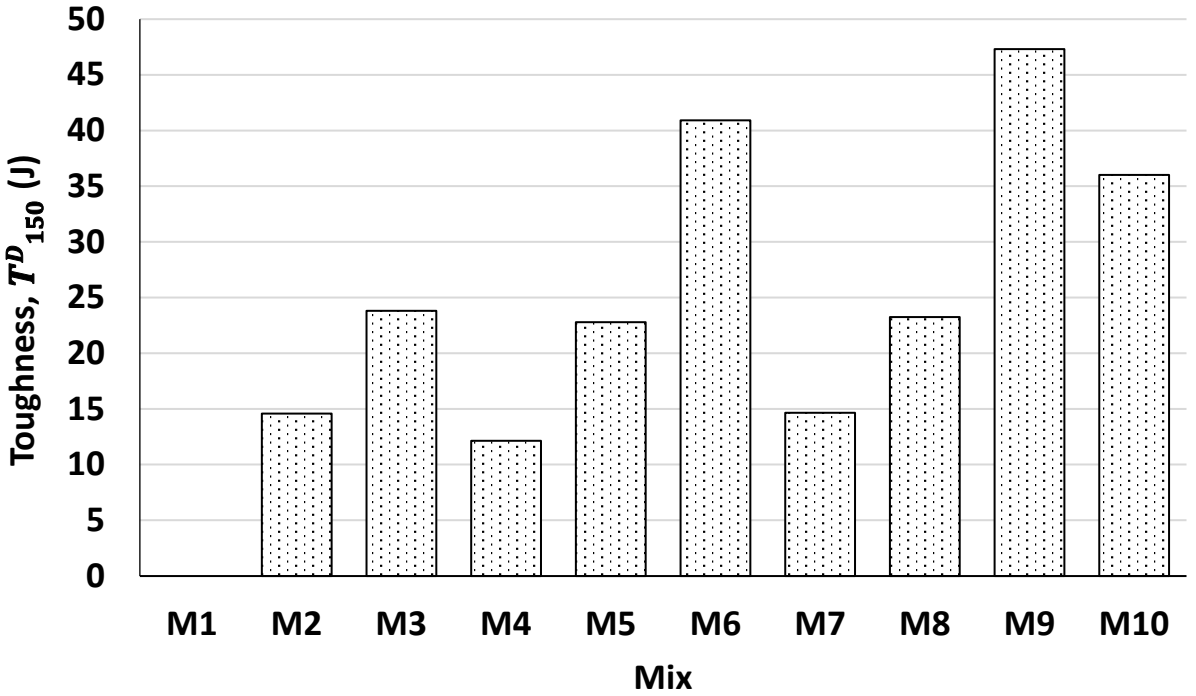


Figure 11. Flexural toughness at 2.0 mm deflection of the mortar mixes investigated.

3.3.1. Flexural Strength

The bending stress deflection curves for some of the FRCM mixes investigated, M2, M4, M7, and M8, consist of a linear elastic part up to onset of cracking, a nonlinear part up to peak stress, and a sudden drop in peak stress followed by a stable part until failure. However, the bending stress deflection curves for some mixes, M3, M5, M6, M9, and M10 consist of a linear elastic part up to onset of cracking, a nonlinear part up to peak stress, followed by a stable part with a gradual decrease in stress until failure. The superior post-peak response of mixes M3, M5, M6, M9, and M10 could be due to the homogeneous

distribution and alignment of the fibers within the mortar matrix, as well as due to the dual action of the hybrid blends of recycled plastic and tire steel fibers at pre-cracking and post-cracking levels, respectively. Figure 12 shows a section cut through typical prisms taken at the primary crack region to illustrate the different fiber distribution. Regardless of the variation in the mechanical and geometrical properties of the fibers and the differences in the mortar mix composition, the flexural response presented in this investigation compares fairly well with some of the test results reported in the literature [8,20,21]. The test results presented in Table 6 and Figure 8 show a substantial increase in the peak flexural strength for most of the fiber-reinforced cement mortar mixes (FRCM) investigated compared to control mixes without fibers. This is due to the important role of the fibers in bridging the micro cracks, and preventing the growth of macro cracks before and after the onset of cracking, respectively.

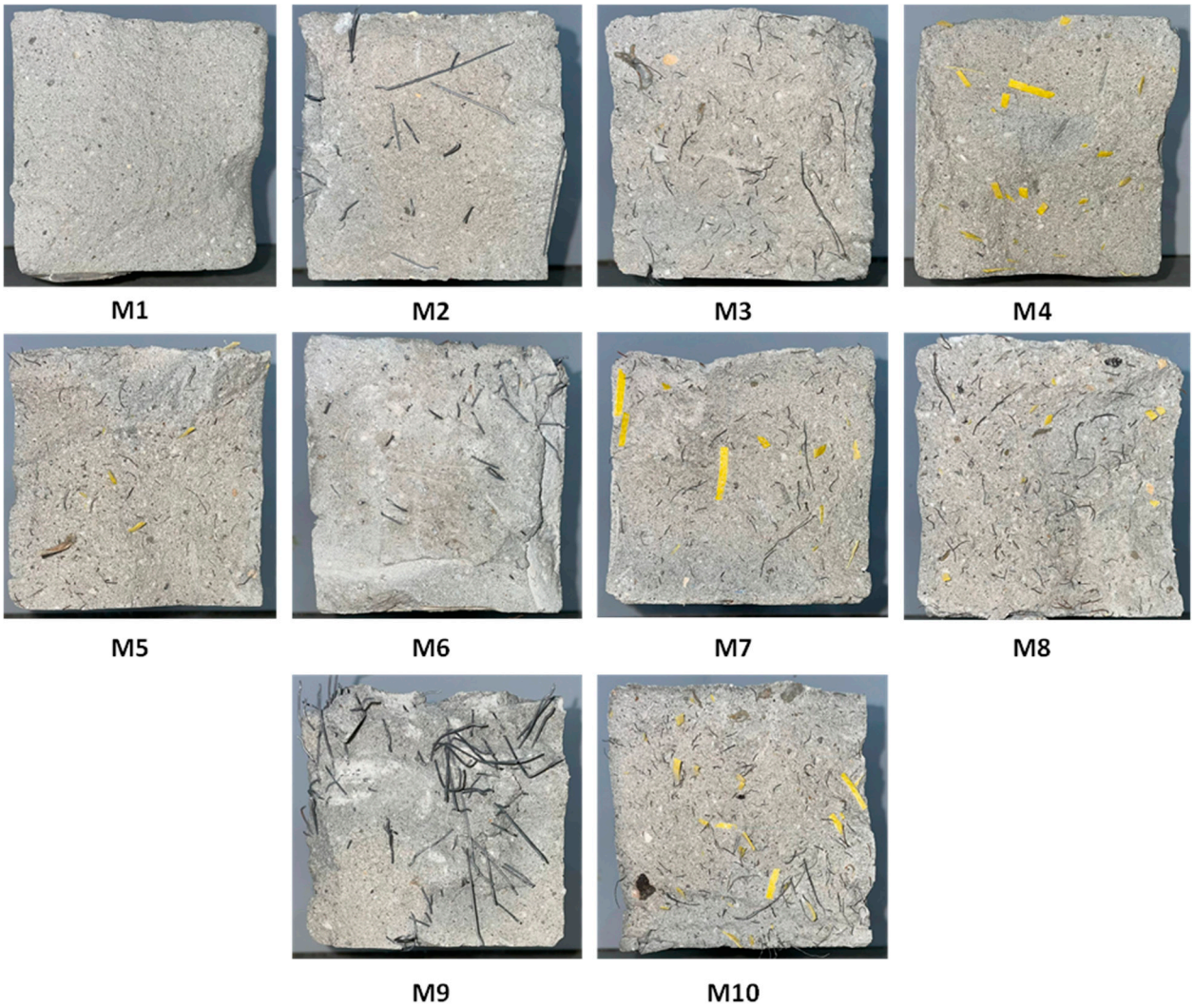


Figure 12. Section cut through a representative prism from each mix taken at the primary crack region.

The test results presented in Figures 9–11 also indicate that the mortar mixes reinforced with MSF exhibited less drop in post-cracking strength with further increase in mid-span deflection. For instance, the mixes reinforced with MSF showed up to 6% drop in post-cracking strength at 2 mm deflection, f^{D}_{150}, compared to the post-cracking strength at 0.5 mm deflection, f^{D}_{600}, whereas the mixes reinforced with hybrid blends of RTSF and RPF showed up to a 29% drop in post-cracking strength for the same deflections. Both types of fiber-reinforced mixes were effective in sustaining relatively high stress levels after

the peak load. This is due to the crack-arresting capability and gradual pullout of these types of fibers from the mortar matrix after cracking. The larger drop in strength for the recycled fibers could be due to the variation in their geometrical and mechanical properties compared to manufactured steel fibers. It is worth noting that both types of recycled fibers investigated, RTSF and RPF, are unsorted and had different surface characteristics. The RTSFs, in particular, had some residual rubber on their surfaces as a result of the mechanical shredding process of tire recycling. This may affect negatively the interfacial bond strength of recycled fibers embedded in the mortar matrix, whereas the manufactured steel fibers are produced under high quality control and had uniform surface characteristics and hooked ends as well. Among the recycled fiber blends investigated, the mix containing 0.5% RTSF and 0.5% RPF (M10) exhibited the least drop in peak flexural strength and post-cracking strength compared to the mix reinforced with an equivalent content of MSF. The high tensile strength and stiffness of RTSF improved the first crack and ultimate strengths of the cement mortar matrix, whereas the high ductility and flexibility (i.e., low modulus) of RPF improve the toughness and post-cracking strength. Furthermore, for the same fiber dosage, the hybridization of these types of fibers could definitely improve the overall response of cement-based composites. However, the performance of this mix could be enhanced further by sorting the recycled fibers and cleaning their surfaces from rubber remnants, in addition to increasing RTSF content slightly within the mortar matrix.

3.3.2. Flexural Toughness

Fiber-reinforced concrete is distinguished from plain concrete by its large energy absorption, higher deflections at peak load, ability to withstand large deformations, and superior crack arresting mechanism. In general, these characteristics are expressed in terms of toughness, and are responsible for the wide spread use of fiber-reinforced concrete in many structural applications. In this investigation, the flexural toughness of all the mortar mixes was computed following the procedure described in ASTM C1609 [31] standards, as the area under the stress deflection curve at a specified deflection. For all the specimens tested, a deflection limit of 2 mm was determined by dividing the span of the prism by 150 (T^{D}_{150}). The test results presented in Table 6 and Figure 11 show a substantial increase in flexural toughness of the fiber-reinforced mixes compared to the plain mortar mix. The mixes reinforced with 0.75% and 1.0% of MSF on volume basis, M6 and M9, exhibited about a 1.8 to 2.24 times increase in flexural toughness, respectively, compared to the mix reinforced with 0.5% of MSF. Moreover, the mix reinforced with a hybrid blend of fibers M8 (0.5% of RTSF and 0.25% of RPF), outperformed the flexural toughness of M2 by 60%, and achieved a flexural toughness of 57% and 49% of the toughness of M6 and M9, respectively. Meanwhile, the mix reinforced with a hybrid blend of fibers M10 (0.5% of RTSF and 0.5% of RPF), outperformed the flexural toughness of M2 by 146%, and achieved a flexural toughness of 88% and 76% of the toughness of M6 and M9, respectively. The superior flexural toughness of M10 among all mixes could be due to the homogenous distribution of the fibers within the mortar matrix and the dual action of the hybrid blend of RTSF and RPF at the micro and macro structural levels, respectively. Despite the differences in the properties of the fibers, mix composition, and test conditions, the flexural toughness of the recycled fiber blends reported in this investigation compare favorably well with some of the test results reported in the literature in this field [5,8,32,33].

It should be noted that the flexural toughness of M10 reinforced with a hybrid blend of recycled plastic and tire steel waste fibers could be enhanced further to match or exceed the flexural toughness of M9 reinforced with a similar dosage of manufactured steel fibers. This can be achieved by using a special processing technique for sorting and cleaning the surfaces of RTSF from rubber remnants and thus obtain recycled fibers with uniform properties and better surface characteristics. Moreover, regardless of the small reduction in the performance of M10 compared to M9, it is believed that an echo friendly material that is recycled locally at a relatively lower cost would justify the slight reduction in its performance compared to commercially produced recycled steel fibers. It is worth

mentioning herein that the local cost of the manufactured steel fibers is relatively high, at USD 2900/ton, compared to the cost of post-consumer tire waste of USD 347/ton. This represents about an 88% reduction in the total cost of manufactured steel fibers. Moreover, besides the positive impact on the environment, the test results of the current investigation are expected to boost the application of recycled waste fibers in concrete industry. Practical applications of interest include pavement applications, runway overlays, tunnel linings, reinforced concrete slabs, slabs on grade, and the structural repair of concrete structures [5,34–36].

4. Conclusions

Based on the experimental test results and discussions presented in this investigation, the following conclusions could be drawn:

(1) Echo-friendly, unsorted, recycled fibers extracted from post-consumer tire steel and plastic wastes could be recommended for enhancing the flexural performance of cement-based composites at a lesser cost.
(2) All the mortar mixes reinforced with hybrid blends of recycled fibers exhibited flexural behavior characterized by the occurrence of numerous fine cracks within the middle third of the specimens tested, followed by the formation of a major single crack at failure.
(3) Both types of recycled fibers, RTSF and RPF, were effective in sustaining relatively high stress levels after the peak load. This is due to the crack arresting capability and gradual pullout of these fibers from the mortar matrix after cracking.
(4) At the same total dosage of fibers, the flexural toughness of the mortar mix reinforced with a hybrid blend of fibers M10 (0.5% of RTSF and 0.5% of RPF), outperformed the flexural toughness of M2 by 146%, and achieved a flexural toughness of 88%, and 76% of the toughness of M6 and M9, respectively.
(5) At the same total dosage of fibers, the mortar mixes reinforced with MSF showed up to a 6% drop in post-cracking strength at 2 mm deflection, compared to the post-cracking strength at 0.5 mm deflection, whereas the mixes reinforced with hybrid blends of RTSF and RPF showed up to a 29% drop in post-cracking strength at the same deflection limits.
(6) Among the recycled fiber blends investigated, the mix containing 0.5% RTSF and 0.5% RPF (on volume basis) exhibited relatively superior flexural characteristics compared to the mixes reinforced with the same dosage of manufactured steel fibers (MSF) only.

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References

1. Naaman, A.E. Engineered steel fibers with optimal properties for reinforcement of cement composites. *J. Adv. Concr. Technol.* **2003**, *1*, 241–252. [CrossRef]
2. Farooq, M.; Bhutta, A.; Banthia, N. Tensile performance of eco-friendly ductile geopolymer composites (EDGC) incorporating different micro-fibers. *Cem. Concr. Compos.* **2019**, *103*, 183–192. [CrossRef]
3. Aiello, M.A.; Leuzzi, F.; Centonze, G.; Maffezzoli, A. Use of steel fibres recovered from waste tyres as reinforcement in concrete: Pull-out behaviour, compressive and flexural strength. *Waste Manag.* **2009**, *29*, 1960–1970. [CrossRef]
4. Wang, C.; Yang, C.; Liu, F.; Wan, C.; Pu, X. Preparation of ultra-high performance concrete with common technology and materials. *Cem. Concr. Compos.* **2012**, *34*, 538–544.
5. Hu, H.; Papastergiou, P.; Angelakopoulos, H.; Guadagnini, M.; Pilakoutas, K. Mechanical properties of SFRC using blended recycled tyre steel cords (RTSC) and recycled tyre steel fibres (RTSF). *Constr. Build. Mater.* **2018**, *187*, 553–564. [CrossRef]
6. Alsaif, A.; Alharbi, Y.R. Strength, durability and shrinkage behaviours of steel fiber reinforced rubberized concrete. *Constr. Build. Mater.* **2022**, *345*, 128–295. [CrossRef]
7. Graeff, A.G.; Pilakoutas, K.; Neocleous, K.; Peres, M.V.N. Fatigue resistance and cracking mechanism of concrete pavements reinforced with recycled steel fibres recovered from post-consumer tyres. *Eng. Struct.* **2012**, *45*, 385–395. [CrossRef]
8. Al-Tulaian, B.; Al-Shannag, M.; Al-Hozaimy, A. Recycled plastic waste fibers for reinforcing Portland cement mortar. *Constr. Build. Mater.* **2016**, *127*, 102–110. [CrossRef]
9. Randjbaran, E.; Majid, D.L.; Zahari, R.; Sultan, M.T. Mazlan, N. Impacts of volume of carbon nanotubes on bending for carbon-Kevlar hybrid fabrics. *J. Appl. Comput. Mech.* **2021**, *7*, 839–848.
10. Attari, N.; Amziane, S.; Chemrouk, M. Flexural strengthening of concrete beams using CFRP, GFRP and hybrid FRP sheets. *Constr. Build. Mater.* **2012**, *37*, 746–757. [CrossRef]
11. Alhozaimy, A.; Shannag, M. Performance of concretes reinforced with recycled plastic fibres. *Mag. Concr. Res.* **2009**, *61*, 293–298. [CrossRef]
12. Isa, M.; Pilakoutas, K.; Guadagnini, M.; Angelakopoulos, H. Mechanical performance of affordable and eco-efficient ultra-high performance concrete (UHPC) containing recycled tyre steel fibres. *Constr. Build. Mater.* **2020**, *255*, 119–272. [CrossRef]
13. Sivakumar, A.; Santhanam, M. Mechanical properties of high strength concrete reinforced with metallic and non-metallic fibres. *Cem. Concr. Compos.* **2007**, *29*, 603–608. [CrossRef]
14. Naser, M.H.; Naser, F.H.; Dhahir, M.K. Tensile behavior of fiber reinforced cement mortar using wastes of electrical connections wires and galvanized binding wires. *Constr. Build. Mater.* **2020**, *264*, 120–244. [CrossRef]
15. Caggiano, A.; Folino, P.; Lima, C.; Martinelli, E.; Pepe, M. On the mechanical response of hybrid fiber reinforced concrete with recycled and industrial steel fibers. *Constr. Build. Mater.* **2017**, *147*, 286–295. [CrossRef]
16. Graeff, A. Long Term Performance of Recycled Steel Fibre Reinforced Concrete for Pavement Applications. Ph.D. Thesis, The University of Sheffield, Sheffield, UK, April 2011.
17. Hu, H.; Papastergiou, P.; Angelakopoulos, H.; Guadagnini, M.; Pilakoutas, K. Mechanical properties of SFRC using blended manufactured and recycled tyre steel fibres. *Constr. Build. Materials.* **2018**, *163*, 376–389. [CrossRef]
18. Younis, K.H.; Pilakoutas, K.; Guadagnini, M.; Angelakopoulos, H. Feasibility of Using Recycled Steel Fibres To Enhance the Behaviour of Recycled Aggregate Concrete. In Proceedings of the Fibre Reinforced Concrete: From Design to Structural Applications, Montreal, QC, Canada, 24–25 July 2014; pp. 598–608. Available online: https://www.researchgate.net/publication/296847629_Feasibility_of_Using_Recycled_Steel_Fibres_To_Enhance_the_Behaviour_of_Recycled_Aggregate_Concrete (accessed on 13 October 2022).
19. Al-Kamyani, Z.; Figueiredo, F.P.; Hu, H.; Guadagnini, M.; Pilakoutas, K. Shrinkage and flexural behaviour of free and restrained hybrid steel fibre reinforced concrete. *Constr. Build. Mater.* **2018**, *189*, 1007–1018. [CrossRef]
20. Banthia, N.; Soleimani, S.M. Flexural response of hybrid fiber-reinforced cementitious composites. *ACI Mater. J.* **2005**, *102*, 382.
21. Li, Z.X.; Li, C.H.; Shi, Y.D.; Zhou, X.J. Experimental investigation on mechanical properties of Hybrid Fibre Reinforced Concrete. *Constr. Build. Mater.* **2017**, *157*, 930–942. [CrossRef]
22. *ASTM C150/C150M-22*; Standard Specification for Portland Cement. ASTM International: West Conshohocken, PA, USA, 2022. Available online: https://www.astm.org/c0150-07.html (accessed on 13 October 2022).
23. *EN 1097-6*; Tests for Mechanical and Physical Properties of Aggregates, Determination of Particle Density and Water Absorption. BSI: London, UK, 2013. Available online: https://standards.iteh.ai/catalog/standards/cen/7eb55eec-cf2d-449c-bdf5-45534b169181/en-1097-6-2022 (accessed on 13 October 2022).
24. *EN 1097-3*; Tests for Mechanical and Physical Properties of Aggregates, Determination of Loose Bulk Density and Voids. BSI: London, UK, 1998. Available online: https://standards.iteh.ai/catalog/standards/cen/1e043df4-6c8e-423c-9ba7-3bcb715a6cf3/en-1097-3-1998 (accessed on 17 October 2022).
25. *C136/C136M-19*; Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates. ASTM International: West Conshohocken, PA, USA, 2019. Available online: https://www.astm.org/c0136-06.html (accessed on 13 October 2022).
26. DCP. Technical Data Sheet-Dramix 3D 80/60BG. 2022. [Cited 10/10/2022]. Available online: https://dcp.bg/index.php?lng=en&p=prod43 (accessed on 21 September 2022).
27. UFSD. *Thin Wire Reinforcement for Concrete*; British Patent Application: Sheffield, UK, 2001.

28. *ASTM C109/C109M-20*; Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50-mm] Cube Specimens). ASTM International: West Conshohocken, PA, USA, 2020. Available online: https://www.astm.org/c0109_c0109m-20.html (accessed on 13 October 2022).
29. *ASTM C1437-20*; Standard Test Method for Flow of Hydraulic Cement Mortar. ASTM International: West Conshohocken, PA, USA, 2020. Available online: https://www.astm.org/c1437-15.html (accessed on 13 October 2022).
30. *EN 12390-3*; Part3: Compressive Strength of Test Specimens. BSI: London, UK, 2019. Available online: https://knowledge.bsigroup.com/products/testing-hardened-concrete-compressive-strength-of-test-specimens-1/tracked-changes (accessed on 13 October 2022).
31. *ASTM C1609/C1609M-19a*; Standard Test Method for Flexural Performance of Fiber-Reinforced Concrete (Using Beam With Third-Point Loading). ASTM International: West Conshohocken, PA, USA, 2019. Available online: https://www.astm.org/c1609_c1609m-12.html (accessed on 13 October 2022).
32. Wang, Y.; Wu, H.; Li, V.C. Concrete reinforcement with recycled fibers. *J. Mater. Civ. Eng.* **2000**, *12*, 314–319. [CrossRef]
33. Naaman, A.E.; Garcia, S.; Korkmaz, M.; Li, V.C. Investigation of the use of carpet waste PP fibers in concrete. In *Materials for the New Millennium*; ASCE, 1996; Available online: https://cedb.asce.org/CEDBsearch/record.jsp?dockey=0102945 (accessed on 13 October 2022).
34. Alsaif, A.; Koutas, L.; Bernal, S.A.; Guadagnini, M.; Pilakoutas, K. Mechanical performance of steel fibre reinforced rubberised concrete for flexible concrete pavements. *Constr. Build. Mater.* **2018**, *172*, 533–543. [CrossRef]
35. Alsaif, A.; Garciaa, R.; Figueiredoa, F.P.; Neocleousb, K.; Christofeb, A.; Guadagnini, M.; Pilakoutas, K. Fatigue Performance of Flexible Steel Fibre Reinforced Rubberised Concrete Pavement. *Eng. Struct.* **2019**, *193*, 170–183. [CrossRef]
36. Al-musawi, H.; Huang, H.; Di Benedetti, M.; Guadagnini, M.; Pilakoutas, K. Effect of shrinkage on rapid hardening plain and recycled steel fibre concrete overlays. *Cem. Concr. Compos.* **2022**, *125*, 104246. [CrossRef]