Development of Portland Cement Mortars Reinforced with Hybrid Blends of Recycled Waste Fibers

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Abstract: The flexural performance of Portland cement mortars reinforced with recycled fibres was tested in the lab. Finding the ideal combination of unsorted recycled post-consumer tyre steel fibres (RTSF) and recycled plastic fibres (RPF) was the goal in order to improve the flexural behaviour and ductility of composites made of cement. Ten mortar mixtures with different RTSF and RPF compositions were cast and put through an ASTM displacement-controlled four-point bending test. According to test results, recycled fiber-reinforced mortar mixes met ASTM flow standards and had a flexural response and toughness comparable to those of mixes with the same fibre dose but solely contained manufactured steel fibres (MSF). In comparison to mixtures reinforced with the same dose of MSF alone, the mix comprising 0.5% RTSF and 0.5% RPF (on a volume basis) had considerably improved flexural properties. Additionally, at 0.5% RTSF and 0.5% RPF (on a volume basis), the beneficial synergistic effect of fibre blends on the post-cracking strength and flexural toughness was evident. Recycled fibre blends of RTSF and RPF might therefore be suggested as an echo-friendly material for improving the flexural performance of cement-based composites at a lower cost.
Keywords: recycled tires steel fibers; recycled plastic fibers; steel fiber-reinforced mortar; hybrid steel fiber reinforcement; flexural pot-peak behavior; flexural toughness

1. Introduction

To green the construction sector and achieve the sustainability targets established by the UN, real environmental impact reduction solutions must be identified. Post-consumer tyres and plastic beverage containers amount to millions of tonnes of annual global waste. It is essential to discover suitable methods for reducing their environmental impact since landfill locations are fast running out and the cost of disposing of solid waste is rising. Recycling has a great deal of potential to transform waste resources into useful goods. Recently, there has been a rise in curiosity about the possibility of using recycled waste products instead of synthetic fibres to make fiber-reinforced concrete (FRC). Concrete is the most widely used construction material in the world, therefore the possibility of employing industrial waste items to improve its performance has drawn interest from practitioners in both developed and developing nations. Numerous studies have established that recycled fibres may be used in reinforced concrete and are less expensive than virgin fibres [1–8].

Engineers have access to an exceptional mix of qualities, such as strength, ductility, and durability, using fiber-reinforced cement-based composites. To further improve the performance of cement-based composites, different types of fibres, both metallic and non-metallic, can be mixed in a certain ratio. The flexural strength of reinforced carbon-Kevlar hybrid textiles subjected to impact damage was examined by Randjbaran, E. et al. [9] and contrasted with the strength of the intact specimen. The test findings show that the flexural strength and toughness of the clean epoxy composite laminate samples were higher than those of the system reinforced with 1.5% carbon nanotubes, CNT. Additionally, the reinforced carbon-Kevlar hybrid textiles laminated reinforced with 1.5% CNT by volume showed a decrease in the flexural modulus and the maximum flexural stress following ballistic impact damage and fibre fracture, across a range of 0 to 40 degrees.

N. Attari et al. [10] investigated the effectiveness of fiber-reinforced polymer (FRP) fabric (glass-carbon) external strengthening systems for reinforced concrete beams. To strengthen reinforced concrete beams in flexure, they suggested a variety of strengthening techniques, such as the use of separate unidirectional glass and carbon fibres with some U-anchorages or bidirectional glass-carbon fibre hybrid fabric. The usage of twin layer glass-carbon FRP fabric was the most successful strategy among those examined for reinforcing reinforced concrete buildings. With sufficient mixing time and great workability, Farooq et al. [2] sought to create a fiber-reinforced geopolymer mortar utilising 1%, 2%, and 3% volume fractions of fibres and natural river sand as a filler. Polyvinyl alcohol (PVA), polypropylene (PP), high strength steel (HSS), and chopped steel wool (CSW) are the fibres under investigation. The performance of eco-friendly ductile geopolymer composites (EDGC) under strain is tested using a number of factors, including the impact of fibre type, solution concentration, and sand content. Both PVA and HSS fibres showed a pseudo-strain hardening response in every instance. Due to the significant elongation of PP fibres before to fracture, a low post-crack bridging tensile strength was seen with PP fibres, although a very high (>4%) tensile strain capacity was found. Multiple characteristics of fiber-reinforced concrete have been improved using techniques that combine different kinds and sizes of discrete fibres [5-8,11-15]. The mechanical characteristics of high-strength concrete reinforced with steel fibres and non-metallic fibres, such as micro polypropylene fibres, polyester fibres, and glass fibres, were studied by Sivakumar and Santhanam [13]. According to their test results, steel and polypropylene fibres worked better together than they did alone.

Naser et al.'s [14] combination of long steel fibres from galvanised binding wires and short copper fibres from electrical connection wire wastes. They discovered that mixing 0.45% copper fibres with 0.1% steel fibres produces the maximum flexural and tensile strengths. In addition, they found that hybridization increased flexural and tensile strengths while also saving money. According to Caggiano et al. [15], a single-fiber composite made up of an equal quantity of commercial and recycled metallic fibres resulted in a 20% improvement in initial fracture strength. Furthermore, at a fibre volume percentage of 1.25%, the ratio of recycled to industrial fibres was equivalent to 70:30, yielding the maximum initial fracture strength. Graeff [16] investigated the viability of employing manufactured steel fibres (MSFs) and recycled tyre steel fibres (RTSFs) for reinforcing roller-compacted concrete (RCC) and steel fiber-reinforced concrete (SFRC) pavements.

According to their research, RTSF concrete responded effectively to RCC's accelerated corrosion and freeze-thaw cycles. Additionally, RTSF slowed the growth of microcracks, although MSFs were more successful in containing macrocracks. MSF and sorted RTSF blends were just two of the hybrid fibre mixtures that Hu et al. [17] examined for their mechanical behaviour. They came to the conclusion that mixtures reinforced with hybrid fibres performed better than mixes reinforced with only one kind of fibre for the same fibre dose. Younis et al. [18] discovered that mixtures having a combination of sorted RTSF and crimped type MSF fibres had greater flexural strength and toughness than mixes containing solely MSF. AL-kamyani et al. [19] looked at how recycled steel fibres from old tyres and produced steel fibres affected the mechanical characteristics of steel fiber-reinforced concrete (SFRC). According to their test results, hybrid mixes incorporating RTSF had mechanical qualities that were equivalent to those of hybrid mixes containing solely MSF in the same doses. Additionally, test findings show a beneficial synergistic impact for hybrid mixtures including only 10 kg/m3 of RTSF. Recycled tyre steel fibres (RTSF) and recycled tyre steel cords (RTSC) hybrid mixes were used in Hu et al.'s [5] study of the flexural behaviour of steel fiber-reinforced concrete (SFRC). According to their test results, the post-cracking strength of recycled-fiber mixes was around twice as high as the mixes for the same dosage of fibres. Further advancements in the flexural behaviour of concrete reinforced with greater RTSC contents were also noted. The effects of a hybrid system of steel fibres on the tensile strength, tensile durability, and shrinkage of rubberized concrete were the subject of an experimental examination by Alsaif and Alharbi [6]. Their test results suggest that employing 40 kg/m3 of steel fibres along with 20% of ground rubber might result in rubberized concrete with qualities similar to those of regular concrete. Laboratory tests were done on the effects of recycled plastic fibres on the flexural behaviour and plastic shrinkage of Portland cement mortar by Al-Tulian et al. [8], Alhuzaimy and Alshannag [11], and others. According to their test findings, flexural behaviour has been improved, and plastic shrinkage fractures have significantly decreased. On the hybridization of recycled fibres with a volume proportion less than 1.5% in the concrete industry, there are few experimental data in the literature [20]. According to some studies, combining many types of fibres at once can significantly enhance the mechanical behaviour of cement-based composites.

This is primarily because the joined fibres play an important part in improving the composite's performance at the micro, meso, and macro structural levels. The goal of this inquiry is to develop an eco-friendly fiber-concrete blend that meets the demands of cement-based mortar for workability, strength, and ductility. The main goal of the current research is to create a hybrid system of recycled fibres, where one type has high strength and stiffness for improving ultimate and first crack strengths, and the other type has high ductility for improving toughness and post-cracking strengths. The uniqueness of the current method focuses on combining the high strain capacity and flexibility of recycled plastic fibres (RPF) with the stiffness and strength of echo-friendly recycled tyre steel fibres (RTSF) to improve the performance of cement-based composites. The hybrid system proposed in the current inquiry has undergone testing, and the authors are reporting its first-ever test findings. The combined impacts of recycled plastic strands and tyre steel wastes on the behaviour of cement-based composites have not been studied in the literature. The volume fractions of RTSF, RPF, and manufactured steel fibres (MSF) will range from 0.25% to 1.0%. Flow, compressive and flexural strengths, and ductility are among the parameters examined.

2. Experimental Program

The goal of the experimental programme was to examine how various recycled fibre types affected the compressive and flexural strengths of high-strength Portland cement mortar. A total of 40 100 x 100 x 100 mm cube specimens were cast to test the compressive strength, 30 100 x 100 x 500 mm prism specimens were cast to test the flexural strength, and 10 semi cone specimens were made to test the flow of new mortar.

2.1. Materials Properties

White silica sand with a specific gravity of 2.65, tap water, and Portland cement, type I, meeting ASTM C150 requirements were the materials utilised.

The fibres utilised comprised unsorted recovered post-consumer tyre steel fibres (RTSFs), commercially available manufactured hooked-end steel fibres (MSFs) and unsorted recycled plastic fibres (RPFs). The RPFs were made by slicing thin strands of distorted plastic sheeting and then trimming it to the required lengths. After mechanically shredding the used tyres, electromagnets were used to separate the steel fibres to produce the RTSFs.

2.2. Mortar Matrix

To meet the requirements of ASTM C1437-20 for a standard flow of 110 5% and a 28-day compressive strength of 50 MPa, a total of ten mortar mixes were created in accordance with ASTM C10 standards. In terms of water, cement, and white silica sand, the ratios were 0.5:1.0:2.0. The mortar was mixed in a tilting drum mixer with a 0.15 m3 capacity. The mortar mixes were gradually mixed with a variety of fibre kinds and contents, such as recycled plastic and steel fibres and manufactured and post-consumer steel fibres. This was done to guarantee that the fibres were distributed randomly throughout the matrix and prevent fibre lumping.

2.3. Casting and Curing

The cube and prism specimens were crushed on a vibrating table after being cast in two layers. All samples were stored in the lab setting for 24 hours with wet hessian covering them. After being demolded and curing in water for 28 days, they were then ready for testing.

2.4. Test Methods

The flow of new mortar, compressive strength, flexural strength, and flexural toughness were among the tests carried out in this study. According to ASTM C14372, the flow was calculated as a percentage increase in the average base diameter of the table. As directed by the ASTM C1437-20 standard, the average of four diameter measurements taken at about equal intervals for each mix was calculated. Following the BS EN 12390-3 standard, the compressive strength at 28 days was evaluated on 100 mm cubes. A compression machine with a 3000 Kn capacity and a 0.4 Mpa/s speed was used for the experiments. For each blend, the findings are shown as an average of four specimens. Using prisms of 100 mm by 100 mm by 500 mm, the flexural strength was evaluated after 28 days in accordance with ASTM C1609. Using a displacement control servo-hydraulic actuator with a 3000 Kn capacity and a rate of 0.075 mm/min, a four-point bending test was performed. Two LVDTs (linear variable differential transducers) were positioned on either side of the yoke to monitor mid-span deflections. For each blend, the three prisms' average value was noted. The calculation of toughness was done in accordance with ASTM C1609 guidelines.

3. Discussion of Test Results

3.1. Flow of Mortar

For the control mix, M1, it took several trial mixes to get the typical ASTM C1437-20 flow of 110 5%. The measured flow diameters of the tested fiber-reinforced mortar mixtures are reported. Four diameter measurements are averaged out to create each flow value. As can be observed, the majority of the fiber-reinforced mortar mixes flowed within the range allowed by ASTM C1437-20 and was nearly identical to that of the control mix. This is due to the cement mortar mixture's homogeneous characteristics as well as the usage of smaller fibre doses per unit volume. Furthermore, all mixes reinforced with hybrid RTSF/RPF blends (M5, M7, and M10) showed flow characteristics that were comparable to those of mixes reinforced with MSF, with the exception of M8, which displayed a 2% reduction in flow. This decrease is relatively little and falls within the flow table apparatus's claimed testing error range of 2 percent (ASTM C1437-20 standard).

3.2. Compressive Strength of Mortar

The tests for compressive strength were carried out for quality assurance. The test findings for four cube specimens at 28 days are represented as the average ultimate compressive strength. The mortar mixes reinforced with hybrid blends of recycled fibres, M5, M7, M8, and M10, had compressive strengths that were somewhat comparable to those of the mortar mixes reinforced with made steel fibres, M2, M6, and M9. However, compared to control mix M1, several of the fiber-reinforced mixes, M2, M3, M8, M9, and M10, displayed a 3% to 10% reduction in compressive strength. This could be as a result of fibre lumping brought on by the uneven distribution of recycled fibres in these mixtures. The ultimate compressive strengths of certain mixtures decreased slightly, although they still fell within the range of high-strength mortar. Additionally, of all the mixes examined, M7 had the highest compressive strength overall. This mix had a hybrid blend of 0.25% RTSF and 0.50% RPF on a volume basis. As anticipated, it is anticipated that the impacts of the fibres on compressive strength would be less substantial than those on flexural and tensile strengths. This is consistent with test results that some other researchers [1,8] have published in the literature.

3.3. Flexural Behavior of Mortar

Flexural strength, flexural toughness, and cracking pattern were all examined in relation to the flexural behaviour of the fiber-reinforced mortar mixtures. The whole bending stress deflection response for all the mixtures under investigation. Using specialised software, the average flexural response of the prisms under test was also calculated and presented on the same graphs for comparison. In addition, The averages of the flexural properties and the accompanying standard deviations for each of the examined specimens. The residual flexural stresses at 0.5 mm and 2.0

mm deflections as well as the averages of the peak flexural stresses. Following the recommended procedure, the flexural toughness was also estimated at 2 mm deflection.

3.3.1. Flexural Strength

For certain of the FRCM mixes under investigation, M2, M4, M7, and M8, the bending stress deflection curves are composed of a linear elastic component up to the commencement of cracking, a nonlinear part up to peak stress, a rapid reduction in peak stress followed by a stable part till failure. However, the bending stress deflection curves for several mixes, M3, M5, M6, M9, and M10, are nonlinear up to the peak stress, linear elastic up to the commencement of cracking, and stable with a steady stress decline till failure. The more uniform distribution and alignment of the fibres within the mortar matrix, as well as the dual action of the hybrid blends of recycled plastic and tyre steel fibres at pre-cracking and post-cracking levels, may be responsible for the superior post-peak response of mixes M3, M5, M6, M9, and M10. Typical prisms are sliced through to show the various fibre distribution. This part was obtained near the principal fracture zone. The flexural response provided in this inquiry matches rather well with some of the test findings reported in the literature [8,20], despite variations in the mechanical and geometrical characteristics of the fibres and variations in the composition of the mortar mix. For the majority of the fiber-reinforced cement mortar mixes (FRCM) studied, the test findings show a significant increase in the peak flexural strength when compared to control mixes without fibres. This is a result of the fibres' crucial function in bridging microcracks and, separately, suppressing the formation of macrocracks before and after the start of cracking.

3.3.2. Flexural Toughness

Fiber-reinforced concrete differs from ordinary concrete in that it can absorb a lot of energy, has larger peak deflections, can sustain massive deformations, and has a better fracture arresting mechanism. Fiber-reinforced concrete is widely used in many structural applications because of these qualities, which are typically defined in terms of toughness. According to ASTM C1609 guidelines, the flexural toughness of each mortar mix used in this experiment was calculated as the area under the stress deflection curve at a given deflection. By dividing the prism's span by 150, a deflection limit of 2 mm was established for all of the examined specimens. According to the test findings, the fiber-reinforced mixtures' flexural toughness has significantly increased when compared to the mix reinforced with 0.5% of MSF, the reinforced mixes, M6 and M9, showed roughly a 1.8 to 2.24 times increase in flexural toughness, respectively. Additionally, the hybrid fibre blend M8 used to reinforce the mix surpassed M2's flexural toughness by 60% and outperformed M6's and M9's respective toughnesses by 57% and 49%, respectively. The hybrid fibre mix M10, which contains 0.5% RTSF and 0.5% RPF, surpassed M2 in terms of flexural toughness by 146% and exceeded M6 and M9 in terms of flexural toughness by 88% and 76%, respectively. The homogeneous distribution of the fibres inside the mortar matrix and the dual action of the hybrid blend of RTSF and RPF at the micro and macro structural levels, respectively, may be the causes of M10's higher flexural toughness among all mixtures. The flexural toughness of the recycled fibre blends described in this inquiry compares favourably well with some of the test findings reported in the literature in this subject [5,8], despite the changes in the characteristics of the fibres, mix composition, and test circumstances.

It should be highlighted that the M10 reinforced with a hybrid blend of recycled plastic and tyre steel waste fibres should be further improved to meet or exceed the M9 reinforced with a comparable dose of produced steel fibres in terms of flexural toughness. This may be done by adopting a unique processing method to separate and clean the surfaces of RTSF from rubber scraps, resulting in recycled fibres with superior surface features and more uniform qualities. Furthermore, it is thought that an echo-friendly material that is locally recycled at a comparatively cheaper cost would justify the modest drop in its performance compared to commercially manufactured recycled steel fibres, regardless of the slight reduction in performance of M10 compared to M9. It is important to note that, when compared to the cost of post-consumer tyre waste, which is USD 347/ton, the local cost of made steel fibres is rather high at USD 2900/ton. The overall cost of steel fibre production has been reduced by around 88% as a result. In addition to having a favourable effect on the environment, it is anticipated that the test findings of the current inquiry will encourage the use of recycled waste fibres in the concrete industry. Pavement applications, runway overlays, tunnel linings, reinforced concrete slabs, slabs on grade, and structural concrete structure restoration are examples of useful practical uses [5].

4. Conclusions

The following conclusions might be taken from the experimental test findings and conversations included in this investigation:

1. The flexural performance of cement-based composites might be improved at a lower cost by using echo-friendly, unsorted, recycled fibres derived from post-consumer tyre steel and plastic wastes.
2. All of the mortar mixtures reinforced with hybrid blends of recycled fibres had flexural behaviour that was characterised by the appearance of a large number of little fractures in the middle third of the specimens tested, followed by the development of a single, big crack, and finally collapse.
3. After the peak load, both RTSF and RPF recycled fibres were capable of withstanding reasonably high stress levels. This is as a result of the fibres' capacity to stop cracks and their slow removal from the mortar matrix following.
4. At the same total fibre dosage, the hybrid fibre blend M10 (0.5% RTSF and 0.5% RPF) reinforced mortar mix surpassed M2's flexural toughness by 146% and obtained flexural toughness values of 88% and 76% of M6 and M9, respectively.
5. In comparison to the post-cracking strength at 0.5 mm deflection, the mortar mixes reinforced with MSF showed a drop in post-cracking strength of up to 6% at 2 mm deflection, whereas the mixes reinforced with hybrid blends of RTSF and RPF showed a drop in post-cracking strength of up to 29% at the same deflection limits.
6. In comparison to mixes reinforced with the same dose of manufactured steel fibres (MSF) alone, the mix including 0.5% RTSF and 0.5% RPF (on a volume basis) showed considerably better flexural properties.

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