Influence of fibres on the mechanical behaviour of fibre reinforced concrete matrixes

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Abstract

An experimental analysis focused on the mechanical behaviour of fibre reinforced concrete matrixes (FRCM) is presented using a total of three hundred and twelve specimens. A reference plain mixture was first defined and then three types of fibres were chosen to reinforce it (polypropylene, glass and steel fibres). Within each type of reinforcement, four volumetric proportions were adopted, ranging from 0.5% to 2% in 0.5% increments. The influence of each type of fibre and dosage on the properties of the FRCM, including compressive strength, bending behaviour, cracking and maximum loads and ductility was analysed. In summary, it was observed that the compressive strength generally grows with the reinforcement dosage, and that this growth is greatly affected by the properties of the fibre, namely by its tensile strength. The load-displacement curves are also highly affected by the type of reinforcement. Steel and polypropylene fibres provide the composite material a better capacity to withstand high deformations. Glass fibres have a reduced effect on this regard, due to their brittle behaviour. For each type of fibre, by increasing the fibres percentage, an increase in the load capacity is also observed, with a maximum of 160% for an addition of 2.0% of steel fibres. The cracking loads are consistently lower than that of the reference mixture, due to the loss of homogeneity and increased porosity caused by fibre addition, in spite of the favourable influence associated to the mechanical properties of the fibres. For polypropylene FRCM the cracking loads were approximately 35% lower than that of the reference mixture. For steel and polypropylene fibres the toughness indexes (I5, I10 and I20) were defined, being observed that for 1.5% volume fraction of steel fibres the I5 and I20 are respectively 6.80 and 35.08, whereas for the polypropylene fibres those indexes are respectively of 3.61 and 15.75 for the same fraction.

Keywords: FRCM; steel, polypropylene, and glass fibres; compressive strength; bending behaviour; cracking load; ductility.

1. Introduction

Fibres have been consistently used in construction since the beginnings of 20th century. During the 1960s and 1970s, the use of asbestos fibres decreased with the awareness of the health problems caused by long-term heavy exposure to these airborne fibres [1]. Since then, fibres have been produced using different materials, such as steel, polypropylene, and glass, among others, that gradually widespread to different applications, in particular to the production of fibre reinforced concrete (FRC) [2].

Concrete is considered a construction material with strong heterogeneous behaviour, with a good compressive strength and a low tensile strength typically around 5-8% of the compressive strength [3]. Moreover, concrete has a low strain capacity and is brittle in fracture. The use of fibre reinforced concrete is currently of particular interest, especially in structures with high standards of performance and durability. The behaviour of these concretes is mainly conditioned by the binding matrix properties and by its interaction with the reinforcing fibres. The most common fibres capable of improving the properties of plain concrete are made of steel, glass or polypropylene. Table 1 show the properties of fibres used to reinforce concrete. To choose the type of reinforcement fibres, the behaviour of the several FRC must be known with a high certain level. Therefore, it is important to understand the influence of each fibre parameters on the general behaviour of the structural composite material. Many parameters can be analysed, being length, diameter, shape and type of material the most important. The geometry and type of material have great influence over the behaviour of fibre reinforced concrete [4,5]. Even the distribution of fibres is affected by the diameter, length and proportion of fibres, as well as by the flowability of the concrete matrix, the placement method and formwork [6]. Obviously, the behaviour of FRC with different fibres will be also significantly different. So, the choice of fibre type, and its properties must be made carefully and should satisfy the structural requirements.

Table 1 – Typical properties of fibres [7,8]

Fibre	Specific density	Young's modulus (GPa)	Tensile strength (GPa)	Elongation at failure (%)
Steel	7.84	200	0.5–2.0	0.5–3.5
E-glass	2.55	72.4	3.45	4.7
S-glass	2.5	86.9	4.71	5.2
Crocidolite (asbesto)	3.4	196	3.5	2.0–3.0
Chrysolite (asbesto)	2.6	164	3.1	2.0–3.0
Polypropylene	0.90–0.95	3.5–10.0	0.45–0.76	15–25
Polyethylene	0.92–0.96	5	0.08–0.60	3–100
Carbon (high strength)	1.5	230	5.7	2.0
Carbon (high modulus)	1.5	640	1.9	0.36

Polypropylene and glass fibres are commonly used in industrial pavements and when its required a concrete with shrinkage cracking control [7]. Many studies refer that the flexural strength of glass FRC seems to increase 15 to 20% compared with plain concrete mixtures, showing also an improved toughness [9–14].

Most those studies [9–13] also reported an increase in the compressive strength ranging from 20 to 25%, although other publications [14] pointed out only a marginal decrease of this parameter.

For polypropylene FRC, some studies [15–17] mention the compressive strength of polypropylene FRC to be nearly unchanged by adding fibres, whereas others [18,19] show an increase up to 20%. In terms of flexural strength, some authors [15,16] report no impact on this material property, whereas others [17,18,20] state an increase of 10% maximum, or even a decrease on this property [21]. Furthermore, some authors [15,18,20,21] report increased flexural toughness and ductility relatively to plain concrete, for both lower and higher dosages, increasing with the percentage of reinforcement.

Most research about FRC has been focused on steel fibres. This type of fibres is typically used in industrial pavements [22], precast industry [23] and tunnel linings [24]. Studies highlight that the failure mode of steel FRC changes from fragile to ductile and that the post-cracking response is significantly improved [25,26]. Many studies refer to the enhanced toughness, ductility and flexural strength of the steel FRC, the latter reaching values ranging from 30 to 125% when compared to plain concrete and depending of concrete strength and fibres dosage [4,25–29]. However, even for these fibres there are still contradictory results concerning the prediction of material properties. For example, some authors suggest the compressive strength of steel FRC [25,27] to increase up to 10% when compared to plain concrete, whereas other studies claim this change to be only marginal or not even related with the introduction of fibres [26,28].

The great majority of studies found in the literature on FRC, some of them above mentioned, are essentially focused on a single type of fibre and corresponding mechanical behaviour. When new types of fibres are provided by the market, e.g., carbon and, more recently, basalt, the natural tendency of researchers is to redirect their studies to these. However, there are significant differences in FRC mixes produced with current fibres, namely steel, polypropylene and glass, that for some reason have not yet been fully addressed. These are quite difficult to be determined from published studies (on single fibres), due to the large variation in mixes and tests. Having this into consideration, this work aims at presenting an extensive comparative experimental study on three different types of fibres (polypropylene, glass and steel) with the same binding matrix. The purpose was to assess the influence of the type of fibre adopted in the mechanical properties of FRCM. The following specific aims were defined:

- access the FRCM compressive strength evolution with the introduction and proportion of fibres;
- characterise the bending behaviour of FRCM depending on the type of reinforcement fibres;
- determine the FRCM cracking and maximum loads and identify the influence of fibres type on those values;
- define some ductility parameters that show the influence of each type of fibre on the post-peak behaviour of FRCM.

2. Experimental Programme

The experimental programme was outlined according to the different aims set in the previous section. In the following, the geometry and number of specimens, FRCM mixtures and test set-up for the characterisation of mechanical properties, are described.

2.1. Material properties and specimens production

A reference self-compacting cementitious plain matrix (without fibres) was first selected, which was the basis for comparing the effect of three types of fibres: polypropylene, glass and steel respectively. The choice for a self-compacting mixture aimed compensating the workability reduction caused by fibres addition. For this purpose, four dosages were defined for the reinforced mixtures, ranging from 0.5% up to 2%, considering increments of 0.5%.

The number of fibres present in the polypropylene and glass FRCM is obviously very high when compared to steel FRCM, due to the reduced cross-sectional area of the first (Table 2). Although this could be a reason to adapt the proportions for the corresponding mixtures, these were kept unchanged as to maintain coherence and allow direct comparisons. For each mixture, twenty-four prismatic specimens were produced according to EN 196 [30] to support a statistical study. A total of three hundred and twelve samples were defined.

Considering the high number of specimens to be produced in this study and since the reference mixture did not contained coarse aggregates, the size of the specimen used for matrix characterisation was settled as 40 × 40 × 160 mm^3. The FRCM mixtures were obtained based on the reference and by adding fibres and adjusting the volume proportion of sand and keeping the binding matrix unchanged in all the series. The reference binding matrix was produced using cement CEM II/A-L 42.5R, limestone filler, third generation superplasticiser (eter-polycarboxylates based) and water. Due to the geometry of the specimen, the maximum aggregate size was limited to siliceous medium oven-dried sand (0/4 mm). As mentioned before, the fibres were made of steel (Dramix® OL 13/.20), polypropylene (Vimafibre 512) or glass (Vimacrack). The corresponding properties are listed in Table 2.

Table 2 – Main properties for the fibres

Type of fibre	Diameter (μm)	Length (mm)	Specific density	Young's modulus (GPa)	Tensile strength (MPa)
Dramix® OL 13/.20	200	13	7.84	200	2600
Vimafibre 512	34–45	12	0.91	3.5–4.0	340–400
Vimacrack	14	12	2.68	72	1700

The target compressive strength at 28 days was 65 MPa for the reference mixture. To define a suitable mixture in this regard, the method described in [31] was followed. This method is based on the Feret's expression to predict the strength of the binding paste. The mixture compactness and the air content were first determined in a preliminary test mixture (Figure 1) and the mixture was successively modified until reaching a final formulation (Table 3) matching the initially predicted parameters and, in particular, the compressive strength.

Figure 1 – Preliminary mixture

Table 3 – Final FRCM mixtures (kg per cubic meter)

Mixtures	Constituents							
	CEM II/A-L 42.5R	Limestone filer	Water	BASF Glenium Sky 526	Medium Sand	Fibres		
						St	Po	Gl
Reference	475.0	285.0	197.6	6.2	1340.6	-	-	-
St 0.5					1327.7	39.3	-	-
St 1.0					1314.8	78.5		
St 1.5					1301.1	117.8		
St 2.0					1288.2	157.0		
Po 0.5					1327.7	-	4.6	-
Po 1.0					1314.8		9.1	
Po 1.5					1301.1		13.7	
Po 2.0					1288.2		18.2	
Gl 0.5					1327.7	-	-	13.4
Gl 1.0					1314.8			26.8
Gl 1.5					1301.1			40.2
Gl 2.0					1288.2			53.6

* ‘St’ stands for ‘Steel’, ‘Po’ stands for ‘Polypropylene’ and ‘Gl’ stands for glass.

To produce de FRCM mixtures, the recommendations suggested by [2] were followed and the fibres were added to the mixture after all the other constituents (cement, filler, sand, water, superplasticizer). The mixing process continued until reaching a homogeneous state (Figure 2a and 2b). Afterwards, the specimens were cast and the formwork was removed after 24 hours. The specimens were then cured in water immersion at 20 ± 2°C [30] and removed and dried approximately 24 hours before being tested, at 28 days of age.

Six additional 40 × 40 × 160 mm^3 specimens were produced with the reference mixture for assessing the compressive strength at 28 days (Figure 3). An average value of 67.7MPa and a standard deviation of 2.8 MPa was found for compressive strength.

(a) (b)

Figure 2 – Specimen production: a) fibres being added to the mixture; b) final stage of mixing.

Figure 3 – Compressive tests of the reference mixture specimens

2.2. Test setup

The specimens were tested in a four point bending scheme. Each sample was placed on two hinged supports, at both edges, with 120 mm span, and loaded by two local and symmetrical forces, distanced 40 mm (Figure 4).

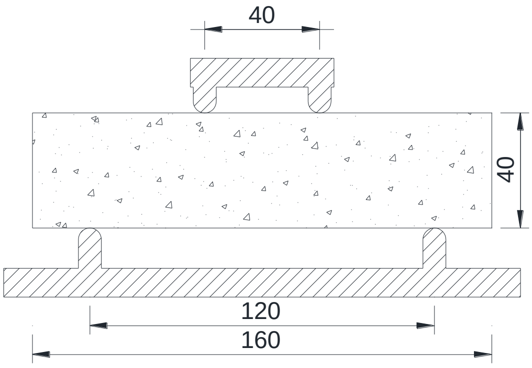


Figure 4 – Test setup

Loading was applied by a hydraulic servo-actuator, with 200 kN capacity and controlled by a constant vertical displacement rate of 0.8 mm/m to obtain the post-peak behaviour – see set-up and typical curves in Figure 6. Two separate data acquisition systems were used to measure loads and displacements. In the first system, load and displacements were read by an internal load cell and the displacement transducer of the test machine. The second system was composed by a load cell placed below the specimen and two linear variable differential transformers (LVDT). With the remaining flexural tests, the compressive strength was determined using three randomly selected specimens of each series. The specimens were cut in half and tested in compression on a 40 × 40 mm^2 area set-up and in a total of six tests.

3. Results and discussion

In the following sub-sections, results addressing compressive strength, general bending behaviour, cracking and maximum loads and ductility are presented and discussed.

3.1. Compressive strength

The FRCM compressive strength was determined for all reinforcement types and percentages. The variation in relation to the reference was calculated and presented in Figure 5.

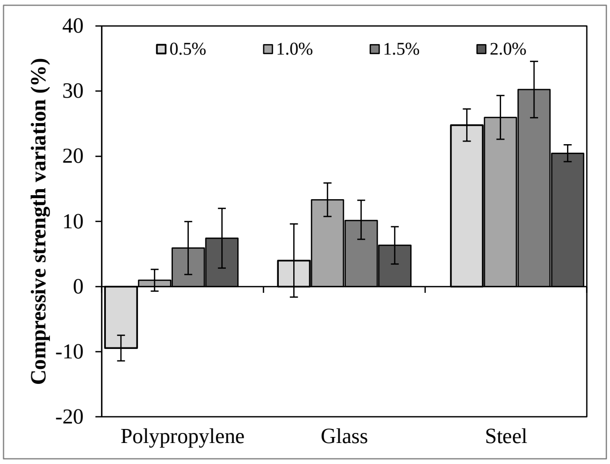


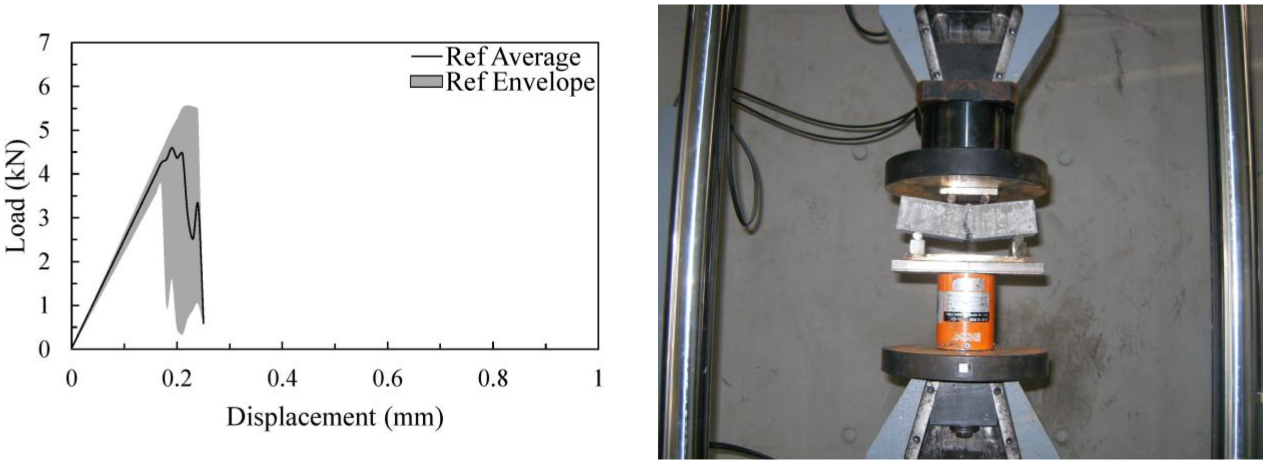
Figure 5 – Compressive strength variation, in relation to the reference mixture

The compressive strength of the polypropylene FRCM increases with the reinforcement ratio. However, the strength found with the 0.5% fibre content is 10% lower than the reference, whilst all other reinforcement ratios show higher strengths. The glass FRCM mixtures always have higher strength than the reference mixture. Interestingly, the compressive strength only increases up to ratios of 1%, after which starts decreasing proportionally to the fibre content. This phenomenon seems to be related with the loss on workability and increase of air consequent in the matrix. The steel fibres are the ones impacting more significantly on the compressive strength of the FRCM with a gain increasing proportionally up to a 1.5% volume of fibres and up to 30% of reference strength. It then decreases to about 20% for 2.0% of fibres.

Generally, the FRCM compressive strength tends to increase with the fibres addition. This property is enhanced by the confinement provided by the fibres to the concrete matrix. In compression, the latter tends to expand by Poisson’s effect and the fibres oppose to this effect, thus increasing the strength. Results show that the compressive strength increases with the tensile strength and stiffness of fibres, being lower for polypropylene and larger for steel.

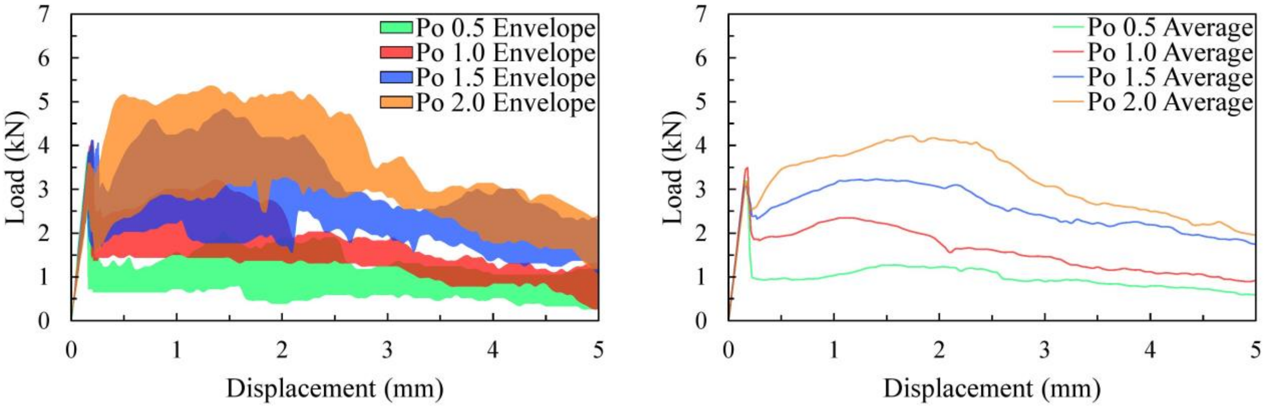
3.2. Load-displacement relation

Figure 6a shows the envelope and the average load-displacement curve for the reference mixture. Figures 7, 8 and 9 represent, respectively, the envelope and the average load-displacement curves for the mixtures reinforced with polypropylene, glass and steel fibres. The envelope curves were traced with all the curves from the tests and are the minimum and maximum load values achieved by the sets and give a good information relatively to the variation within each sets. Some envelope curves intercept each other, meaning that, in some zones, different reinforcement percentages result in similar behaviour. With the reinforcement increase, the results dispersion tends to increase.



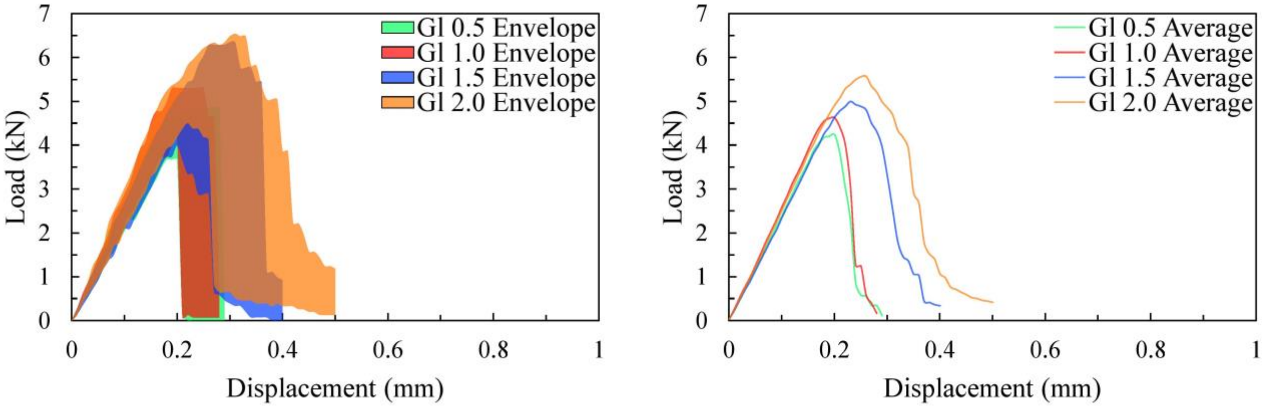
(a) (b)

Figure 6 – (a) Envelope and average load-displacement curve for the reference mixture; and (b) experimental setup.



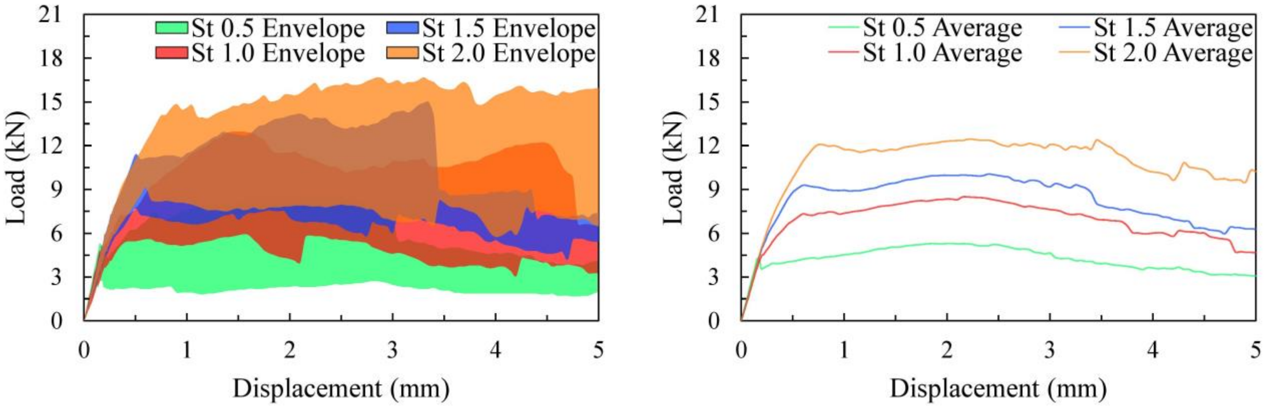
(a) (b)

Figure 7 – Polypropylene FRCM load-displacement curves: (a) envelopes; and (b) average curves.



(a) (b)

Figure 8 – Glass FRCM load-displacement curves: (a) envelopes; and (b) average curves.



(a) (b)

Figure 9 – Steel FRCM load-displacement curves: (a) envelopes; and (b) average curves.

In the case of polypropylene fibres, the peak load of the resulting mixtures is always lower than the reference. This was due to the reduced workability that the mixtures show in the presence of a large number of thin fibres, and corresponding loss of homogeneity and high porosity. After the specimen cracks, there is a plastic behaviour that depends on the reinforcement percentage. The evolution of strength after the first peak load also depends on the reinforcement ratio. For 0.5 and 1.0% the latter is approximately constant, and below the peak load; whereas for 1.5 and 2.0%, the value is higher and can overtake the peak value. The ductility of these specimens increases considerably, especially for percentages of 1.5 and 2.0%.

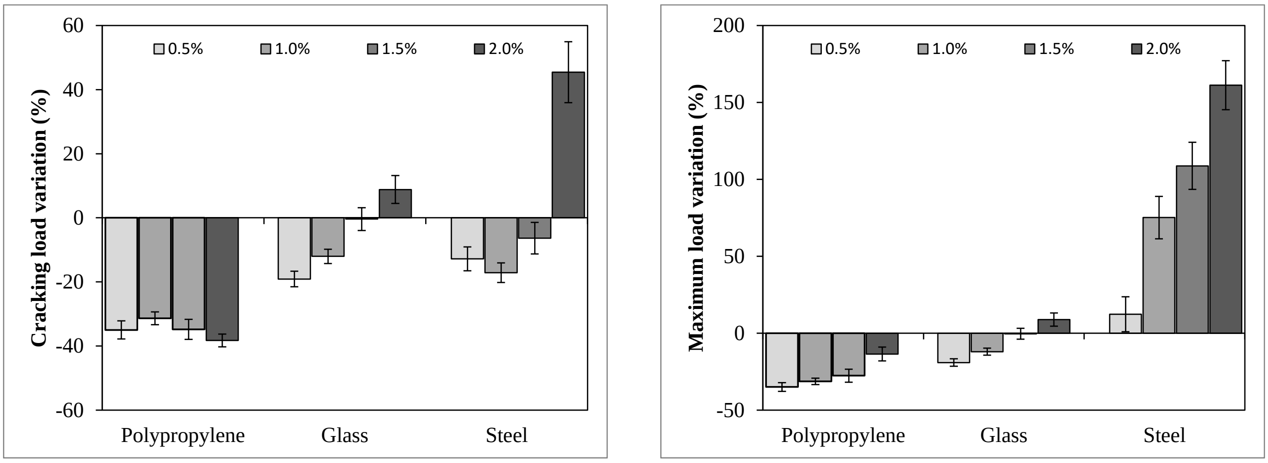
In the mixtures reinforced with glass fibres, failure is always fragile with the maximum load remaining nearly unchanged for 0.5 and 1.0%, and increasing gradually for higher percentages. At 1.5 and 2% the strength seems to be similar and exceed that of the reference mixture.

For the mixtures reinforced with steel fibres the deformation capacity increases significantly, particularly when comparing with that of the reference mixture. The response also changes from fragile to ductile with three stages identifiable on the load-displacement relation: a first elastic stage until the onset of the first crack; a second linear stage, with decreased stiffness and ranging between the load for the first crack and peak load where the internal stresses on the cracks openings are performed by the fibres; and a third stage following the peak load and showing plasticity, where a slipping phenomenon between the binding matrix and the reinforcement fibres is evident. For a ratio of 0.5%, the behaviour until cracking is similar to the reference mixture, then the stiffness decreases until the peak load. Next the behaviour changes into an approximately plastic section where the remaining load often exceeds the peak. For the remaining percentages, the peak load is progressively higher and the second stage stiffness slightly decreases, as a result of the gradual crack opening of the specimens (transition between phase one and phase three). In the post-peak stage, the load capacity remains approximately constant for large displacements.

In brief, after the first crack, the internal stresses are mostly supported by the reinforcement that sustains the load. With crack opening, the FRCM matrix shows a ductile behaviour if fibres also present a ductile behaviour, as in the case of polypropylene and steel fibres, and a fragile behaviour if fibres also present a fragile behaviour, as in the case of glass fibres.

3.3. Cracking and maximum loads

Figure 10a presents the variations, relatively to the reference mixture, of the cracking load, i.e., the load that causes the first crack, of each studied sets. In can be seen that the latter is often lower than that of the reference mixture. The loss of homogeneity of the matrix caused by fibres addition can explain this behaviour, since the first crack always localises at imperfections or weaker regions. For 1.5 and 2.0% percentages of steel reinforcement there is a smooth transition between the stiffness identified in the first two stages of behaviour. For this reason it is harder to identify the cracking load. In the mixtures reinforced with steel and glass fibres the cracking load increases with the reinforcement ratio. The growth ranges from -13 to 45% and from -20 to 9% respectively. In the mixtures with polypropylene fibres the cracking load is nearly 35% lower than the reference.



(a) (b)

Figure 10 – (a) Cracking load variation; and (b) maximum load variation.

In Figure 10b the maximum load variations relatively to the reference mixture, for each of the studied sets are presented. The maximum load of the mixtures with polypropylene and glass fibres is consistently lower than that of the reference mixture, probably due to the high porosity of these mixtures (Table 4). In fact, only for high percentages of glass fibres (1.5 and 2.0%) the strength of the reference mixture is exceeded. For the polypropylene FRCM the maximum load increases with the increase in fibre addition from -31 to -19%, despite being always lower than the reference. For steel fibre mixtures, the maximum load is always higher than that of the reference mixture, being the increase higher for higher percentages of fibres addition. This behaviour was expected, since more fibres in the tension zone mean more material to resist to the load. With the increase in the fibre tensile strength, from the lower value (corresponding to polypropylene fibres) to the higher value (corresponding to steel fibres), the maximum load also increases.

Table 4 – Mixtures porosity

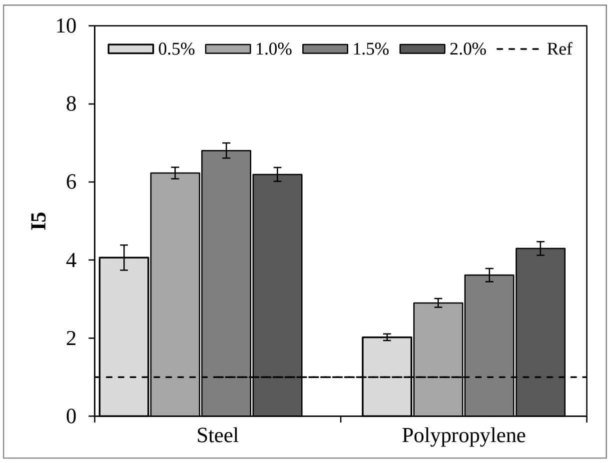
Mixture	Porosity (%)
Reference	8.54
St 0.5	8.62
St 1.0	8.46
St 1.5	7.56
St 2.0	9.61
Po 0.5	12.96
Po 1.0	11.96
Po 1.5	8.95
Po 2.0	7.98
Gl 0.5	8.87
Gl 1.0	9.80
Gl 1.5	9.82
Gl 2.0	11.52

3.4. Ductility

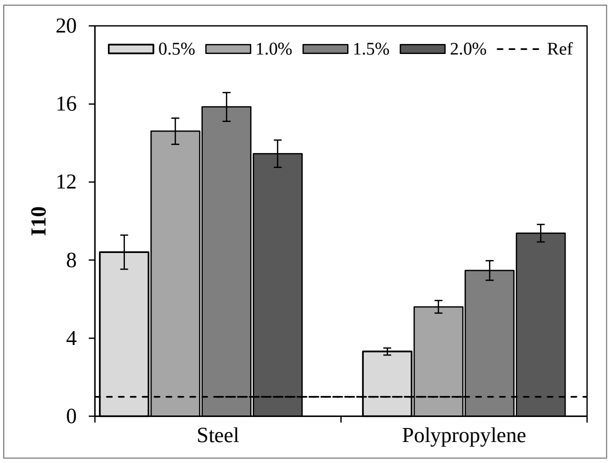
Figure 11 shows the studied toughness indexes, I5, I10 and I20 [32]. As already mentioned, the mixtures reinforced with polypropylene and steel fibres exhibited a ductile behaviour. For these mixtures, with the increase in fibres addition, cracks have more fibres linking their boundaries, this way showing more energy absorption capacity and, thus, the toughness indexes grow. In the polypropylene reinforced mixtures, this behaviour occurs for all the reinforcement percentages, which suggests that on the studied reinforcement range, increasing in the fibres percentage improves the ductility. However, the high porosity and low workability presented by these mixtures may be a limitative factor for the use of this type of fibres, especially in high percentages.

Mixture	I5	I10	I20
Reference	1.00	1.00	1.00
St 0.5	4.06	8.41	18.20
St 1.0	6.23	14.61	32.57
St 1.5	6.80	15.85	35.08
St 2.0	6.19	13.45	25.35
Po 0.5	2.02	3.32	6.52
Po 1.0	2.90	5.61	10.92
Po 1.5	3.61	7.47	15.75
Po 2.0	4.30	9.38	20.57
Gl 0.5	1.00	1.00	1.00
Gl 1.0	1.00	1.00	1.00
Gl 1.5	1.00	1.00	1.00
Gl 2.0	1.00	1.00	1.00

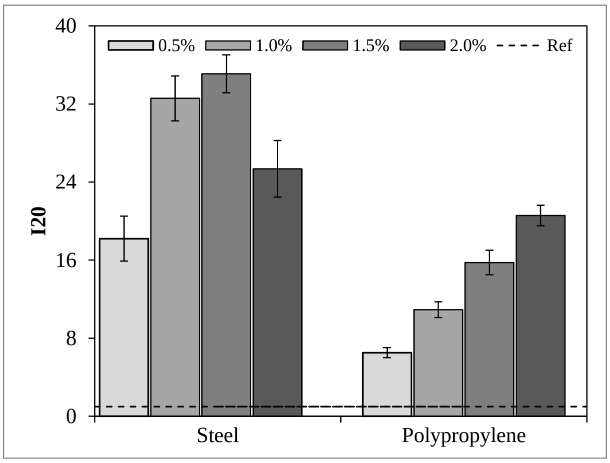
(a)



(b)



(c)



(d)

Figure 11 – (a) Table containing the average toughness indexes for all mixtures; and corresponding charts for (b) I5; (c) I10; and (d) I20.

In the mixtures reinforced with less than 1.5 % of steel fibres, there is also an increase in all toughness indexes. For the mixture with 2.0% of steel fibres, all the toughness indexes show a significant decrease, being even lower than those determined for the 1.0% mixture. For this particular case, a smooth transition between the uncracked/cracked phases is observed. For this reason, the following procedure has been adopted to determine the cracking point: two straight lines were adjusted to the slope of the load-displacement curve, one for Stage I (before cracking), and the other for Stage II (after cracking) and the point of intersection of these lines was assumed as the cracking point., as suggested by [33] It seems that, although the load and deformation capacities increase for all percentages of fibres reinforcement, the cracking point also increases for high percentages, which can result in a decrease of the toughness indexes, although the increase of the total absorbed energy.

Finally, ductility in these particular specimens can be achieved by two different approaches: either the fibre material has the ability to withstand plastic deformation; or the plastic deformations on the FRCM occur at the interface fibre/paste allowing some energy absorption. In the polypropylene FRCM, it seems to mainly occur the first since the fibres do not seem to experience considerable debonding from the matrix. For steel FRCM the two processes seem to happen because, in addition to present plastic deformation, the fibres also show significant debonding and slippage from the matrix.

For the mixtures reinforced with glass fibres the toughness indexes were not determined since it is considered that for this type of reinforcement, the tested samples did not show a ductile behaviour, failing with no evidence of a plastic zone in the load-displacement curves.

4. Conclusions

This research aimed at studying the effect of steel, polypropylene, and glass fibres on the mechanical properties of FRCM. The cementitious matrix was kept constant to facilitate the comparison of different material properties, including compressive strength, bending behaviour, cracking and maximum loads, and ductility, only changing the type and dosage of fibre, the latter ranging from 0.5% up to 2% in 0.5% increments. A total of three hundred and twelve samples, twenty four for each mixture, were produced and tested. The following main conclusions were drawn:

– The compressive strength of the FRCM matrix tends to increase with the increase of fibres addition. Results also show that the compressive strength growths according to the tensile strength and stiffness of the fibre, being lower for polypropylene and larger for steel fibres.

– Regarding the FRCM matrix flexural behaviour, a ductile behaviour is observed if fibres also exhibit a ductile behaviour, as in the case of polypropylene and steel fibres, and a fragile behaviour is observed, if fibres also present a fragile behaviour, as in the case of glass fibres.

– For mixtures with polypropylene or glass fibres additions, the increase in porosity is noticeable, leading to lower cracking loads, compared to the reference plain matrix. The maximum load rises with the increase in fibres addition for each type of fibre. With the increase in the fibre tensile strength from the weaker (polypropylene) to the stronger (steel) the maximum load also increases.

– For the specimens reinforced with glass fibres the toughness indexes were not determined, due to the exhibited fragile behaviour. For the remaining fibres, the increase in fibres addition leads to an increase of both toughness index and energy absorption capacity.

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