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Experimental Characterization of a Functionally Graded Composite Using Recycled Steel Fiber

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Abstract

Many industries have recently focused on cost-effective materials with good mechanical properties. Steel fiber reinforced cementitious composites have proven their mechanical performance in industrial and structural components. The concept of recycled fiber-reinforced FGM is used as an alternative construction material, which can be one of the proposed cost-effective solutions. To achieve these objectives, an experimental program has been developed. A cementitious composite based on local materials was strengthened in two designs; one strengthened over the entire cross-section and the other strengthened only in the tensile zone. We also substituted a functional gradient material reinforced with recycled fibers considering the following volume fractions: 0, 0.5, 1, and 1.5%. This paper investigates the feasibility of using recycled fibers from industrial waste from steel wool manufacturing as reinforcement. We also characterized their mechanical properties using ultrasonic pulse velocity, compressive strength, flexural tensile strength, and shear strength. The results show that the corrugated recycled fibers are the ideal choice to increase the mechanical performance of the reinforced composite, including the improvement of flexural and shear behaviors. Therefore, the investigated FGC could be a valuable tool to optimize the design process in various structural applications and make the production of mechanically and environmentally economical composites possible.

Keywords: Recycled Steel Fibers; Reinforced Cementitious Composites; Mechanical Performance; Functionally Graded.

1. Introduction

One of the most widely used materials in civil engineering is cement-based composite due to its high quality and favourable cost-durability ratio. Nevertheless, it is a material with disadvantages such as brittleness and low tensile strength [1, 2]. As a result, it has become widely used in structures such as rigid pavements and precast elements. The tensile strength of the cementitious composite is relatively lower than its compressive strength [3]. In order to resolve this issue, fibers are used as reinforcement in the matrix. The method adds different types and amounts of fibers to the composite formulation. Fiber-reinforced cementitious composite (FRCC) was one of the first contemporary materials used in structures [4]. The first fibers designed to reinforce cementitious composites appeared in the early twentieth century. The incorporation of steel fibers into the industry began over 50 years ago, and metal fiber-reinforced cementitious composite (MFC) is a composite that has proven to be a competitive material for many types of structures.

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Over the past two decades, a large amount of research has been conducted on (CCRFM) [5–7]. Several studies have concluded that metal fibers improve the mechanical response and can partially or entirely replace traditional reinforcement in some cases.

Many benefits can be achieved by incorporating steel fibers into the cementitious matrix. These include preventing unexpected failure, improving fracture energy, and reducing shrinkage [8, 9]. On the other hand, some researchers claim that adding metal fibers to the cementitious composite does not affect its compressive strength or elastic modulus. Khayat et al. (2014) [10] and Zeyad (2019) [11] claim that the fibers significantly impact the strength of the cementitious matrix. According to Pająk and Ponikiewski (2013) [12], the global market for steel fibers is estimated to be more than 25,000 tons sold each month and is growing at about 1.6% each month. Steel fibers with deformed ends, treated surfaces, twists, grooves, and hooks make up most of the market supply [13]. Many major manufacturers of engineered steel fibers are currently operating worldwide [14]. They offer different steel fibers with distinct geometric shapes, diameters, and surface treatments [15].

According to some studies, the fresh and hardened qualities of the concrete mix can be directly affected by length, mass, length-to-diameter ratio, shape, and surface roughness. They can also be affected by the properties of the fiber material, including type, volume, and dispersion in the matrix. According to Naaman (2003) [15], the most commonly used steel fibers are those with a round cross-section and a length of between 25 and 60 millimeters. In general, the aspect ratio is less than 100. The fibers are explicitly shaped [16, 17]. Twisted, crimped, flattened, spiked, tapered, and hooked steel fibers have been manufactured over the past 50 years. Steel fibers have a variety of cross-sectional shapes, squares, rectangles, and irregular sections. Threads of various diameters and lengths have been produced recently [18]. Over the years, some geometric fiber shapes have proven simple to manufacture and convenient [19]. Today, a wide selection of fibers of various sizes and shapes can be used for multiple purposes. The five most common steel fiber shapes are traditional straight fibers, fibers with hooks on the ends, wavy fibers (tapered, paddle-shaped, or button-shaped), and deformed metal fibers (indented, etched, or rough-surfaced).

The metal fiber in question has a schematic geometry (Figure 2); other uncommon fiber types are usually made to order for specific customers. Based on the variety offered by the major fiber producers, statistics show that fibers with hooks at the ends lead in total sales and are used in recently published studies [20]. Competing corrugated fibers come in second place. Then straight fibers are the other most popular fiber forms [21]. When it comes to mechanical performance, the geometric qualities of the fiber (defined by its outer surface and the effectiveness of its hook) are essential. From an economic and technical point of view, metallic fibers demonstrate their applicability and popularity in engineering practices. At the same time, the volume of fiber in the composition has a significant impact on the cost of the composite. The sharp increase in steel prices in recent years has inflated fiber prices. In addition, most of the raw materials used in the manufacture of steel fiber are often mined. One solution to reduce costs is to use cheaper and more economical reinforcing and recycled fibers. In addition, it has been stated that the reuse of waste can help save resources and reduce waste disposal in the industries concerned. Therefore, the effective management of industrial waste is essential for environmental sustainability. Recycled tire steel fiber (RSF) can be used as a potential reinforcing fiber to improve the ductility of high-performance concrete [22].

On the other hand, chips resulting from the machining of steel parts are used as reinforcement [23]. At the same time, the inclusion of aluminum scrap can fibers in concrete improves the mechanical properties of the composite [24]. Steel fibers made from recycled materials can protect the environment and decrease pollution. On the other hand, industrial steel fibers can participate in destroying natural resources by releasing CO_2 [25].

Efficiency and economy were inextricably linked to the design approach. This study focused on a waste management strategy of using industrial waste from steel wool manufacturing as reinforcement in the construction sector to reduce landfill disposal, which can be an alternative solution since these fibers are obtained from waste disposed of when manufacturing steel wool manufacturing. Mechanics were the first to use steel shavings for sanding. Then, factories manufacturing cleaning and hygiene products soon took over to produce steel wool cleaning sponges for domestic and industrial use. The principle of mass production was invented in the early 20th century. A twisted steel rod is unwound through metal guiding devices to produce this wire. This device pulls the wire through smaller and smaller dies to make it uniform; spools wind the rod after it passes through the die to avoid tangles. The pulls are repeated each time through the discs, reshaping the basic structure of the steel and doubling its tensile strength. The steel rod is 3.25 mm in diameter when it leaves the production line, making it thinner, more robust, and easier to work. It passes through a chain roller where blades shave two-thirds of the section. As for the remaining part of the wire, it has been made in a corrugated form to be used later as steel fiber in the composite.

This work has developed a combined process for manufacturing fibrous cement composite characterized by factors ensuring economy. This fact is mainly based on two principles: The first one is the concept (FGC), which guarantees the use of less fiber, and thanks to this concept, we thus contribute to the economy. The second principle, which also plays an important role, is the replacement of industrial fibers with recycled fibers to reduce the import factor and valorize, especially the remaining waste from the manufacture of steel wool which was not intended for this use. These factors reduce the consumption of raw materials and reduce costs by revalorizing and reusing the waste of steel wool production as reinforcement. It is in this context that this study aims to explore a new concept of functionally graded cementitious composite (FGCC), inspired by a functionally graded material (FGM) [26] which is usually applied to materials such as metals and ceramics [27]. In the present study, a combination of two materials was proposed: an ordinary cementitious composite (OCC) and a steel fiber reinforced cementitious composite (SFRCC), including the reinforcements only in the most tensile stressed areas, in the lower layer, where they are more effective in terms of resistance to the bending forces introduced by the loads. Therefore, the OCC portion remains above the neutral axis. This allows the same performance to be achieved at a lower cost. This concept aims to combine the advantages of these two composites and create a more efficient composite material [28], offering good properties compared to the ordinary full-depth cementitious composite [29]. The interest of this innovative approach is to ensure optimal performance while reducing expenses. The concept (FGC) optimizes steel fibers in the composite and reduces the cost since steel fibers can account for up to 90% of the price [30].

The main objective of this research is to experimentally evaluate the mechanical performance of standard strength composite mixtures with the incorporation of steel fibers (industrial fibers or recycled fibers from steel wool manufacturing waste) with the following different volume fractions: 0%; 0.5%; 1% and 1.5%, and thus study the effect of their reinforcement on the performance of these mixtures. To this end, various tests such as propagation velocity, compression, bending tension, and shear stress were performed. In addition, the use of reinforcing fibers in two designs, one for the entire section and the other only in the tension zone, is functionally graded (FG). The components are identical for all mixtures, except the volume fraction, fiber type, and reinforced section.

2. Experimental Program

2.1. Properties of the Materials

Cement

The type of cement used for the ordinary composite and the fiber composite is manufactured by the *BISKRIA* cement plant (Algeria) [31]. The characteristics of this type of cement are presented in (Tables 1 and 2).

Table 1. Chemical composition

Chemical composition (%)	
SiO_2	20.83
Al_2O_3	4.13
Fe_2O_3	5.58
CaO	62.91
MgO	1.42
SO_3	2.30
K_2O	0.38
Cl	0.028
Loss on ignition (LOI)	2.04
Insoluble Residue (IR)	0.382

Table 2. Physical properties

Physical properties	
Solid density (kg/m^3)	3150
Bulk density (kg/m^3)	980
Blaine fineness (cm^2/g)	3571.78

Superplasticizer

The superplasticizer used in the test is the high-water reducer type *VISCOCRETE TEMPO 12*. It is a product of the *Algerian Company Sika*, following the standard NF EN 934-2. The characteristics of the superplasticizer are given in (Table 3).

Table 3. The characteristics of the superplasticizer

The characteristics	
Color	Brown
Density (kg/m^3)	1.06
PH	61

Water

The mixing water used in this study is drinking water from the tap, according to the conditions imposed by the NF EN 1008 standard.

Aggregates

Three types of aggregates were used in this study. Two crushed limestone aggregates of sizes (3-8 mm) and (8-15 mm) and the river sand with a diameter of less than 5.0 mm. The gravel density is 2.56 kg/dm^3, 2.72 kg/dm^3 and 2.55kg/dm^3, respectively. The granular distribution of all used aggregates is shown in (Figure 1).

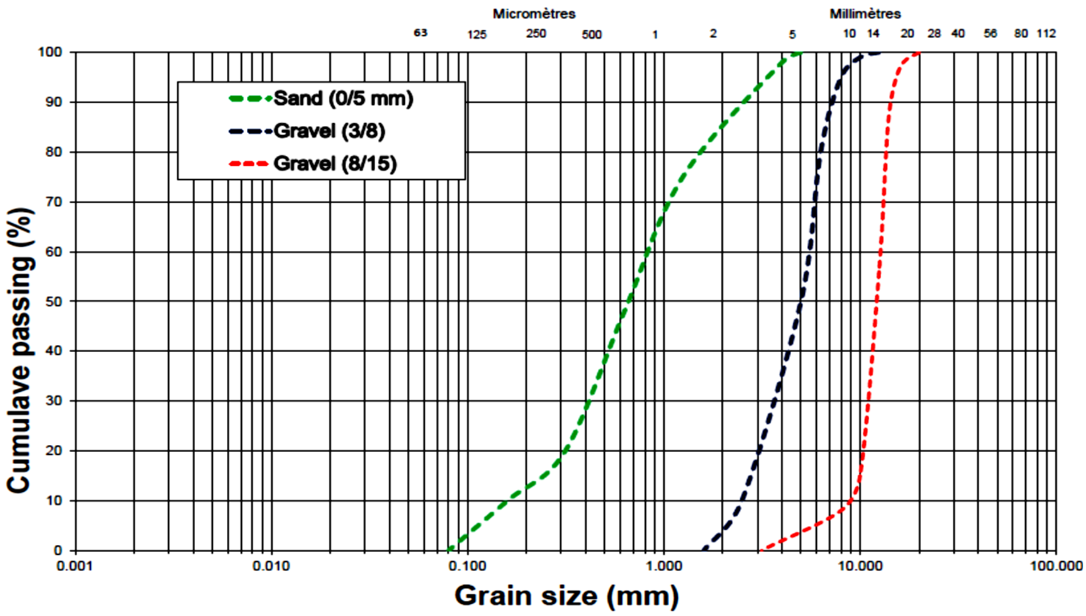
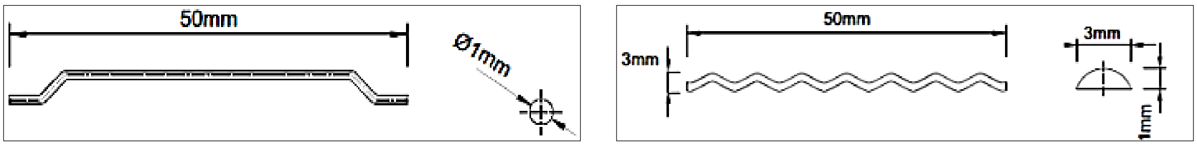


Figure 1. Granulometric curves for the used materials

Steel Fibers

Type-A-Industrial steel fibers used are SIKA FIBRE RL-45/50-BN manufactured from steel wire. They are mechanically anchored with hooked ends. For a circular cross-section, see (Figure 2).



(a) (b)

Figure 2. Schematic geometry of the fibers: (a) Type-A industrial steel fibers; (b) Type-B Recycled steel fibers

Type-B-Recycled steel fibers (Figure 3) show the recycled fibers used before and after manufacturing. These wires are corrugated with a semi-spherical cross-section; their equivalent diameter is calculated according to EN 14889-1 [32]. Table 4 gives an overview of their properties

(a) (b)

Figure 3. (a) Recycled steel fibers (b) sponge of cleaning out of steel wool

Table 4. Geometry and mechanical properties of steel fibers

	Fibre-A-	Fibre-B-
Diameter df (mm)	1.00±0.05	1.86±0.05
Length lf (mm)	50±0.5	50±2
Aspect ratio (lf/df)	50	27.95
Number of fibers per kg	2800	820
Tensile strength (MPa)	1000	600

2.2. Preparation of the Sample

The mixtures selected for this study were made from locally available basic raw materials; the mixing of the composites in the laboratory was carried out in a vertical rotating tank concrete mixer with 100 kg. The dry basic raw materials needed to make the composite with the calculated proportions were added and dry-mixed initially for 2 min before mixing with water. Finally, two-thirds of the water was mixed and continued for another two minutes. The superplasticizer was added after mixing with the remaining water. The whole was mixed until the OCC mixture was homogenized. For mixing (SFRCC), the fibers were dispersed equally.

The two fibers of various shapes with a length equal to 50 mm and different cross-sections are used with the OC. The composite is manufactured with a W/C ratio = 0.47, four-volume fractions of steel fibers were selected: 0.0, 0.50, 1.00, and 1.5 %. The percentage of superplasticizer was adjusted to maintain workability and workability. The composite mix design was determined according to "*Dreux*". Two groups of each fiber type were tested at volume fractions (Vf) of 0.5, 1.0, and 1.5 % (Figure 3, Tables 5, and 6). The following coding was used to identify the mixtures:

The First Two Letters + Third Letter + Number. For example, RCA0.5
FG+ The First Two Letters + Third Letter + number. For instance, FGRCA1.5.

The first two letters stand for the reinforced composite, the third letter stands for the fiber type used, the number stands for the fiber volume fractions (Vf), and (FG) stands for the functionally graded concept.

Table 5. Details of group 01 mixtures with different fibers

	OCC	RCA0.5	RCA1.0	RCA1.5	RCB0.5	RCB1.0	RCB1.5
Volume fractions of fiber-A-(%)	0.00	0.50	1.00	1.50	0.00	0.00	0.00
Volume fractions of fiber -B-(%)	0.00	0.00	0.00	0.00	0.50	1.00	1.50

Table 6. Details of group 02 mixtures with different fibers

Gradient functional	FGRCA0.5	FGRCA1.0	FGRCA1.5	FGRCB0.5	FGRCB1.0	FGRCB1.5
Volume fractions of fiber-A-(%)	0.50	1.00	1.50	0.00	0.00	0.00
Volume fractions of fiber -B-(%)	0.00	0.00	0.00	0.5	1.00	1.50

The first group consists of seven types of cementitious composite reinforced throughout their total volume from the materials in Table 5.

The second group consists of six types of reinforced cementitious composite with the FGC concept. The height of the specimens is decomposed into two layers of equal thickness, the top layer was made from OCC, and the bottom tension layer was made from RFCA or RFCB. All specimens were cast in steel molds. Oil was applied to the molds to facilitate demolding. Mixtures of OCC and RCA0.5 to RCA1.5 and RCB0.5 to RCA1.5 were poured to full depth, compacted, and leveled. For FGRCA0.5 to FGRCA1.5 mixes and FGRCB0.5 to FGRCA1.5 mixes.

Their bottom layer was made from RFCA or RFCB, compacted, and graded to the mid-depth, then the top layer in OCC was filled, compacted, and leveled to maintain the height of the specimen. The time between the beginning and the end of pouring was kept shorter than the initial setting time of the cement used to take into account the experimental operability and ensure the bond strength. The time interval between the fabrications of the layers has also been reported in the work of other researchers [28, 33-35]. Three specimens were cast for each case to take the average. According to NF EN 12390-2 [36], all the molds were covered with plastic sheets and stored 24 hours after casting. After demolding, the specimens should be stored at room temperature in a water tank (about 20° C) until testing.

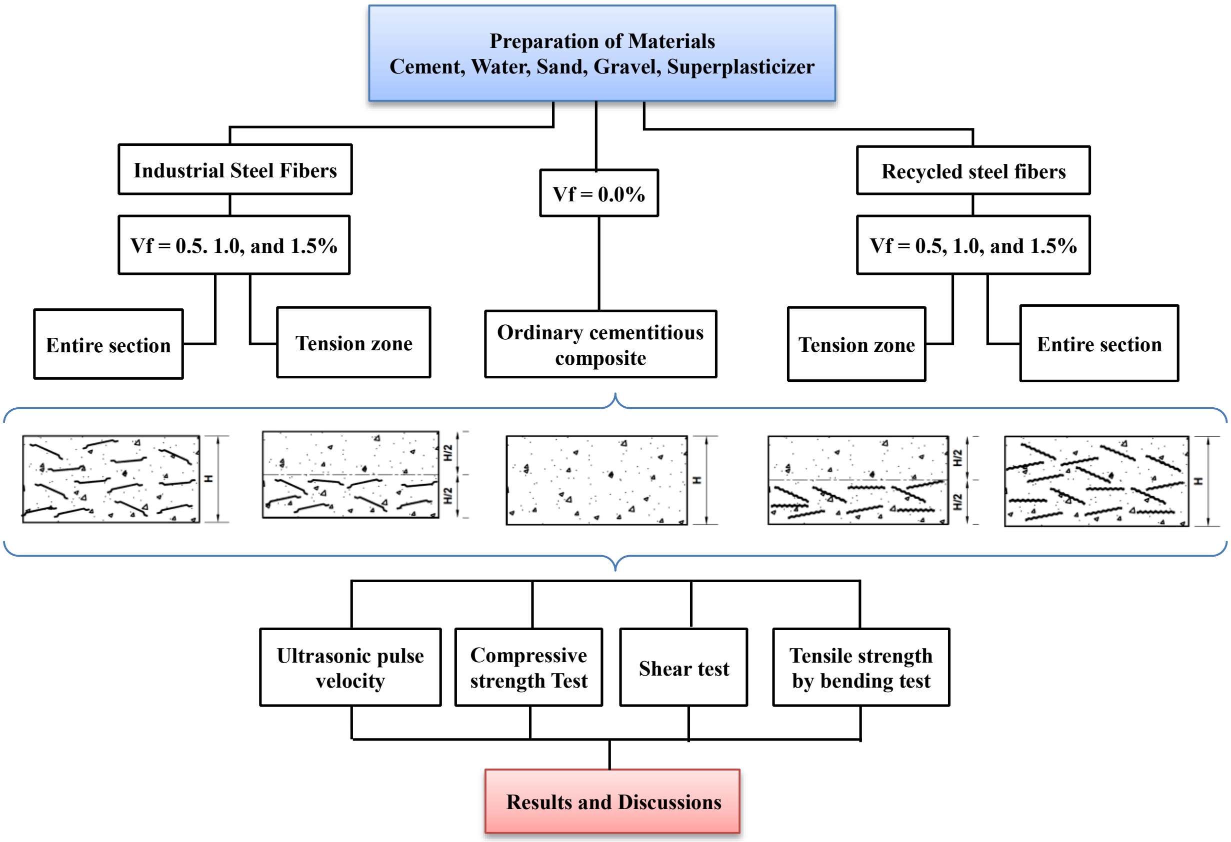


Figure 4. Flow Chart of Experimental Work

3. Test Procedures

3.1. Test of (UPV)

Non-destructive testing of concrete, such as ultrasonic pulse velocity UPV, can reveal the ideal comparison and homogeneity of the composite. This technique is standardized by the NF P 18-418 standard. The ultrasonic pulse has been studied by several researchers [37]. The direct method (placement of the transducer on both sides of the concrete sample) was used in this experiment. Figure 5 describes the procedure used to experiment. The equation used to calculate the pulse velocity, EN 12504-4, 2005 [38], is as follows Equation 1:

$$V = \frac{L}{t} \tag{1}$$

where V is the pulse velocity in km/sec; L is the length of space between the two transducers; and t is the propagation time.

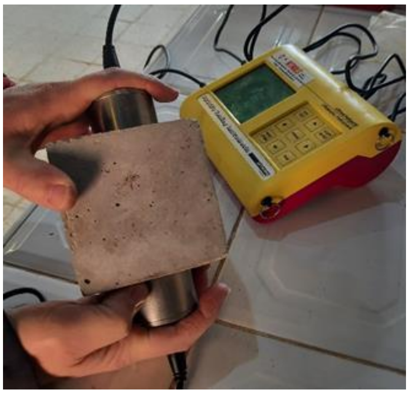


Figure 5. The UPV Test

3.2. Compressive Strength Test

The compressive strength test was performed using 5000 kN compression test equipment by EN 12390-03 [39]. This test was performed using 100 mm wide cubic specimens. Figure 6 shows the setup of the compression test. The test was performed on three specimens of each design (with one of two steel fibers or no fiber). Equation 2 is used to calculate the compressive strength.

$$f_c = \frac{P}{Ac} \quad (2)$$

where, P is the maximum load; and *Ac* is the cross-sectional area of the specimen to which the compressive force is applied.

Figure 6. Test setup compressive strength

3.3. Shear Test

The JSCE-SF6 test of the Japan Society of Civil Engineers was used to perform the shear tests (JSCE) [40]. Figure 7 shows the test setup and its instruments. A 15 mm deep notch was sawn around the specimen to prevent cracking outside the projected fracture shear plane. A CONTROLS AUTOMAX 5 testing machine with a capacity of 5000 kN was used for the tests. Equation 3 is used to calculate the pulse velocity.

$$\tau = \frac{P}{2b_e a_e} \quad (3)$$

where, P is applied shear force; and a_e and b_e are effective width and depth of the specimen.

Figure 7. Test setup of shear strength

3.4. Tensile Strength by Bending Test

This test was carried out by the AFNOR EN 12390-5 standard [41], using the three-point bending principle. Prismatic composite specimens of 400 mm length, 100 mm width, and 100 mm height were supported by two rollers. The force was applied perpendicular to the interface line of the composite specimens. The load is applied evenly and without shock. Figure 8 shows the setup of the flexural test. The flexural tensile strength is calculated using Equation 4.

$$ff = \frac{3PL}{2a^2} \quad (4)$$

where, P is the applied bending force; L is the span length between the support rolls (mm); and a is the lateral dimensions of the specimens (mm).

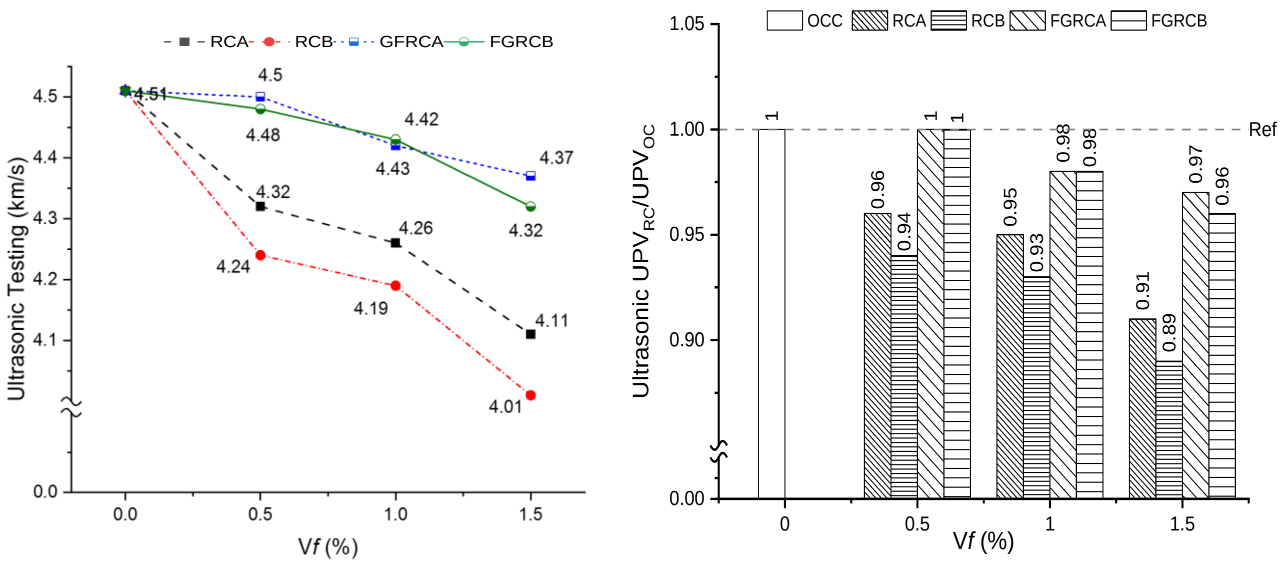
Figure 8. Test setup of flexural strength

4. Test Results and Analysis

4.1. UPV Test Results

The UPV test is well known to be considered a promising initial inspection method for the cementitious matrix. It is used to determine certain properties of the composite and can be evaluated using the UPV pulse velocity measurement, which is used to detect air and cracks [42]. Composites with a high UPV value are generally considered of excellent quality. A composite with a pulse velocity of 3.66 to 4.57 Km/s offers good durability [43]. Several scientists have compared the relationship between ultrasonic velocity and the mechanical properties of the composite [44]. The compressive strength of the composite is classified according to the following values: If the UPV is greater than 4.5 Km/s, it is "excellent"; from 3.5-4.5 Km/s, it is "good"; from 3.0-3.5 Km/s, it is "doubtful"; from 2.0-3.0 Km/s, it is "poor"; and it is "very poor" below 2.0 Km/s [45].

Figure 9-a illustrates the graphic representation of UPV of all mixtures and the effects of volume fraction of the two types of fibers (industrial fibers or recycled fibers) in both designs, one reinforced on the whole section and the other only in the tensile zone, we substitute a functionally graded. The OCC without steel fibers exhibited an average UPV_{OCC} = 4.51 Km/s at 28 days. However, when Vf reached 1.5%, the slightly different downward trend with the various forms of steel fibers was 0.99% and 0.97% for the fully reinforced and functionally graded specimens, respectively. The slope of the recycled fibers is slightly lower. The decrease is limited, and the lowest value of UPV_{RC} is 4.32 Km/s and 4.01 Km/s for FGRCB and RCB, respectively. The highest value of UPV_{RC} is 4.50 Km/s and 4.32 Km/s than that affected by Vf = 0.5% for FGRCA and RCA, respectively. The relationship between the ratio (UPV_{RC}/ UPV_{OCC}) and Vf of the two types of steel fibers is shown in Figure 9-b. The ratio (UPV_{RC}/ UPV_{OCC}) decreased continuously while the Vf increased from 0% to 1.5%.



(a) (b)

Figure 9. Effects of Fibers on UPV: (a) Effect of the Vf of the two types of fibers on UPV; (b) Relationship between UPV_{RC}/UPV_{OCC} and Vf (%)

A decrease in the ratio (UPV_{RC}/ UPV_{OCC}) which reached its maximum value when Vf = 1.5%, is observed to be about 11%, 9%, 4%, and 3% for RCB, RCA, FGRCB, and FGRCA composites, respectively compared to the OCC specimens without steel fibers. On the other hand, when Vf = 1%, a recorded decrease in the ratio (UPV_{RC}/ UPV_{OCC}) is about 7%, 5%, 2%, and 2% for RCB, RCA, FGRCB, and FGRCA composites, respectively, compared to OCC specimens without steel fibers. In addition, the incorporation of the fibers with Vf = 0.5% seems to lead to a decrease in the ratio (UPV_{RC}/ UPV_{OCC}) of about 6% and 4% for the RCB and RCA composites, respectively, compared to the OCC specimens without steel fibers. However, the addition of the steel fibers does not seem to change the UPV of FGRCB and FGRCA compared to the OCC specimens without steel fibers when Vf = 0.5%.

The results of this study highlight the high sensitivity of the UPV value of the fibered composite. In addition, it was observed that the results of this test campaign of UPV, their value decreased continuously when Vf increased from 0% to 1.5% for both types of industrial or recycled metal fibers. This fact has already been observed and discussed several times in the literature [46].

Through all the results, we can group the behavior of the UPV value according to the type of design. The first design, the fully reinforced section, shows a significant decrease in UPV regardless of the type of fiber. The second design is functionally graded and characterized by a slight decrease in UPV. This means that increasing the percentage of steel fibers has a negative effect, in agreement with [47]. However, the negative impact of industrial fibers is much smaller than those of recycled fibers. The UPV decreases in an almost linear way. This decrease is due to increased pore volumes and cracks propagation (Assessment of hybrid FRSC cementitious composite with emphasis on flexural performance of functionally graded slabs). This result indicates that the addition of fibers decreases the compression and increases the amount of air in the composite. The same effect was reported by [48]. This is probably due to the decrease in concrete compactness resulting from the increase in porosity caused by the addition of metal fiber.

According to the results obtained, the pulse velocity of all concrete mixtures after 28 days was in the range of 4.01-4.51 km/s, indicating that the quality of the composite was good.

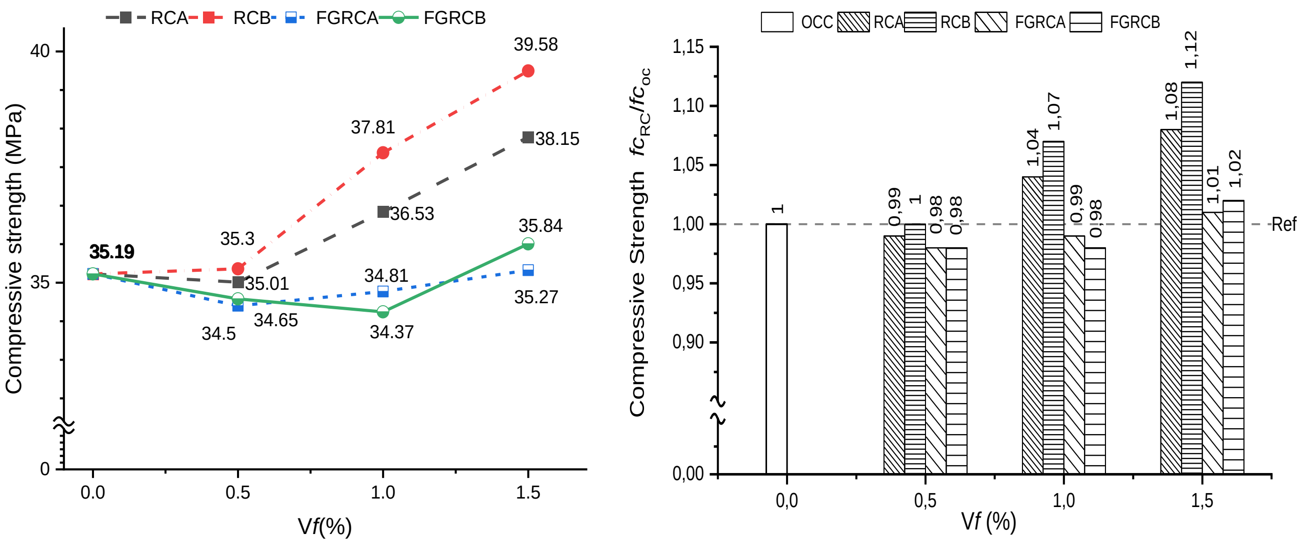
4.2. Compressive Strength Test Results

One of the most desirable characteristics of a cementitious composite is its compressive strength (Fc). Ordinary composites and fiber-reinforced composites have similar compressive strength results, which can be improved or degraded by adding fibers.

Figure 10-a shows the graphical representation of the compressive strength for different composites and the effects of the volume fraction of the two types of fibers (industrial fibers with hooks at the ends or recycled fibers with a wavy shape) in the two models, one reinforced on the whole section and the other only in the tensile zone, we substitute a functionally graded. The OCC without steel fibers showed an average compressive strength of 35.19 MPa at 28 days. However, when Vf reached 1.5%, the trend of increase, slightly different from the various forms of steel fibers, is in the range of 1.05% and 1.02% for the fully reinforced and functionally graded specimens, respectively. The slope of the recycled fibers is slightly larger. The increase is limited, and the highest strength value is 39.58 and 35.48 MPa for RCB and FGRCB, respectively. The lowest strength value is 35.01 and 34.37 MPa than that affected by Vf = 0.5% for RCA and 1% for FGRCB, respectively.

Figure 10-b shows the relationship between the ratio of compressive strength for different composites (fc_{RC}/fc_{OCC}) and the change in Vf of the two types of steel fibers used in this study. It is found that an improvement in the ratio (fc_{RC}/fc_{OCC}) reached its maximum value when Vf = 1.5% is about 12%, 8%, 2%, and 1% for the composites RCB, RCA, FGRCB, and FGRCA, respectively compared to the OCC specimens without steel fibers. On the other hand, when Vf = 1%, a recorded improvement in the ratio (fc_{RC}/fc_{OCC}) is about 7% and 4% for RCB, and RCA composites, respectively, compared to OCC specimens without steel fibers. In contrast to the FGRCB and FGRCA composites, incorporating the fibers with Vf = 1% seems to decrease the ratio (fc_{RC}/fc_{OCC}) by about 2% and 1%, respectively. When Vf = 0.5%, the ratio (fc_{RC}/fc_{OCC}) decreases about 2%, 2%, and 1% for the RCA, FGRCB and FGRCA composites, respectively compared to the OCC specimens without steel fibers. However, the addition of the steel fibers does not change the ratio (fc_{RC}/fc_{OCC}) of RCB compared to the OCC specimens without steel fibers when Vf = 0.5%.

In general, (fc_{RC}) increased continuously as Vf risen from 0 to 1.5%; it is noted that similar behavior has already been observed in the literature [49]. A brittle behavior with a sudden drop in the load-carrying capacity of the mixture Vf = 0 % was observed. However, mixtures incorporating steel fibers exhibited ductile responses after the peak strain, as the steel fibers partially limited the lateral expansion of the fibered zone for both FGRC and RC specimens regardless of the steel fiber type, as in a previous study [50, 51]. It can be concluded from these observations that strength improvement is observed with the addition of recycled metal fibers in an ordinary composite. In contrast, (fc_{RC}) increase is non-linear when Vf increases, especially for the functionally graded composite. The compressive performance of the fully reinforced composite is significantly improved when Vf is higher than 0.5%. This result indicates that adding fibers with a Vf of 1% to 1.5% is more effective. The role of metal fibers in compression is reduced compared to tension, but it can delay specimen deterioration and prevent crack propagation by connecting their lips. This behavior is more pronounced in the work of [52, 53].



(a) (b)

Figure 10. Effects of Fibers on Compressive Strength: (a) Effect of the Vf of the two types of fibers on the compressive strength; (b) Relationship between compressive strength fc_{RC}/fc_{OCC} and Vf (%)

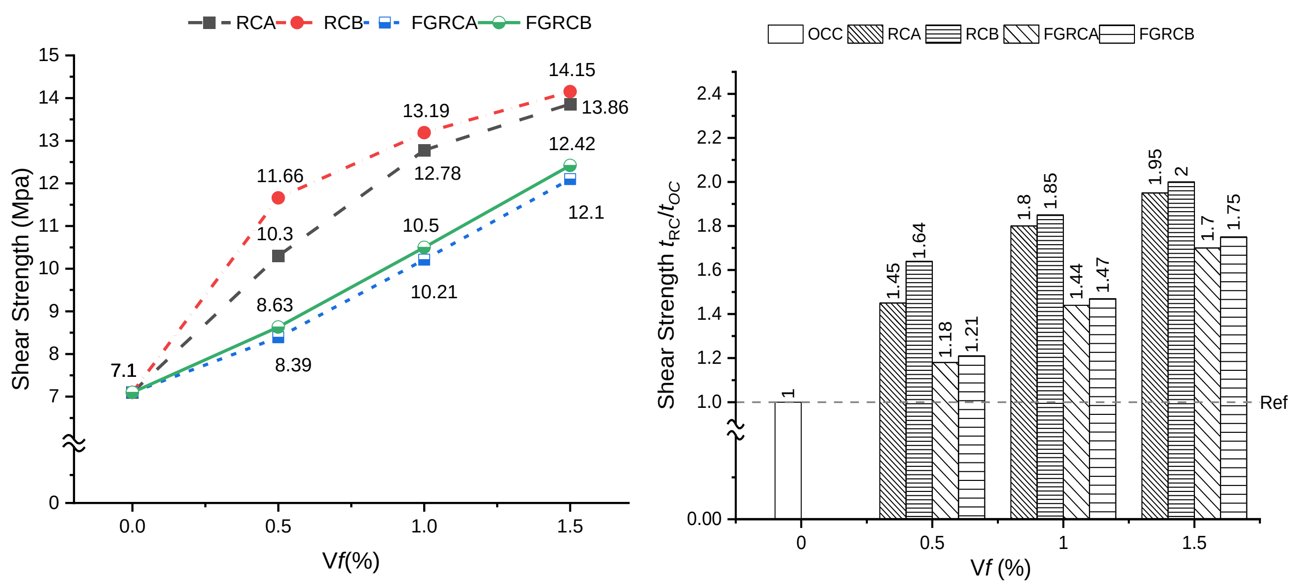
Moreover, when Vf was less than 0.5%, the compressive strength was almost the same for fully reinforced composites. Similar behavior has already been observed in the literature [54]. The addition of a small volume of 0.5% fibers did not produce an appreciable and significant improvement in the compressive strength behavior [55]. Still, concerning the functionally graded composites, a decrease in (fc_{RC}) compared to that of the OCC specimens without steel fibers occurred because the fibers are not uniformly distributed in the mixture, increasing porosity. This result is consistent with the work of [56–58]. Therefore, the mechanical and beneficial role of the metal fibers is activated after the crack appears [59, 60].

4.3. Shear Strength Test Results

The shear test results as a function of Vf in terms of quality are contrary to the UPV results. The values show that the shear strength of the composites is positively influenced by the fiber factor and increases with increasing Vf.

Figure 11-a shows the graphical representation of the shear strength of all the blends, as well as the effects of the volume fraction of the two types of fibers (industrial fibers with hooks at the ends and recycled fibers with a wavy shape) in the two designs, one reinforced on the whole section and the other only in the tensile zone, we substitute a functionally graded. The OCC without steel fibers showed an average shear strength equal to 7.10 MPa at 28 days. However, when Vf reached 1.5%, the slightly different trend of increase with the various forms of steel fibers is 1.02% and 1.03% for the fully reinforced and functionally graded specimens, respectively. The slope of the recycled fibers is slightly larger. The highest value of (τ_{RC}) is 14.15 and 12.42 MPa for RCB and FGRCB, respectively, and the lowest value of (τ_{RC}) is 10.03 and 8.39 MPa than that affected by Vf = 0.5% for RCA and FGRCA, respectively.

The relationship between the shear strength ratio for the different composites (τ_{RC}/τ_{OCC}) and the volume fraction of steel fibers Vf with the various forms of steel fibers (Figure 11-b). The results indicate that the matrix with full-depth steel fibers has higher shear strength than the functionally graded samples. Regardless of the shape of the steel fibers, the shear strength (τ_{RC}) always increases with the increase of Vf from 0% to 1.5%. An improvement in the ratio (τ_{RC}/τ_{OCC}) that reached its maximum value when Vf = 1.5% is observed to be about 100%, 95%, 75%, and 70% for the RCB, RCA, FGRCB, and FGRCA composites, respectively compared to the OCC specimens without steel fibers. When Vf = 1%, we also observe a recorded improvement in the ratio (τ_{RC}/τ_{OCC}) of about 85%, 80%, 47%, and 44% for the RCB, RCA FGRCB, and FGRCA composites, respectively, compared to the OCC specimens without steel fibers. We also notice, when Vf = 0.5%, an improvement in the ratio (τ_{RC}/τ_{OCC}) of about 64%, 45%, 21%, and 18% for the RCB, RCA, FGRCB, and FGRCA composites, respectively, compared to the OCC specimens without steel fibers.



(a) (b)

Figure 11. Effects of Fibers on Shear Strength: (a) Effect of the Vf of the two types of fibers on Shear Strength; (b) Relationship between Shear Strength $\tau_{RC}/\ \tau_{OCC}$ and Vf(%)

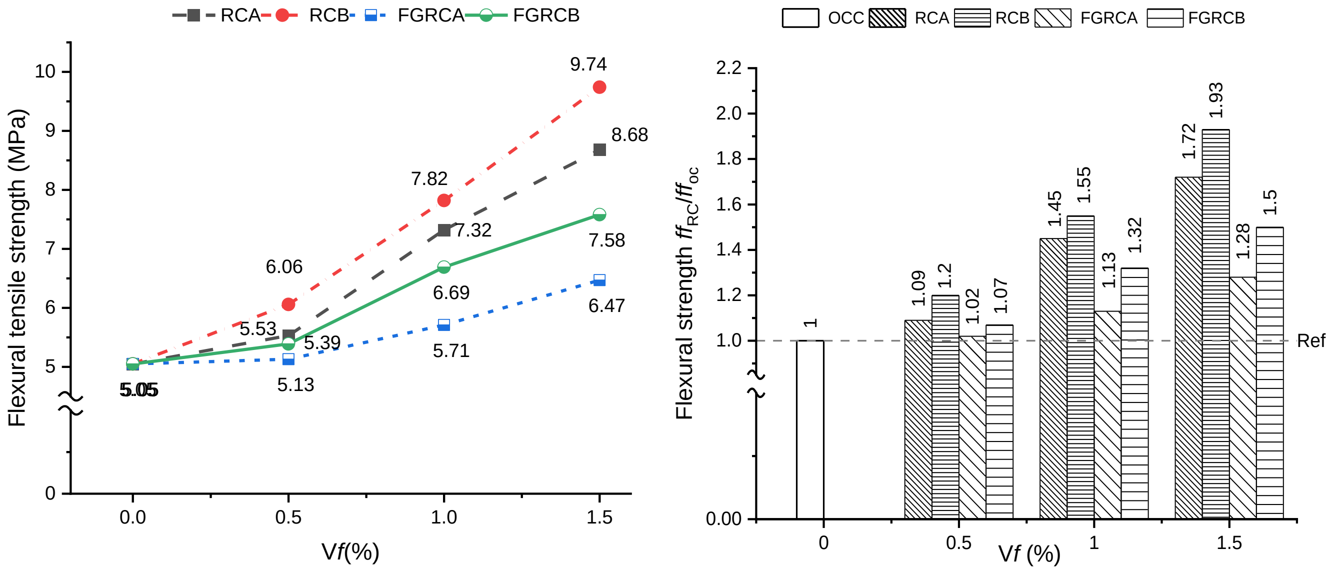
The experimental results obtained in this work are consistent with those obtained in similar experimental campaigns [56, 58]. It is noted that the shear strength increased when Vf increased from 0% to 1.5%. The same observation was made in the literature [56]. One of the criteria to increase and improve the shear strength is the addition of fibers. These results agree with Lakavath and al (2021) [55]. The addition of the higher volume fractions of 1.0% and 1.5% significantly improved the post-cracking behavior, ductility, and ultimate shear strength. Fibers were found to be more effective in increasing the (τ_{RC}) value of the composite. The same observation made by Banthia and al (2014) [61] found that the shear strength of concrete seems to be more related to the fiber content. This increase is attributed to the excellent bond between the reinforcements and the cementitious matrix. Soetens and Matthys (2017) [62] indicate that recycled steel fibers could be effectively used as discontinuous reinforcement in the cementitious composite matrix.

4.4. Flexural Strength Test Results

Figure 12-a illustrates the graphic representation of the flexural test results of all mixtures, the effects of volume fraction, and the two types of fibers (industrial fibers with hooks at the ends and recycled fibers with a wavy shape in both designs, one reinforced on the whole section and the other only in the tensile zone, we substitute a functionally graded. The OCC without steel fibers showed an average flexural tensile strength (ff_{OCC}) = 5.05 MPa at 28 days. However, when Vf reached 1.5%, the trend of increase, slightly different from the various forms of steel fibers, is in the range of 1.12% and 1.17% for the fully reinforced and functionally graded specimens, respectively. The slope of the recycled fibers is slightly larger. With the highest value of (ff_{RC}) of 9.74 and 5.58 MPa for RCB and FGRCB, respectively. The lowest value of (ff_{RC}) is 6.06 and 5.13 MPa for RCA and FGRCA, respectively, when Vf = 0.5%.

Figure 12-b shows the relationship between the ratio of flexural tensile strength for different composites (ff_{RC}/ff_{OCC}) and the variation in Vf of the two types of steel fibers used in this study. The corresponding maximum mid-span load in the third-point bending tests on prisms was used to calculate the flexural tensile strength (ff). For a cement-based composite, the strength at (ff_{RC}) is at the top of the most expected characteristics. The (ff_{RC}/ff_{OCC}) results are also improved by adding steel fibers, as in the shear tests. In addition, they significantly improved the ductility of the matrix compared to OCC; this was observed when Vf was increased from 0% to 1.5%. This has also been reported in numerous publications [63].

An improvement in the ratio (ff_{RC}/ff_{OCC}) which reached its maximum value when Vf = 1.5%, is observed to be about 93%, 72%, 50%, and 28% for RCB, RCA, FGRCB, and FGRCA composites, respectively compared to the OCC specimens without steel fibers. When Vf = 1%, we also observe a recorded improvement in the ratio (ff_{RC}/ff_{OCC}) is about 55%, 45%, 32%, and 13% for RCB, RCA, FGRCB, and FGRCA composites, respectively, compared to OCC specimens without steel fibers. When Vf = 0.5%, we also notice an improvement in the ratio (ff_{RC}/ff_{OCC}) of about 20%, 9%, 7%, and 2% for RCB, RCA, FGRCB, and FGRCA composites, respectively, compared to OCC specimens without steel fibers. The results show that the reinforcing fibers are extremely useful in improving (ff_{RC}/ff_{OCC}). The hooks on both ends of the industrial steel fibers and the deformed shape (corrugation) of the recycled steel fibers make them more stable and provide better bonding in the matrix. These deformations prevent slippage and allow maximum utilization of the tensile force. The same improvement in (ff_{RC}) due to fiber reinforcement has been reported previously [58, 64]. Similar to the shear strength test, the 3-point bending test observed the significant effect of recycled fibers on increased flexural tensile strength.



(a) (b)

Figure 12. Effects of Fibers on Flexural Strength: (a) Effect of the Vf of the two types of fibers on Flexural Strength; (b) Relationship between Flexural Strength ff_{RC}/ff_{OCC} and Vf (%)

The great advantage of this fiber addition is that after the matrix cracks, the fibers form a bridge on both sides of the flexural crack created in the tensile zone, carrying the cracks and preventing them from widening. On the other hand, contrary to the compressive strength, the test results prove that the tensile strength is significantly influenced by the addition of fibers and increases by about 20% for a Vf = 0.5%. Other researchers have reported similar results [13, 65].

The cost per kilogram of industrial steel fibers for the RCA1.5 mix is about 1.4 times more expensive than that of recycled fibers; the latter also reduces the cost and makes economical mixes. In this study, the mechanical performance was evaluated using experimental tests on specimens of a composite reinforced in full depth by locally manufactured recycled fibers. This type of composite has a maximum net gain of about 3%, 4%, and 12%, respectively, for the resistances to shear, compression, and flexural tension compared to industrial steel fibers. One of the main parameters of materials is cost. Each mixture must be made, considering the savings on the amount of materials used. Although metal reinforcing fibers are costly, their potential benefits cannot be ignored in the economic analysis. With the functionally graded concept, it can be said that a reduction of the fiber-reinforced area can help save the cost and natural resources by 50%.

5. Conclusions

In this study, the mechanical properties of a metal fiber-reinforced cementitious composite are investigated experimentally. As well as the comparison of the use of industrial fibers with hooks at the ends and recycled fibers of corrugated shape as reinforcement in the two designs, one reinforced on the whole section and the other only in the tensile zone, functionally grading has been carried out based on the test results.

The following conclusions can be drawn from the study presented in this paper:

- The volume percentage of both fibers directly impacts the flexural and tensile strengths. In particular, the recycled fibers from steel wool manufacturing waste showed a beneficial effect on the behavior of the composite, as the presence of fibers improves the resistance to the first crack.
- The test results prove that FGRC with recycled fibers from steel wool manufacturing waste could be useful for optimizing the design process in structural applications such as bicycle paths and walkways.
- The incorporation of metal fibers in the cementitious composites reduced the velocity of sonic waves with a maximum decrease in UPV, recorded at about 11% for the RCB1.5 composite, compared to the OCC specimens without steel fibers. This increased the air content in the mixture and reduced the metal fiber-reinforced cementitious composite quality. In addition, the UPV was not significantly reduced in the functionally graded specimens.
- The maximum increase in compressive strength due to the addition of steel fiber was minimal, less than or equal to 12%, regardless of the type of steel fiber used, and for both designs used in this study. However, the functionally graded specimens showed approximately similar compressive strength values to the OCC specimens without steel fibers, which were found for steel fiber volume fractions of 0.5, 1.0, and 1.5%.

- The shear and flexural strengths showed a linear increase with an increase in the volume ratio of steel fibers from 0 to 1.5%. The functionally graded specimens containing industrial or recycled steel fibers showed sufficient and greatly improved shear and flexural strength compared to the OCC specimens without steel fibers. However, the FGRCB1.5 specimens showed the highest shear strength and most ductile behavior of all tested specimens of this design type.
- The recycled fibers from corrugated steel wool manufacturing waste are a good choice to increase the mechanical performance of the reinforced cementitious composite, especially for the functional gradient composite. This could be used as a valuable tool to optimize the design process in various structural applications and make the production of mechanically and environmentally efficient composites possible.
- This study revealed that recycled fibers from industrial steel wool manufacturing waste have a high potential to limit crack propagation, and this ability offsets the negative effects of increased porosity. Because the Vf of the reinforced mixture was so high, there was an increasing trend in the composition of the mixture.
- From the cost point of view, the same value of shear strength and flexural strength can be achieved by using recycled fibers from steel wool manufacturing waste for the same dosage, as imported industrial fibers. We bring a saving of the order of 25–35% of the cost of the fibers and allow to realize economic composites.
- Finally, the results of the FGRC justified the replacement of 50% of the specimens from RCA or RCB in the lower functionally graded layer. Given the quantity of fibers employed and recycled fibers of industrial waste from the manufacture of steel wool as reinforcing fibers, we obtained good performance in terms of quality (shear strength and tensile strength by bending) and economic aspects.

6. Declarations

6.1. Author Contributions

Conceptualization, M.Y. and A.B.; methodology, M.Y., M.M. and A.B.; resources, M.Y. and M.M.; experimental program, M.Y. and A.B.; data curation, M.Y. and M.M.; writing—original draft preparation, M.Y., A.Z., A.B. and M.M.; writing—review and editing, M.Y., A.Z. and A.B. All authors have read and agreed to the submitted version of the manuscript.

6.2. Data Availability Statement

The data presented in this study are available in the article.

6.3. Funding

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6.4. Acknowledgements

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6.5. Conflicts of Interest

The authors declare no conflict of interest.

7. References

[1] Nili, M., & Afroughsabet, V. (2010). The effects of silica fume and polypropylene fibers on the impact resistance and mechanical properties of concrete. Construction and Building Materials, 24(6), 927–933. doi:10.1016/j.conbuildmat.2009.11.025

[2] Nili, M., & Afroughsabet, V. (2012). The long-term compressive strength and durability properties of silica fume fiber-reinforced concrete. Materials Science and Engineering A, 531, 107–111. doi:10.1016/j.msea.2011.10.042.

[3] Choi, Y., & Yuan, R. L. (2005). Experimental relationship between splitting tensile strength and compressive strength of GFRC and PFRC. Cement and Concrete Research, 35(8), 1587–1591. doi:10.1016/j.cemconres.2004.09.010.

[4] Havlikova, I., Merta, I., Schneemayer, A., Vesely, V., Šimonová, H., Korycanska, B., & Kersner, Z. (2015). Effect of Fibre Type in Concrete on Crack Initiation. Applied Mechanics and Materials, 769, 308–311. doi:10.4028/www.scientific.net/amm.769.308.

[5] Abbass, W., Khan, M. I., & Mourad, S. (2018). Evaluation of mechanical properties of steel fiber reinforced concrete with different strengths of concrete. Construction and Building Materials, 168, 556–569. doi:10.1016/j.conbuildmat.2018.02.164.

[6] Kazemi, M. T., Golsorkhtabar, H., Beygi, M. H. A., & Gholamitabar, M. (2017). Fracture properties of steel fiber reinforced high strength concrete using work of fracture and size effect methods. Construction and Building Materials, 142, 482–489. doi:10.1016/j.conbuildmat.2017.03.089.

[7] Vogel, F., Holčapek, O., Jogl, M., Kolář, K., & Konvalinka, P. (2014). Development of Mechanical Properties of Steel Fibers Reinforced High Strength Concrete. Advanced Materials Research, 1077, 113–117. doi:10.4028/www.scientific.net/amr.1077.113.

[8] Jansson, A. (2011). Effects of steel fibres on cracking in reinforced concrete. Chalmers Tekniska Hogskola, Gothenburg, Sweden.

[9] Døssland, Å. L. (2008). Fibre reinforcement in load carrying concrete structures: laboratory and field investigations compared with theory and finite element analysis. Ph.D. Thesis, Department of Structural Engineering, Faculty of Engineering Science and techno9logy, Norwegian University of Science and Technology (NTNU), Trondheim, Norway.

[10] Khayat, K. H., Kassimi, F., & Ghoddousi, P. (2014). Mixture design and testing of fiber-reinforced self-consolidating concrete. ACI Materials Journal, 111(2), 143–152. doi:10.14359/51686722.

[11] Zeyad, A. M. (2019). Effect of curing methods in hot weather on the properties of high-strength concretes. Journal of King Saud University - Engineering Sciences, 31(3), 218–223. doi:10.1016/j.jksues.2017.04.004.

[12] Pająk, M., & Ponikiewski, T. (2013). Flexural behavior of self-compacting concrete reinforced with different types of steel fibers. Construction and Building materials, 47, 397-408. doi:10.1016/j.conbuildmat.2013.05.072.

[13] Mohammadi, Y., Singh, S. P., & Kaushik, S. K. (2008). Properties of steel fibrous concrete containing mixed fibres in fresh and hardened state. Construction and Building Materials, 22(5), 956–965. doi:10.1016/j.conbuildmat.2006.12.004.

[14] Katzer, J., & Domski, J. (2012). Quality and mechanical properties of engineered steel fibres used as reinforcement for concrete. Construction and Building Materials, 34, 243–248. doi:10.1016/j.conbuildmat.2012.02.058.

[15] Naaman, A. E. (2003). Engineered Steel Fibers with Optimal Properties for Reinforcement of Cement Composites. Journal of Advanced Concrete Technology, 1(3), 241–252. doi:10.3151/jact.1.241.

[16] Domski, J. (2011). Cracking moment in steel fibre reinforced concrete beams based on waste sand. "Ovidius" University Annals Constantza. Series Civil Engineering, (13), 29. doi:10.3390/ma13020392.

[17] Wang, J., Dai, Q., Si, R., Ma, Y., & Guo, S. (2020). Fresh and mechanical performance and freeze-thaw durability of steel fiber-reinforced rubber self-compacting concrete (SRSCC). Journal of Cleaner Production, 277, 123180. doi:10.1016/j.jclepro.2020.123180

[18] Maidl, B. (1995). Steel fiber reinforced Concrete (1st Ed.). Ernst & Sohn, Berlin, Germany.

[19] Spinella, N. (2013). Shear strength of full-scale steel fibre-reinforced concrete beams without stirrups. Computers and Concrete, 11(5), 365–382. doi:10.12989/cac.2013.11.5.365.

[20] Hussain, H. K., Zewair, M. S., & Ahmed, M. A. (2022). High Strength Concrete Beams Reinforced with Hooked Steel Fibers under Pure Torsion. Civil Engineering Journal (Iran), 8(1), 92–104. doi:10.28991/CEJ-2022-08-01-07.

[21] Katzer, J. (2006). Steel fibers and steel fiber reinforced concrete in civil engineering. Pacific Journal of science and technology, 7(1), 53-58.

[22] Ali, B., Kurda, R., Ahmed, H., & Alyousef, R. (2022). Effect of recycled tyre steel fiber on flexural toughness, residual strength, and chloride permeability of high-performance concrete (HPC). Journal of Sustainable Cement-Based Materials, 1–17. doi:10.1080/21650373.2021.2025165.

[23] Djebali, S., Bouafia, Y., Atlaoui, D., & Bilek, A. (2011). Study of Mechanical Behavior of Chips Reinforced Concrete. In Advanced Materials Research, 324,360-363. doi:10.4028/www.scientific.net/AMR.324.360

[24] Channa, I. A., & Saand, A. (2021). Mechanical behavior of concrete reinforced with waste aluminium strips. Civil Engineering Journal (Iran), 7(7), 1169–1182. doi:10.28991/cej-2021-03091718.

[25] Lourenço, L., Zamanzadeh, Z., Barros, J. A. O., & Rezazadeh, M. (2018). Shear strengthening of RC beams with thin panels of mortar reinforced with recycled steel fibres. Journal of Cleaner Production, 194, 112–126. doi:10.1016/j.jclepro.2018.05.096.

[26] Bever, M. B., & Duwez, P. E. (1972). Gradients in composite materials. Materials Science and Engineering, 10(C), 1–8. doi:10.1016/0025-5416(72)90059-6.

[27] Roesler, J., Paulino, G., Gaedicke, C., Bordelon, A., & Park, K. (2007). Fracture behavior of functionally graded concrete materials for rigid pavements. Transportation Research Record, 2037(1), 40–49. doi:10.3141/2037-04.

[28] Río, O., Nguyen, V. D., & Nguyen, K. (2015). Exploring the potential of the functionally graded SCCC for developing sustainable concrete solutions. Journal of Advanced Concrete Technology, 13(3), 193–204. doi:10.3151/jact.13.193.

[29] Jirawattanasomkul, T., Kongwang, N., Jongvivatsakul, P., & Likitlersuang, S. (2018). Finite element modelling of flexural behaviour of geosynthetic cementitious composite mat (GCCM). Composites Part B: Engineering, 154, 33–42. doi:10.1016/j.compositesb.2018.07.052.

[30] Chan, R., Liu, X., & Galobardes, I. (2020). Parametric study of functionally graded concretes incorporating steel fibres and recycled aggregates. Construction and Building Materials, 242, 118186. doi:10.1016/j.conbuildmat.2020.118186.

[31] Biskria Cement (2021). Biskria Ciment Company. Available online: https://biskriaciment.com/Nos-Produits.aspx (accessed Jan. 26, 2022).

[32] EN 14889-1. (2006). Fibres for concrete-Part 1: Steel fibres-Definitions, specifications and conformity. Slovenian Standard, Slovenian Institute for Standardization, Ljubljana, Slovenia. (In Slovenian).

[33] Cao, Y. Y. Y., Li, P. P., Brouwers, H. J. H., Sluijsmans, M., & Yu, Q. L. (2019). Enhancing flexural performance of ultra-high performance concrete by an optimized layered-structure concept. Composites Part B: Engineering, 171, 154–165. doi:10.1016/j.compositesb.2019.04.021.

[34] Prasad, N., & Murali, G. (2021). Exploring the impact performance of functionally-graded preplaced aggregate concrete incorporating steel and polypropylene fibres. Journal of Building Engineering, 35, 102077. doi:10.1016/j.jobe.2020.102077.

[35] Liu, X., Yan, M., Galobardes, I., & Sikora, K. (2018). Assessing the potential of functionally graded concrete using fibre reinforced and recycled aggregate concrete. Construction and Building Materials, 171, 793–801. doi:10.1016/j.conbuildmat.2018.03.202.

[36] BS EN 12390-3. (2002). Testing hardened concrete. Compressive strength of test specimens. British Standards Institution, London, United Kingdom.

[37] Benali, R., Mellas, M., Baheddi, M., Mansouri, T., & Boufarh, R. (2021). Physico-mechanical behaviors and durability of heated fiber concrete. Civil Engineering Journal (Iran), 7(9), 1582–1593. doi:10.28991/cej-2021-03091745.

[38] BS EN 12504-4:2004. (2004). Testing Concrete — Part 4: Determination of ultrasonic pulse velocity. British Standards, 3(April), 18.

[39] BS EN 12390-1. (2021). Testing hardened concrete-Shape, dimensions and other requirements for specimens and moulds. British Standards Institution, London, United Kingdom.

[40] JSCE-SF6. (1990). Method of test for shear strength of steel fiber reinforced concrete. Japan Society of Civil engineering, Tokyo, Japan, 67-69.

[41] BS EN 12390-5. (2019). Testing hardened concrete. Flexural strength of test specimens. British Standards Institution, London, United Kingdom.

[42] ASTM C597-16. (2016). Standard Test Method for Pulse Velocity through Concrete. ASTM International, Pennsylvania, United States.

[43] Malhotra, V. M. (1976). Testing hardened concrete: non-destructive methods. Iowa State University Press, Ames, United States

[44] Demirboǧa, R., Türkmen, I., & Karakoç, M. B. (2004). Relationship between ultrasonic velocity and compressive strength for high-volume mineral-admixtured concrete. Cement and Concrete Research, 34(12), 2329–2336. doi:10.1016/j.cemconres.2004.04.017.

[45] Whitehurst, E. A. (1951). Soniscope Tests Concrete Structures. ACI Journal Proceedings, 47(2), 433–444. doi:10.14359/12004.

[46] Omidinasab, F., Moazami Goodarzi, S., & Sahraei Moghadam, A. (2022). Characterization and Optimization of Mechanical and Impact Properties of Steel Fiber Reinforced Recycled Concrete. International Journal of Civil Engineering, 20(1), 41–55. doi:10.1007/s40999-021-00656-2.

[47] Hassiba, B., Mekki, M., & Fraid, R. (2018). The relationship between the compressive strength and ultrasonic pulse velocity concrete with fibers exposed to high temperatures. International Journal of Energetica, 3(1), 31. doi:10.47238/ijeca.v3i1.63.

[48] Mo, K. H., Yap, S. P., Alengaram, U. J., Jumaat, M. Z., & Bu, C. H. (2014). Impact resistance of hybrid fibre-reinforced oil palm shell concrete. Construction and Building Materials, 50, 499–507. doi:10.1016/j.conbuildmat.2013.10.016.

[49] M. A. Ismail, D. (2007). Compressive and Tensile Strength of Natural Fibre-reinforced cement base Composites. AL-Rafdain Engineering Journal (AREJ), 15(2), 42–51. doi:10.33899/rengj.2007.44954.

[50] Kazemi, S., & Lubell, A. S. (2012). Influence of Specimen Size and Fiber Content on Mechanical Properties of Ultra-High-Performance Fiber-Reinforced Concrete. ACI Materials Journal, 109(6), 675. doi:10.14359/51684165.

[51] Pansuk, W., Sato, H., Sato, Y., & Shionaga, R. (2008). Tensile behaviors and fiber orientation of UHPC. Proceedings of Second International Symposium on Ultra High Performance Concrete, Kassel, Germany, March 05-07, 2008, 161-168.

[52] Aslani, F., & Nejadi, S. (2013). Self-compacting concrete incorporating steel and polypropylene fibers: Compressive and tensile strengths, moduli of elasticity and rupture, compressive stress-strain curve, and energy dissipated under compression. Composites Part B: Engineering, 53, 121–133. doi:10.1016/j.compositesb.2013.04.044.

[53] Li, L., Zhang, R., Jin, L., Du, X., Wu, J., & Duan, W. (2019). Experimental study on dynamic compressive behavior of steel fiber reinforced concrete at elevated temperatures. Construction and Building Materials, 210, 673–684. doi:10.1016/j.conbuildmat.2019.03.138.

[54] Abadel, A., Abbas, H., Almusallam, T., Al-Salloum, Y., & Siddiqui, N. (2016). Mechanical properties of hybrid fibre-reinforced concrete - Analytical modelling and experimental behavior. Magazine of Concrete Research, 68(16), 823–843. doi:10.1680/jmacr.15.00276.

[55] Lakavath, C., Suriya Prakash, S., & Dirar, S. (2021). Experimental and numerical studies on shear behaviour of macro-synthetic fibre reinforced prestressed concrete beams. Construction and Building Materials, 291, 123313. doi:10.1016/j.conbuildmat.2021.123313.

[56] Boulekbache, B., Hamrat, M., Chemrouk, M., & Amziane, S. (2012). Influence of yield stress and compressive strength on direct shear behaviour of steel fibre-reinforced concrete. Construction and Building Materials, 27(1), 6–14. doi:10.1016/j.conbuildmat.2011.07.015.

[57] Domagala, L. (2011). Modification of properties of structural lightweight concrete with steel fibres. Journal of Civil Engineering and Management, 17(1), 36–44. doi:10.3846/13923730.2011.553923.

[58] Khaloo, A., Raisi, E. M., Hosseini, P., & Tahsiri, H. (2014). Mechanical performance of self-compacting concrete reinforced with steel fibers. Construction and Building Materials, 51, 179–186. doi:10.1016/j.conbuildmat.2013.10.054.

[59] Centonze, G., Leone, M., & Aiello, M. A. (2012). Steel fibers from waste tires as reinforcement in concrete: A mechanical characterization. Construction and Building Materials, 36, 46–57. doi:10.1016/j.conbuildmat.2012.04.088.

[60] Awwad, E., Mabsout, M., Hamad, B., Farran, M. T., & Khatib, H. (2012). Studies on fiber-reinforced concrete using industrial hemp fibers. Construction and Building Materials, 35, 710–717. doi:10.1016/j.conbuildmat.2012.04.119.

[61] Banthia, N., Majdzadeh, F., Wu, J., & Bindiganavile, V. (2014). Fiber synergy in Hybrid Fiber Reinforced Concrete (HyFRC) in flexure and direct shear. Cement and Concrete Composites, 48, 91–97. doi:10.1016/j.cemconcomp.2013.10.018.

[62] Soetens, T., & Matthys, S. (2017). Shear-stress transfer across a crack in steel fibre-reinforced concrete. Cement and Concrete Composites, 82, 1–13. doi:10.1016/j.cemconcomp.2017.05.010.

[63] Sahraei Moghadam, A., Omidinasab, F., & Abdalikia, M. (2021). The effect of initial strength of concrete wastes on the fresh and hardened properties of recycled concrete reinforced with recycled steel fibers. Construction and Building Materials, 300, 124284. doi:10.1016/j.conbuildmat.2021.124284.

[64] Singh, N. K., & Rai, B. (2021). Assessment of synergetic effect on microscopic and mechanical properties of steel-polypropylene hybrid fiber reinforced concrete. Structural Concrete, 22(1), 516–534. doi:10.1002/suco.201900166.

[65] Boulekbache, B., Hamrat, M., Chemrouk, M., & Amziane, S. (2010). Flowability of fibre-reinforced concrete and its effect on the mechanical properties of the material. Construction and Building Materials, 24(9), 1664–1671. doi:10.1016/j.conbuildmat.2010.02.025.