

Mechanical Characterization of Synthetic Macrofibres

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The present study proposes a methodology to characterize the mechanical properties of synthetic macrofibres, which are used as a reinforcement of new composites applied in civil construction industry. Some standards suggest that this characterization should be performed on original filaments and others propose using the current methodology used to characterise metallic fibres. These recommendations turn difficult the quality control procedure, so it was developed a methodology to characterize the mechanical properties of the macrofibres as they are supplied in the construction site, using the tensile test. In that sense, two types of macrofibres were evaluated obtaining their tensile strength and elastic modulus. Additionally, the macrofibres were mixed with aggregates in order to study how the abrasion affects their mechanical properties. Summing up, the proposed methodology is feasible, especially to estimate the tensile strength allowing its application in ordinary laboratories. Regarding the elastic modulus results, they may be underestimated using this method. Finally, it was observed that the abrasion between the macrofibre and the aggregates during the mixing process compromises the mechanical properties decreasing both the tensile strength and the elastic modulus.

Keywords: *Synthetic fibres, Mechanical properties, Tensile test, Tensile strength, Elastic modulus*

1. Introduction

The most important mechanical properties of fibres that are used to produce fibre reinforced concrete (FRC) are the tensile strength and the elastic modulus¹. The first directly affects the post-cracking behaviour of the FRC. In that sense, when the matrix cracks there is a stress transference from the matrix to the fibres. Then, the higher the fibre tensile strength is, the higher the capacity of the residual strength is¹. The elastic modulus of the fibre is important as it gives the stiffness and the capacity to restrain the propagation of the cracks². Hence, the characterization of these two properties is essential.

Regarding the mechanical properties, the behaviour of polymers presents variations that depend on their molecular structure, chemical composition, temperature, period of application and polymer processing history. The production process has a great influence on the final properties of the fibre. Extrusion is the most used method for the production of fibres. In this method, the polymer is heated and passes through a matrix with multiple holes. Then, the filaments produced are stretched in order to introduce permanent deformation increasing the orientation of the molecular chains^{3,4}. The mechanical properties of the fibres may also be affected for the cutting process during their production⁵⁻⁷.

It should be emphasize that the mechanical behaviour of fibres is affected by the variable characteristics of the material along its length. This may be attributed to two main factors: the probability to find weak spots on fibres with greater length and, in the case of crimped fibres, the possibility of having stress concentrations due to the geometrical irregularities^{8,9}.

Furthermore, these properties may be affected during the mixing process with the other concrete components because of the lower hardness presented by the synthetic fibres. In Salvador¹⁰, synthetic fibres were mixed in a fresh concrete for 20 minutes and it was found that, after the mixing, these fibres presented rough surfaces due to the abrasive process. Then it is important to know the impact that the concrete mixture has over the fibre mechanical properties.

In that sense, tests must be performed in order to characterize the properties of the macrofibres and they should be simple to allow their repeatability in other laboratories. However, there are no Brazilian standards providing referential procedures to characterize synthetic macrofibres for concrete reinforcement. Regarding the international standards, the European Committee for Standardization¹¹ may be considered as the only one focused on the characterization of these material. However, regarding the mechanical characterization (tensile test) of the synthetic macrofibres, this standard establishes that the test should be performed following the requirements of the European Committee for Standardization¹², which focuses on metallic fibres.

Apart from the European standard, other standards were found regarding the mechanical characterization of fibres in general, although they apply to textile fibre and not to synthetic macrofibres. These were the American standards ASTM^{6,13}. Besides, the literature presents different standards that prescribe that, the mechanical properties determination should be done through testing the original filaments used for the fibre production. An example of these is the American standard ASTM⁵ that indicates that 500 mm-length filaments must be tested in order to determine the tensile strength. The

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main drawback of this kind of test is that only the manufacturer is able to characterise the material. If the purchasers are willing to perform the tests, they must ask for the sample directly from the producer, preventing the free application in case of a reception control of the material. Furthermore, the use of original filaments in the tests prevents a proper assessment of the abrasive effect of the mixture on the fibre, which is one objective of this work. Thus, the existence of a test methodology to assess directly the fibre opens a series of possibilities for research and development.

Then, a proper test method was developed in order to allow testing the macrofibres as they are applied in concrete (60 mm-length). The methodology development was based on the information obtained from literature and from the experience achieved performing experimental tests. So, the mechanical properties (tensile strength and the elastic modulus) of two different synthetic macrofibres, which are usually used as reinforcement of concrete, were estimated. In that sense, it was also evaluated the influence of the abrasive effect due to the aggregates during the mixing process on the mechanical properties of the macrofibres. Hence, the tensile test considering the synthetic macrofibres in normal and mixed conditions was developed.

2. Methodology

In this section the synthetic macrofibres considered in this study are presented. Their geometric characteristics, which are essential to characterize their mechanical properties, are described. Finally, the process to prepare the specimens, the mixing process and the tests used in the experimental program are also explained.

2.1 Types of macrofibres and geometric characteristics

Two types of macrofibres available on the Brazilian market (called macrofibres A and B), composed by polypropylene were considered. According to the manufacturers, their main features are shown in Table 1. Notice that the manufacturer does not give the aspect ratio of the macrofibre B.

Macrofibre A exhibited a cord shape as shown in Figure 1a. These cords may be broken down into approximately 20 macrofibre bundles, which present multiple levels of twisting, generating a complicated geometry. Each bundle has one to three filaments bundled together, so that the bundle is composed of irregular cross-sections along its length.

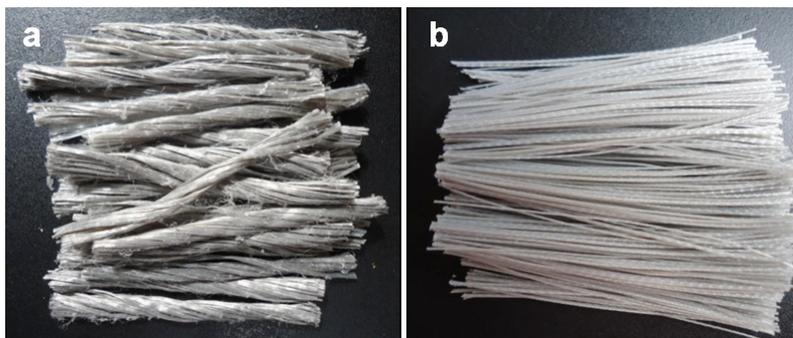


Figure 1- Macrofibre A sample a) and macrofibre B sample b) (Source: Cáceres et al., 2015)

Supplying this macrofibre in the form of bundles coiled in cords is done to facilitate the FRC mixing procedure, avoiding the macrofibre entanglement associated with a larger aspect ratio¹⁴. Thus, the cords may be considered as fibres with a low aspect ratio that will disperse easily in the mixture and simultaneously provide the dispersion of filaments with high aspect ratio. As a result, it is possible to use a macrofibre with a high final aspect ratio to provide better mechanical performance in the post-cracking behaviour of FRC.

On the other hand, macrofibre B (Figure 1b) presented an oval cross-section formed by grouped bundles but with an arrangement unlike that of macrofibre A. Macrofibre B is composed of one, two or three filaments grouped together. This macrofibre is produced in this way for the same reason as macrofibre A: increasing the aspect ratio with minimal impact on the mixing conditions to ensure homogenization of the material.

2.2 Macrofibre mixing process

In order to study how the mixing process affects the properties of the macrofibres, these went through the aggregates abrasive effect in a 120-litre cement mixer. In that sense, 12 litres of granitic coarse aggregate (maximum diameter equal to 9.5 mm) were used, being the macrofibre dosage approximately equal to 0.5% of the aggregate volume. The dosages were established considering the studies of Salvador (2012)¹⁰ who indicated that, normally, the average content of fibres is around 4.5 kg/m³ for different applications.

Once the aggregates were collocated into the cement mixer and this was switched on, the macrofibres were introduced manually in order to guarantee a good dispersion of the material. This procedure is indicated in the Japanese Society of Civil Engineers - JSCE-SF1¹⁵ for producing FRC. The total mixing time considered was 5 minutes. Notice that, the mixing process does not include fine

Table 1- Main characteristics of the macrofibres considered

Properties	Macrofibre A	Macrofibre B
Density (g/cm ³)	0.91	0.90 – 0.92
Length (mm)	54	58
Aspect ratio	158	*
Tensile strength (MPa)	570 - 660	620
Elastic modulus (GPa)	5	>7

aggregate nor water, which could have a significant influence in the result.

After the mixing process, the macrofibres were localized interlacing the aggregates as presented in Figure 2. These macrofibres showed an irregular geometry presenting fibre wall delamination, curvatures and tortuosity over their length. After the mixing process, a random selection of 10 macrofibres was done. These were carefully washed and manually dried with a cloth in order to avoid any interference during the preparation and the test result due to the possible adhered particles on the macrofibre surface. Then, the geometric and mechanical characterisation of the 10 macrofibres was performed using the same procedure applied to the original macrofibres.

2.3 Specimen preparation

The tensile test method developed to characterize the mechanical properties of the macrofibres followed as closely as possible the recommendations of the American standard



Figure 2- Synthetic macrofibres interlaced to the aggregates after the mixing process

ASTM ¹³, which is a general standard to assess the tensile strength of different kinds of fibres. The standard establishes gluing the fibres in frames and recommends that the total glued fibre length should be 1.5 times greater than the central free gap of the frame. Notice that the tests will be performed on filaments of the macrofibre.

Then, it was necessary to develop a frame to fix the macrofibre to increase the adhesion and friction between the macrofibre and the grips of the testing machine. In addition, the frame was used as a guide or reference to align coaxially the macrofibre and the testing machine grips. In that sense, the study of Cáceres ¹⁶ presented a study focusing the use of different frames regarding dimensions and materials, and the best results were obtained with a textile frame as presented in Figure 3a.

The frames dimensions adopted are those shown in Figure 3b. These are suitable for macrofibres with length around 60 mm. Considering the standard ASTM ¹³ a 10 mm gap was considered in order to guarantee a greater length embedded in the ends of the frame. Notice that before gluing the macrofibres, their end surfaces were manually screwed cautiously using a cutter, so that they have greater adhesion with the frame. On the rear of the frame, small plates of textile material were also glued in order to cover the ends of the macrofibres (Figure 3c) and thus, increase the adherence between the frame and the filament of the macrofibre.

The synthetic glue used must be strong enough to prevent the sample slip during the tensile process. In this study, a synthetic adhesive composed of cyanoacrylate ester was used. Notice that the central axis of the frame were marked (vertical line in Figure 3d) in order to glue the sample coaxially with the line of action of the load testing machine. Therefore, the misalignment or the torque that would tend to induce errors in the results was reduced. Notice that marks have been made to guide the cutting of the side frame (dashed line within the circle in Figure 3d) to facilitate cutting thereof and guarantee that only the macrofibres were stressed during the test.

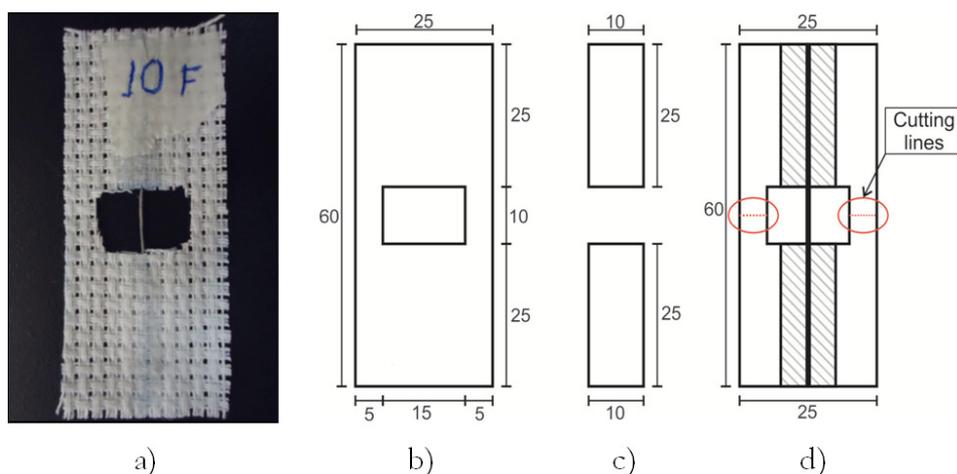


Figure 3- Textile frame a); frame dimensions (mm) b); textile sheets glued on the rear c), and macrofibre glued on the frame and cutting lines d)

2.4 Test methods

As described in Cáceres et al.¹⁷, previously to the test, a sample of macrofibres was taken in order to determine their density (ρ) by means of the picnometer test. This test requires a quantity of 30 g of cut macrofibres and provide an average value. However this value is well known and presents a low variation when working with a polymeric material such as polypropylene (0.90-0.91 g/m³). For the cross section determination 10 macrofibres were randomly selected to be analyzed. This ρ value was then used to determine the cross section (S) using the length (L) and the weight (m) of each macrofibre used in the tensile test as presented in Equation (1).

$$S = \frac{m}{\rho L} \quad (1)$$

2.4.1 Tensile strength

The tensile strength tests were performed using an Instron test machine, model 5569, with a load cell of 1 kN (Figure 4). The load was applied considering a velocity of 0.5 mm/min controlled by the piston displacement.

The samples were carefully placed between the grips of the test machine (Figure 4.a). Then, the lateral parts of the frame were cut (Figure 4.b) so that the macrofibre was the only to be pulled (Figure 4.c). The results of the test were curves load (F) – vertical displacement (δ), that were used to obtain the curves stress (σ) – strain (ϵ) for each sample. In that sense, σ was calculated dividing the load values (F) by the respective value of transversal section (S)⁴. On the other hand, ϵ was estimated considering the 10 mm-span and the results of the vertical displacement (δ).

2.4.2 Elastic modulus

Using the curves $\sigma - \epsilon$ obtained with the tensile test, the elastic modulus of the macrofibres tested was estimated. With that aim, a tangent line was plotted on the elastic region of the curves $\sigma - \epsilon$ considering the stresses related to the 10 and 30% of the macrofibre tensile strength and

their respective strains. These percentages were taken into account based on the requirements of the European Committee for Standardization¹¹. Therefore, the elastic modulus was calculated from the relation of the stress and the strain variations in the interval considered.

3. Results

3.1 Cross-sectional area of macrofibres

Table 2 presents the results of cross-sectional areas (S) of a total of 10 macrofibres under normal and mixed conditions. The determinations were made measuring the diameter according to the density method as indicated in the study of Cáceres et al.,¹⁷. It is noteworthy that were measured exactly the same macrofibres that were tested to direct tensile strength. It can be seen that macrofibre A under mixed conditions has a larger diameter whereas, macrofibre B practically maintain the same diameter. This shows that each macrofibre needs to be treated and studied individually as the mix conditions affect differently their properties.

3.2 Direct tensile stress of macrofibres

The results obtained performing the direct tensile stress test on the macrofibres are shown in Figure 5. These results are load-extension curves for each macrofibre tested. Furthermore, the average curve is presented with a darker color.

Table 3 presents the results of maximum loads of macrofibres under normal and mixed conditions. Furthermore, the mean of the ten results, the standard deviation (SD) and the coefficient of variation (CV) are also presented.

Considering the maximum load values, it can be assumed that, in case of macrofibres under normal conditions, macrofibre B had the maximum average load, reaching a value of 53.02 ± 1.88 N, which is 9% higher than the maximum average load of macrofibre A, which was 48.64 ± 2.94 N. Evaluating the mixing effect, it was observed that there was no significant change for macrofibre A, which had a maximum average load value of 51.07 ± 8.01 N. These showed an increase of a 5% of the value obtained under normal conditions. In case of macrofibre B, there was a decrease in the average load

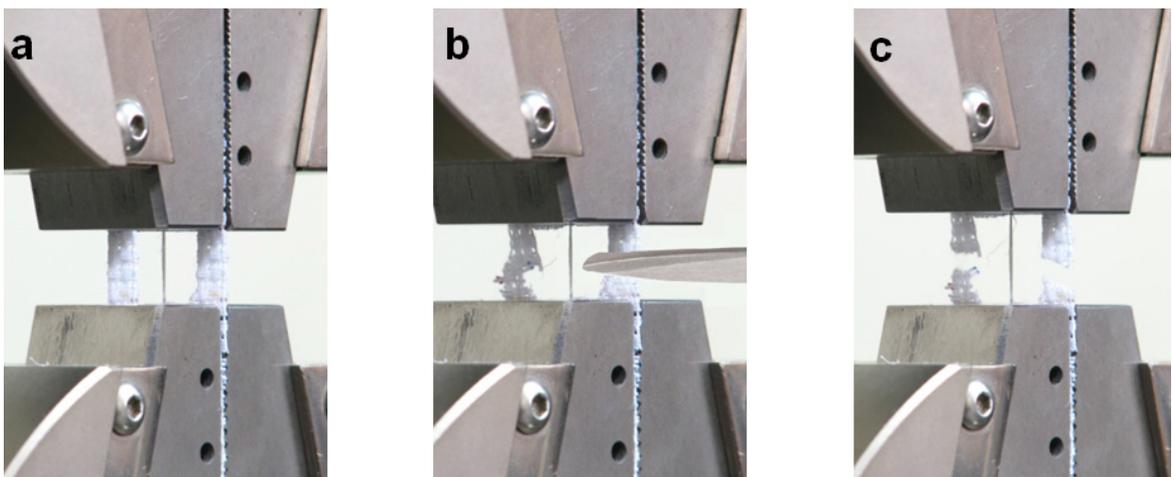
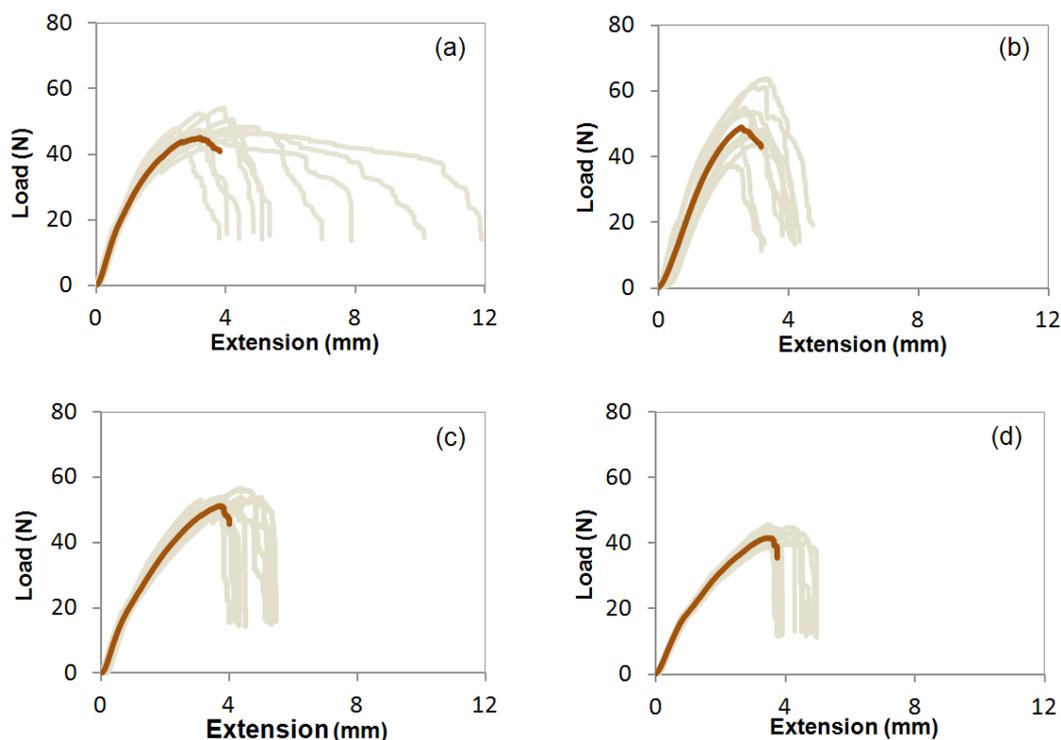


Figure 4- Tensile test: colocation of the sample a); frame cutting procedure b); test development c)

Table 2- Cross-sectional areas of macrofibres, according to the diameter of density method

Fibre	NORMAL CONDITIONS		MIXED CONDITIONS	
	Macrofibre A	Macrofibre B	Macrofibre A	Macrofibre B
	S (mm ²)			
1	0.100	0.075	0.091	0.077
2	0.107	0.075	0.099	0.085
3	0.105	0.083	0.096	0.079
4	0.107	0.080	0.123	0.082
5	0.099	0.079	0.087	0.077
6	0.084	0.077	0.116	0.081
7	0.088	0.079	0.117	0.082
8	0.094	0.074	0.124	0.075
9	0.092	0.080	0.107	0.076
10	0.086	0.077	0.098	0.076
Mean	0.096	0.078	0.106	0.079
SD	0.009	0.003	0.014	0.003
CV (%)	9%	3%	13%	4%

**Figure 5-** Average load-extension curve: macrofibre A (normal conditions) a); macrofibre A (mixed conditions) b); macrofibre B (normal conditions) c); macrofibre B (mixed conditions) d)

value of 20% (42.43 ± 2.52 N). It can be concluded that the total bearing capacity of both macrofibres was affected differently. Hence it is important to check how the effect of the mixture can influence the analysis of tensions.

3.3 Tensile strength and elastic modulus of macrofibres

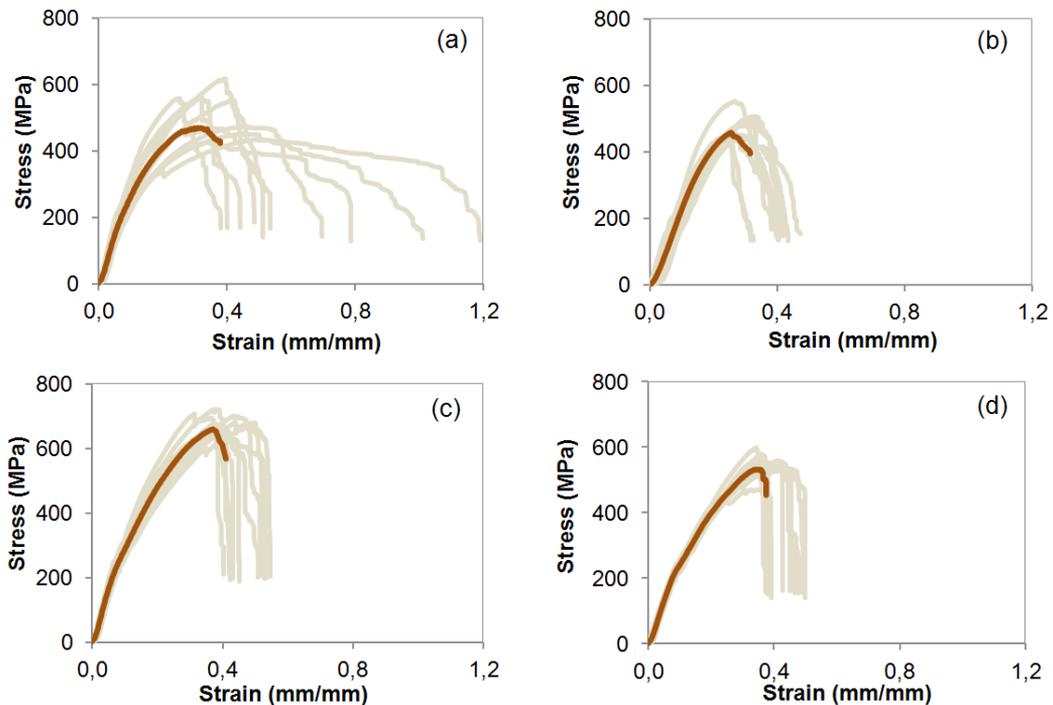
In Figure 6, stress-strain curves of macrofibres under mixed and normal conditions and also the mean curves for each condition are shown. Notice that, in each evaluation was used ten individual macrofibres.

Table 4 presents results of maximum tensile stress and elastic modulus of macrofibres under normal and mixed conditions. To determine tensile stress was used the cross-section values presented in Table 2 and the load values of the direct tensile stress test of Figure 5. The elastic modulus was obtained from the stress-strain curves presented in Figure 6.

It should be emphasized that the average values of tensile stress of both macrofibres A and B under normal conditions, do not coincide with the declared values by manufacturers. In case of the macrofibre A, the average tensile stress is less than specified by the manufacturer (570 MPa to 660 MPa),

Table 3- Maximum loads of macrofibres in normal and mixed conditions

Fibre	NORMAL CONDITIONS		MIXED CONDITIONS	
	Macrofibre A	Macrofibre B	Macrofibre A	Macrofibre B
	(N)	(N)	(N)	(N)
1	46.81	49.62	44.68	41.66
2	48.29	53.05	44.75	40.15
3	45.10	53.44	48.40	44.01
4	46.43	56.47	63.96	44.98
5	46.85	54.02	37.83	39.25
6	47.45	51.25	54.12	45.90
7	54.28	52.99	54.88	43.11
8	52.50	53.85	61.40	45.22
9	50.86	54.00	47.38	40.37
10	47.84	51.52	53.26	39.69
Mean	48.64	53.02	51.07	42.43
SD	2.9392	1.8758	8.0142	2.5170
CV (%)	6%	4%	16%	6%

**Figure 6-** Average stress-strain curve: macrofibre A (normal conditions) a); macrofibre A (mixed conditions) b); macrofibre B (normal conditions) c); macrofibre B (mixed conditions) d)

and on the other hand, in case of the macrofibre B the average tensile stress is greater than the value indicated by the manufacturer (620 MPa). In case of mixed macrofibres it was not possible to make any comparison; since the tensile stress of a blended macrofibre is generally not provided.

It is also necessary to highlight that the scatter of the mechanical results depends on the approach of measuring the cross-sectional area of the macrofibres as observed in Cáceres et al.¹⁷. This study considered three methods to determine the cross-sectional area: caliper, images analysis and density method. Since the density method showed the

lower scatter, it was the one considered in the proposal presented here.

3.2 Representativeness of the sample tested

The European standard EN 14889-2: 2006 (AENOR, 2006)¹¹ recommends testing the tensile strength for at least 30 fibres. However, for each condition evaluated, the number of macrofibres used was 10 units. Nevertheless, it is important to know if the chosen sample is sufficient, or whether it is still necessary to test more samples, to have more reliable results of tensile stress and elastic modulus. So, the determination

of sample size was made according to the established by Bussab and Morettin¹⁸, with the statistical values of tensile stress presented in Table 4 and using Equation 2, where: the number or size of the sample (n); t distribution (t); standard deviation (s); and the acceptable error, corresponding to 10% of the mean value (e). This is an arbitrary value and it was chosen 10% considering that this is a new experimental test and also the expected variation of synthetic macrofibres, once this material does not have well defined mechanical properties and even least geometric characteristics when compared to the steel fibres, for example. In that sense, this value is in accordance to the acceptable variation between the declared value and the obtained one established in the European Committee for Standardization¹¹.

$$n = \frac{\tau_{n-1}^2 \cdot s^2}{e^2} \quad (2)$$

Thus, regarding the maximum tensile stress, the values of 'n' for the macrofibres under normal conditions were, 9 for macrofibre A and 1 for macrofibre B. That results means that 9 and one fibre are samples large enough to guarantee that the results will be within the error of 10% of the average value. In case of macrofibres under mixed conditions, the values of 'n' were, 3 for macrofibre A and 2 for macrofibre B. Then, it is stated that in all cases the selected sample of 10 units is already sufficient and representative, for the determination of maximum average tensile stress.

Referring to the elastic modulus, the values of 'n' for the macrofibres under normal conditions were, 11 for macrofibre A and 5 to macrofibre B. In macrofibres under mixed conditions the values of 'n' were 12 for macrofibre A and 4 for macrofibre B. Therefore, for macrofibre A, both under normal and mixed conditions, the minimum number of units in the sample needs to be slightly higher than 10, to be fully considered representative. However, it is expected that little change could occur if one or two additional tests would be made to characterize this macrofibre. Thus, it can be said that the values obtained are significant for the analysis

of the material presented here. In case of the macrofibre B, in both situations, the analysis sample taken of 10 units is sufficient to obtain reliable results, due to the lower intrinsic variability of this macrofibre.

4. Analysis

4.1 Tensile strength

Due to the effect of the abrasion on the macrofibres surface and the difficulties provided for the cross section determination the tensile strength first analysis is focused on the maximum load results. According to the results presented in Table 3, the macrofibres presented different patterns after being submitted to mixing process. In case of macrofibre A, there is an increase of 5% comparing with the load value under normal condition. On the other hand, in case of macrofibre B the load value decreases in 20% after mixing, as expected. The increase in the load capacity observed for macrofibre A is due to differences in cross sections of the fibres composing each sample. During the sample preparation, the separation process of filaments could be affected by the human factor, resulting on one single filament or one and a half filament for each specimen. This condition is presented mainly in those macrofibres which are grouped by a greater number of microfilaments along its length, as the macrofibre A. It should be noted that the average cross section area of the sample of macrofibre A is greater after mixing denoting that the sample should be composed by thicker fibres. This condition will generate an increase in the average load strength capacity of the macrofibres tested after mixing. Hence, in order to evaluate the real effect of mixture on the macrofibres, it is also necessary to consider the tensile strength.

In this regard it is analysed the tensile strength behaviour of both macrofibres. Thereby, in Figure 6 indicates that macrofibre B has higher tensile strength than macrofibre A under normal conditions (not mixed). The average maximum stress reached by macrofibre B was 680.24 ± 23.83 MPa, which was 33% higher than the result presented by macrofibre A (510.86 ± 66.31 MPa).

Table 4- Maximum tensile stress and modulus of elasticity of macrofibres under normal and mixed conditions

Fibre	NORMAL CONDITIONS				MIXED CONDITIONS			
	Macrofibre A		Macrofibre B		Macrofibre A		Macrofibre B	
	σ (MPa)	E (GPa)	σ (MPa)	E (GPa)	σ (MPa)	E (GPa)	σ (MPa)	E (GPa)
1	468.41	3.23	659.89	3.75	491.13	2.98	542.85	2.98
2	452.01	2.78	707.41	4.16	450.55	2.79	469.69	2.89
3	427.77	3.17	646.62	2.77	506.25	2.68	556.37	3.18
4	435.88	2.73	702.16	3.34	518.23	3.14	550.69	3.04
5	473.28	2.94	682.06	3.45	433.78	3.25	512.32	2.70
6	563.48	4.06	665.81	3.42	464.62	3.07	564.07	3.05
7	616.66	3.42	666.75	3.36	467.24	3.31	523.60	2.33
8	557.66	3.69	723.36	3.62	496.98	3.37	604.11	2.86
9	554.10	3.70	677.53	3.49	443.67	2.52	530.67	3.08
10	559.10	4.19	670.84	3.75	545.99	3.61	520.42	2.83
Mean	510.86	3.39	680.24	3.51	481.85	3.07	537.48	2.89
SD	66.31	0.51	23.83	0.36	35.91	0.34	35.69	0.24
CV (%)	13%	15%	4%	10%	7%	11%	7%	8%

The abrasion suffered by the macrofibres during the mixture process together with the coarse aggregates caused a reduction of tensile strength of both macrofibres. Comparing the results obtained in the post mixture analysis with the primary result, a reduction of 6% in the tensile strength was obtained for macrofibre A that presented an average tensile strength of 481.85 ± 35.91 MPa. The macrofibre B presented an average tensile strength of 537.48 ± 35.69 MPa after mixture, 21% lower than the primary tensile strength.

Probably, the minor reduction of strength observed for macrofibre A is due to the fact that this type of macrofibre is supplied in bundles grouping fibres like ropes (Figure 1a). The macrofibre A itself could be considered as a group of monofilaments that could be separated manually. So, the inner filaments have a protection against abrasion given by the external filaments during the period of mixture when the macrofibres are dispersed in the mix. It is also frequent to observe that group of macrofibres are not perfectly dispersed and separated after mixing. So, as the test was carried out using the filament, this kind of macrofibre could preserve in better condition the original strength. In Figure 7a and 7b is possible to observe the image of macrofibre A previously and after the mixture with the aggregates.

Moreover, it is observed that macrofibre A under normal conditions shows greater strain. This behaviour seems to be associated to the fact that this macrofibre appears to have microfilaments grouped together along its length. So, during

the test, and when the load is increasing gradually, these microfilaments are progressively separated and broken. On the other hand, when the macrofibre is under mixed conditions, the abrasive effect provoke superficial wore or broke several of these filaments reducing its deformation capacity. Thus, the macrofibres does not break gradually and present a lower level of strain during the test.

The macrofibre B presented numerous microfilaments with branch aspect in its surface after the mixing process in contrast with the smooth surface observed earlier as illustrated in Figure 7c, d, respectively. This condition could act as surface defects causing the more intense tensile strength reduction. This severe damage provoked by the mixing process to macrofibre B could be associated to the easier dispersion process that characterizes this type of macrofibre. Although this macrofibre is also a group of two or three filaments, the dispersion of the filaments is easier because the macrofibre is supplied loose. So, the abrasion of the filaments tested in this experimental study had occurred through a longer period of time, since the beginning of the mixture.

It was also observed that macrofibre B, under normal and mixed conditions, have reached a similar maximum strain. This fact shows that the filaments that compose this macrofibre do not break gradually during the test in both conditions. So, even after mixing, these macrofibres presented the same behaviour, despite having a certain level of wear on its surface.

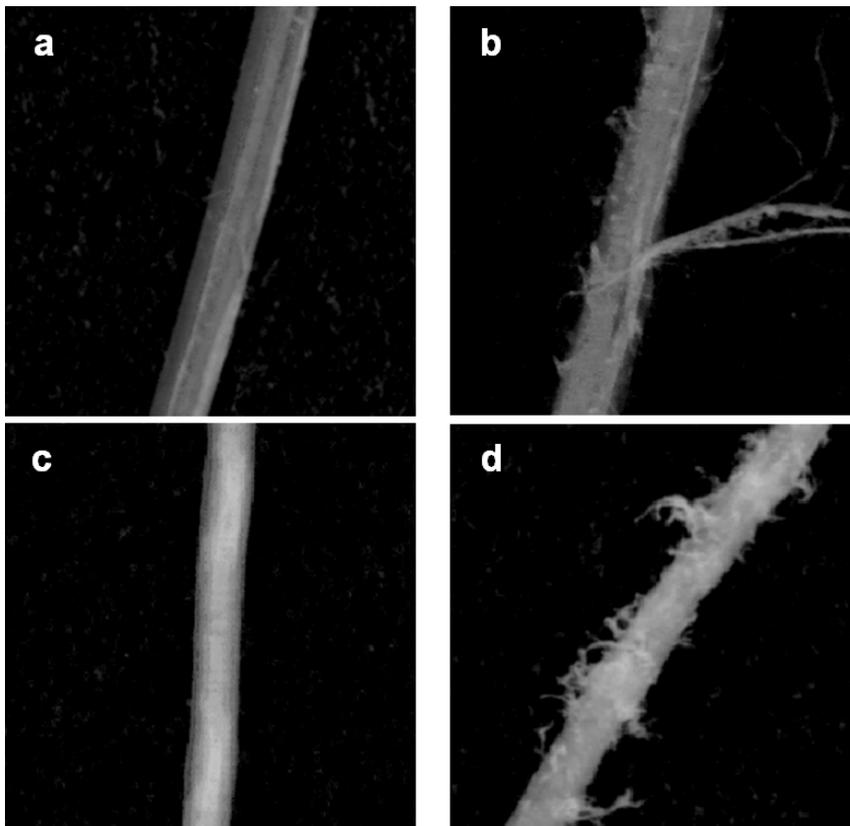


Figure 7- Magnified images: macrofibre A under normal conditions a); macrofibre A after mixing b); macrofibre B in normal conditions c); macrofibre B after mixing d)

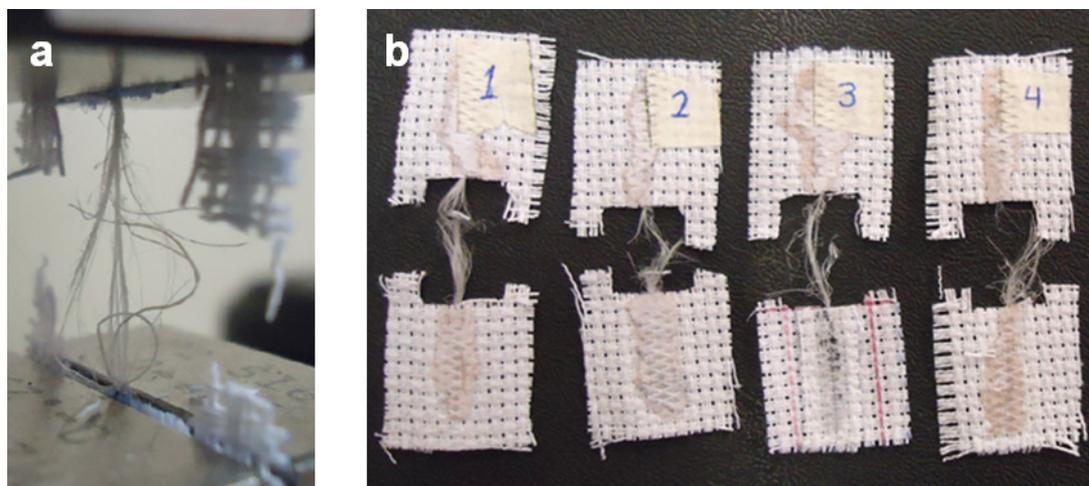


Figure 8- Macrofibre rupture process during the test (shredding) a); Defibrillated macrofibres after test b)

It is necessary to emphasize that, although the macrofibre B shows a further decrease in strength, the maximum stress after mixing obtained with this macrofibre is still 12% higher than the maximum stress reached by macrofibre A after mixing. Finally, it was found that both macrofibres have defibrillated after being mixed, as it could be observed in Figure 7b and Figure 7d. This observation is in accordance with previous studies focusing synthetic macrofibres manufactured with the intention to achieve this ability of splitting into multiple filaments when mixed in concrete¹⁹⁻²¹.

On the other hand, the determination of the cross-sectional area is compromised with the increase of surface defects in the mixed macrofibres. The cross-sectional area determination through the density method¹⁷ that use the macrofibre mass and length, used in this study, could not disregard the branch like filaments that are still attached to the macrofibre surface. So, the total macrofibre mass measured in the test overestimate the actual cross-section area that bear the tension and underestimate the tensile strength value.

Finally, it should be noted that during the test loading process, the macrofibre filaments presented progressive rupture, as shown in Figure 8a. The external filaments suffer rupture earlier than the core filaments that remain intact at the end of test sometimes, as also shown in Figure 8b. Thus, the macrofibre rupture was characterized by a predominant defibrillating failure mechanism instead of a unique transverse crack surface formation during fracture. This means that the macrofibre rupture involves the breaking of bonds between these microfilaments.

4.2 Elastic modulus

Initially, it should be emphasized that the elastic modulus results showed values below the parameters given by producers. This could be, at least, partially explained by the differences in the test methods. The producers test method use the original wires with great length to determinate the elastic modulus of macrofibres. So, the magnitude of deformation is higher and easily measured with higher precision by means of image analysis. In the test method developed here, the macrofibre length is smaller and the strain was measured directly from the displacement control of the testing machine. Thus, all

deformations and sliding associated to the macrofibre contact area with the machine grips are somehow incorporate in the measured strain. Therefore, the deformation tends to be overestimated as compared to that measured in wires where it is possible to isolate extrinsic strains. Hence, although the proposed test method turn feasible to evaluate macrofibres in the application conditions, it is possible to affirm that this test method tends to underestimate the value of the elastic modulus of the macrofibre.

However, in previous study carried out by Salvador¹⁰, which used macrofibre A original wires of greater length (total length of 500 mm and effective length 250 mm), the obtained average value of the elastic modulus was 2.63 ± 0.09 GPa, which is even lower than the result obtained in this study (3.39 ± 0.51 GPa). This means that, although there is still the need for further improvements, this type of test method can be considered as a good tool to characterize the material properties.

The macrofibre B elastic modulus in normal conditions was the highest average value 3.51 ± 0.36 GPa), which is 4% higher than the obtained with macrofibre A (3.39 ± 0.51 GPa). Furthermore, both macrofibres exhibit a decrease in elastic modulus value after being mixed with the aggregates. After mixing, macrofibre A presents an elastic modulus of 3.07 ± 0.34 GPa, 10% less than the original value. The macrofibre B elastic modulus measured after mixing decreased to 2.89 ± 0.24 GPa, corresponding to a reduction of about 21%. This result was not expected as occurred for the tensile strength due to the surface defects. But the results could be affected by the same cross-section area determination inaccuracy that affects the tensile strength determination.

Another considered possibility is associated to the energy applied during the mixing process of the macrofibres that somehow can reduce the degree of crystallinity of the macrofibres. In that situation, there may have been a misalignment of the molecular chains that could negatively influence the macrofibres mechanical properties and, especially, the elastic modulus^{4,22}. Another hypothesis is related to the smaller diameter of the macrofibre B that may have favored more significant damage and, thus, may have reduced the elastic modulus. Finally, the macrofibre A presents an

average elastic modulus of 3.07 ± 0.34 GPa, after mixing, that is 6% higher than result obtained with macrofibre B 2.89 ± 0.24 GPa at the same condition.

5. Conclusions

This experimental study demonstrates the feasibility of direct tensile testing method made in macrofibre in the condition that it is delivered by the supplier. The test method was particularly effective with regard to the tensile strength determination. The elastic modulus determination presented a tendency to underestimate the measured value. Despite that, the test could be used as an instrument to carry out the material quality control. Thus, this test method can be considered a great gain for fibre reinforced concrete reliability making possible to avoid the evaluation based only on the data given by the producers.

The direct tensile test carried out in cut macrofibre also makes possible to evaluate the effect generated by abrasion resulting from the macrofibre mixture with the aggregates in their mechanical properties. There was a decrease in

macrofibres mechanical properties when they were mixed with aggregates. This loss of mechanical performance depends on the type of macrofibres and affects both tensile strength and elastic modulus. This reduction of mechanical capacity alone is not enough to evaluate the composite behaviour, especially in the post-crack stage because the macrofibres post-crack reinforce capacity also depends on the bond with the matrix. This adherence could be enhanced with an increased surface roughness together with the macrofibre filamentising derived by the contact with the aggregates²³. So, the combination between a good adherence and the mechanical properties preservation could be pointed as an interesting strategy to enhance the composite performance. So, further studies should be carried out in the future focusing the mixture procedure together with the post-crack strength evaluation in order to optimize the composite behaviour.

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7. References

1. Figueiredo AD. *Concreto reforçado com fibras* [tese]. São Paulo: Escola Politécnica, Universidade de São Paulo; 2011. 248 p.
2. Tiguman MP. *Estudo comparativo entre métodos de quantificação de tenacidade usando concreto reforçado com macrofibras de polipropileno* [dissertação] São Paulo: Universidade de São Paulo; 2004. 85 p
3. Van Vlack LH. *Princípios de ciência dos materiais*. São Paulo: Edgard Blücher; 1970.
4. Callister WD. *Ciência e engenharia de materiais: uma introdução*. 5a Ed. Rio de Janeiro: Livros Técnicos e Científicos; 2002.
5. America Society for Testing Materials. *ASTM D2256/D2256M-10: Standard test method for tensile properties of yarns by the single-strand method*. ASTM; 2010.
6. America Society for Testing Materials. *ASTM D3822-07: Standard test method for tensile properties of single textile fibers*. ASTM; 2007.
7. Thomason JL, Kalinka G. A technique for the measurement of reinforcement fibre tensile strength at sub-millimetre gauge lengths. *Composites Part A: Applied Science and Manufacturing*. 2001;32(1):85-90. [http://dx.doi.org/10.1016/S1359-835X\(00\)00122-6](http://dx.doi.org/10.1016/S1359-835X(00)00122-6)
8. Zohdi TI, Steigman DJ. The toughening effect of microscopic filament misalignment on macroscopic ballistic fabric response. *International Journal of Fracture*. 2002;118(4): L71-L76. <http://dx.doi.org/10.1023/A:1023390505987>
9. Zhu D, Mobasher B, Erni J, Bansal S, Rajan SD. Strain rate and gage length effects on tensile behavior of Kevlar 49 single yarn. *Composites Part A: Applied Science and Manufacturing*. 2012;43(11):2021–2029. <http://dx.doi.org/10.1016/j.compositesa.2012.06.007>
10. Salvador RP. *Análise comparativa de métodos de ensaio para caracterização do comportamento mecânico de concreto reforçado com fibras* [tese]. São Paulo: Universidade de São Paulo; 2012.
11. European Committee for Standardization. *EN 14889-2. Fibres for concrete – Part 2: Polymer fibres – Definitions, specifications and conformity*. West Conshohocken, PA: ASTM; 2006.
12. European Committee for Standardization. *EN 10002-1:2001. Tensile testing of metallic materials. Part 1. Method of test at ambient temperature*. West Conshohocken, PA: ASTM; 2001.
13. America Society for Testing Materials. *ASTM C1557-03: Standard test method for tensile strength and young's modulus for fibers*. West Conshohocken, PA: ASTM; 2008.
14. Figueiredo AD, Ceccato MR. Workability analysis of steel fiber reinforced concrete using slump and VeBe test. *Materials Research*. 2015;18(6):1284-1290. <http://dx.doi.org/10.1590/1516-1439.022915>
15. The Japan Society of Civil Engineers. JSCE-SF1: Method of making steel fiber reinforced concrete in the laboratory. *Concrete Library*. 1984;3:45-47.
16. Cáceres AR. *Caracterização geométrica e mecânica de macrofibras poliméricas*. [dissertação] São Paulo: Universidade de São Paulo; 2015. 71 p.
17. Cáceres AR, Galobardes I, Rebmann MS, Monte R, Figueiredo AD. Geometric characterization of polymeric macrofibres. *Revista IBRACON de Estruturas e Materiais*. 2015;8(5):644-668. <http://dx.doi.org/10.1590/S1983-41952015000500006>
18. Busabb W, Moretim P. *Estatística básica*. 5a ed. São Paulo: Saraiva; 2002.
19. Bentur A, Mindess S. *Fibre reinforced cementitious composites*. United Kingdom: Elsevier; 2007.
20. Nanni A, Meamarian N. Distribution and opening of fibrillated polypropylene fibers in concrete. *Cement and Concrete Composites*. 1991;13(2):107–114.
21. Trotier JF, Mahoney M. Innovative synthetic fibers. *Concrete International*. 2001;23:23-28. <http://www.swchem.net/image/img/10002188.pdf>
22. Canevarolo SV. *Ciência dos polímeros. Um texto básico para tecnólogos e engenheiros*. 2a ed. São Paulo: Artliber; 2006.
23. Bentur A, Mindess S, Vondran G. Bonding in polypropylene fibre reinforced concretes. *The International Journal of Cement Composites and Lightweight Concrete*. 1989;11(3):153-158.