MECHANICAL CHARACTERIZATION OF CONCRETE REINFORCED WITH COMPOSITE GLASS MACROFIBRE

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Abstract

The introduction of fibre reinforced concrete (FRC) as a structural material in the fib Model Code 2010 represents an important advance for this technology. Nevertheless, it makes even more relevant the concern about the knowledge of parameters for quality control. In this context, the introduction of new fibres in the market should be followed with simple and reliable test methods to perform its evaluation. One of the major problems is the determination of fibres mechanical properties through tests that require the use of yarns, which are not easily available for the consumers. Other concern is related to difficulties associate to the execution of the FRC evaluation through the EN 14651 three-point bending test (3PBT) for regular quality control. This test was chosen by the fib Model Code to parameterize the FRC post-crack behaviour but requires more complex equipment and careful execution. This paper presents an experimental investigation using composite AR-glass macrofibre, performing the fibre characterization directly in the macrofibre and post-cracking behaviour measured with 3PBT test together with the double punch test (DPT). The tensile strength measured directly in the composite glass macrofibre showed good results, but the Young's modulus procedure needed further implementation to increase accuracy in deformation measurements. The results also indicate an excellent correlation between the 3PBT and DPT, what makes possible to perform regular quality control of FRC in a simpler mode, even when composite glass macrofibre was used.

1. INTRODUCTION

The adding of fibres to increase ductility in cementitious materials is a well stablished technology. Fibres can be considered as a randomly distributed reinforcement and they can provide an improvement in the crack distribution restraining the crack width. These fibres can be derived from materials with different characteristics, such as steel, glass or polymers, resulting in composites with different mechanical behaviour.

The new fib Model Code 2010 [1] introduces a parameterization which turns possible to consider the fibre reinforced concrete (FRC) as a structural material, providing a more assuredness condition to designers work. Fibres can be used as partial or total substitution of conventional reinforcement [2]. Nevertheless, fibre produced with materials with a Young´s modulus that are significantly affected by time and/or thermo-hygrometrical phenomena are not covered by this code. Consequently, polymeric macrofibres have been the subject of many studies focusing on creep behaviour [3]. These studies aim to produce subsidies for the specific parameterization of these fibres to be introduced in future revisions of the fib Model Code.

Alkali-resistant (AR) glass fibres have been successfully used as a reinforcement for very thin precast elements produced with cementitious materials, known as GRC (glass fibre reinforced concrete). The use of AR-glass macrofibre as main concrete reinforcement is already been studied, especially on structural applications characterized by a high degree of redundancy, as slabs on ground [4, 5] and concrete pipes [6]. More recently, a new glass macrofibre, composed of filaments grouped in bundle, was introduced in market. This new product was designed to provide post-cracking strength and increase toughness to concrete, improving impact and fatigue resistance. However, it is already known that the type of material with which the fibre is produced affects the FRC behaviour [7]. In this way, the characterization of the fibre is important because this will influence its capacity of reinforcement. The problem is the fact that the standard test methods prescribed for fibre characterization is based on tests performed with the yarn, which is normally inaccessible for users.

The three-point bending test (3PBT) carried out on a notched beam according to EN 14651 [8] is the method chosen by the fib Model Code 2010 to characterize FRC as a structural material. Nevertheless, alternative tests can be used if correlation factors with the EN 14651 are proven [1]. Alternatively, the double punch test (DPT) [9], also known as Barcelona test, has been indicated as a quality control test method for post-cracking evaluation. The DPT has a series of advantages over the traditional flexural beam tests, including (1) smaller and lighter specimens that can be more easily handled by a single technician; (2) specimens made in cylindrical moulds of Φ150 mm x 150 mm or that are cut from standardized cylinders of Φ150 mm x 300 mm normally used in compressive strength tests; and (3) tests can be carried out in a conventional testing machine without closed loop system. Several other advantages of the DPT were highlighted by researchers in comparison with bending tests, such as material and time saving, larger failure surface, lighter specimens and the possibility of testing cores extracted from structural elements [9, 10, 14]. Despite these advantages, the dissemination of DPT for characterization of FRC is limited by the lack of correlations with the 3PBT [9].

The objective of this paper is to present an experimental investigation using composed AR-glass macrofibre, performing the fibre characterization directly in the macrofibre and post-cracking behaviour measured with 3PBT and DPT. The paper also presents a correlation between the FRC post-cracking results obtained with both tests. This correlation is required by the fib Model Code 2010 to assume the DPT as an alternative method to the 3PBT.

2. METHODOLOGY

In order to characterize the FRC, initial tests were carried out to evaluate the geometric characteristics of the fibre, as well as its tensile strength and Young´s modulus. Then, the post-cracking behaviour was analysed by the 3PBT together with the DPT as described in more details in the following items.

– **2.1 Fibre characterization**

It is well known that the type of the fibre and its geometric characteristics directly affect the mechanical proprieties and the fibre-matrix interaction [7]. Therefore, these parameters and the tests used in this experimental program are presented in this section.

This study focused a macrofibre composed by AR-glass microfibres covered by a thermoset resin as shown in the Fig. 1.

Figure 1: Composite AR-glass macrofibre

To verify the geometric characteristics, thirty samples were analysed for length (L), diameter (d) and aspect ratio (length/diameter) determination. The length was measured with digital calliper with an accuracy of 0.1 mm. The density (ρ) of the macrofibres was evaluated using a helium gas pycnometer (Multipycnometer Quantachrome MVP 5DC) at 26 °C. The diameter (d) was obtained based on the Eq. (1). The mass (m) of the macrofibres were measured with a scale accuracy of 0.0001g.

$$d = \sqrt{\frac{4000.m}{\pi.\rho.L}} \tag{1}$$

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Where,
d = diameter of the fibre (cm);
m = mass of the fibre (g);
ρ = density of the fibre (g/cm^3), and
L = length of the fibre (cm).

The ASTM D225 standard [11] describes the procedure to evaluate the tensile strength of many types of yarns, included the glass ones. As the method was developed for yarn testing, both sample length and fixing method cannot be adopted directed for macrofibres, which are shorter. However, the end consumer usually does not have access to yarn samples. Hence, the first need in evaluating the tensile strength directly on the macrofibre is to ensure its fixation, avoiding specimen slipping. In that sense, the macrofibre ends were embedded in epoxy resin, as showed in Fig. 2. Thus, it was possible to fix the samples in the claws, as it can be seen in Fig. 3. Fourteen samples were tested in an Instron machine, Model 5569, with a load cell of 1 kN. The load was applied using the rate of displacement of 0.5 mm/min. The rupture of the fibres occurred in the centre of the sample and not in the epoxy resin, as shown in Fig. 4.

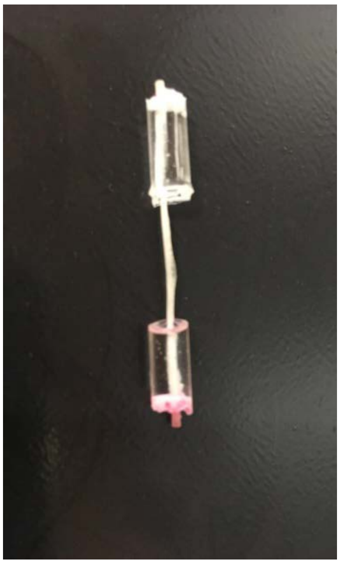


Figure 2: Microfibre embedded in epoxy resin before test

Figure 3: Macrofibre placed between the grips

Figure 4: Microfibre after test

The output of the tensile test was expressed by load (F) versus displacement (δ) curves, which are converted to stress (σ)versus strain (ε) curves. The tensile stress was calculated dividing the load (F) by the transversal section area calculated using the diameters previously obtained by Eq. (1).

The Young´s modulus was estimated as proposed by [12], considering the stresses related to the 10 and 30% of the macrofibres tensile strengths and their respective strains (ε), which were determined by dividing the value of the displacement (δ) by the distance between the grips (L).

− 2.2 FRC characterization

The concrete mix used in this study is presented in Table 1. The amount of superplasticizer was 0.05% by weight of cement. Three macrofibre contents were used in the experiment: 3.8, 7.6 and 11.5 kg/m³. A plain concrete was also tested as a reference.

Table 1: Mix design of the concrete

Cement [kg]	**Fine sand [kg]**	**Coarse sand [kg]**	**Gravel 12.5 mm [kg]**	**Gravel 19 mm [kg]**	**Water [kg]**	**Superplasticizer [g]**
394	134	536	532	532	193	394

The 3PBT followed the recommendations of the standard EN 14651 [8]. The samples were notched beams with dimensions equal to (150x150x550) mm³. The crack opening, measured as crack mouth opening displacement (CMOD), was evaluated with a clip gauge fixed at the notch (Fig. 5). The results are represented through a load-CMOD curve, as illustrated in Fig. 6.

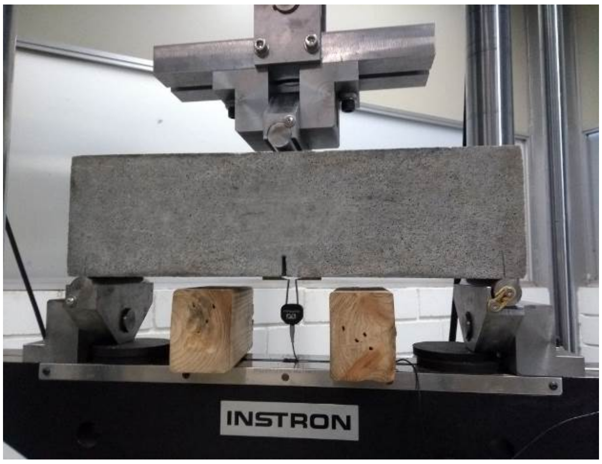


Figure 5: Three-point bending test (3PBT)

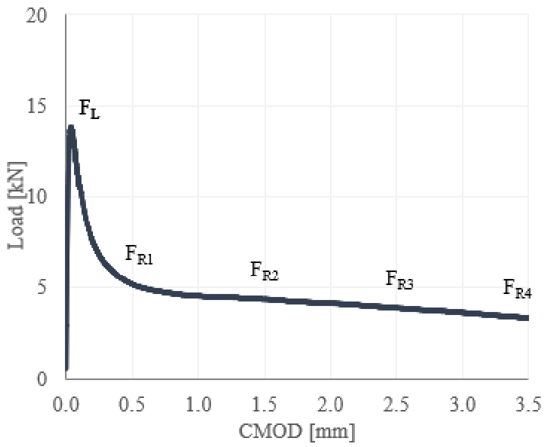


Figure 6: Schematic curve of 3PBT

The DPT was presented in [9] and standardized by UNE 88515 [13]. The initial configuration of the DPT involved measuring the circumferential displacement with a chain extensometer. Nevertheless, the use of this extensometer limits its applicability and an alternative setup controlling the axial displacement without the need of the extensometer was proposed [14] and used in this study. In this new test configuration, the cylindrical specimen is positioned between two steel cylindrical punches that receive the load applied by the plates of the press at a constant rate of displacement of 0.5 mm/min (Fig. 7). The test is characterized by the appearance of 2 to 4 radial cracks, as shown in Fig. 8. The cracking load (F_{cr}) is obtained when the stresses reach the tensile strength of the concrete matrix and, after that, the fibres bridge the crack resulting a residual strength. The results are represented through a load-axial displacement curve, as illustrated in Fig. 9.

Figure 7: Double punch test (DPT)

Figure 8: Cracking patterns observed

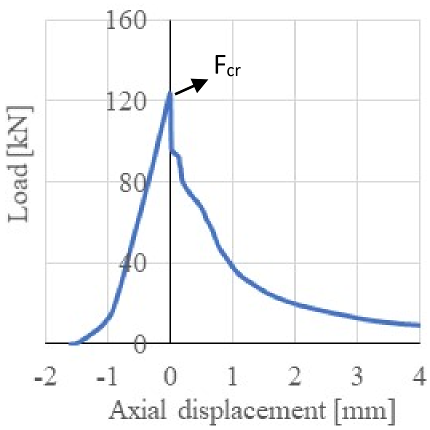


Figure 9: Schematic curve of DPT

The specimen used has a diameter and a height of 150 mm and was produced by cut from standardized cylinders of Φ150 mm x 300 mm. Six specimens were tested for each fibre content. The residual forces ($F_{R,i}$) were obtained from the curves for axial displacements of 0.5, 1.5, 2.5 and 3.5 mm. Also, the energy dissipated at these level of axial displacements ($E_{DPT,i}$)

was determined in order to calculate the predicted residual 3PBT strength ($F_{3PBT,i}$), as proposed by [10] using the Eq. (2).

$$F_{3PBT,i} = \alpha . F_{DPT,i} + \beta . E_{DPT,i}^2 \quad (2)$$

The terms α and β are constants obtained in a regression considering both CMOD and axial displacements of *i* and are presented in [10].

3. RESULTS AND DISCUSSION

– 3.1 Physical and geometric characterization

The geometric characterization of AR-glass macrofibre is presented in Table 2. Standard features were obtained from product data sheet.

Table 2: Geometric characterization of composite AR-glass macrofibre

Characteristics	Product data sheet	Average	Standard deviation	CV (%)
Length [mm]	43 ± 2	43	0.93	2.2
Diameter [mm]	0.70	0.73	0.02	2.1
Density [g/dm³]	2.0 ± 0.1	1.96	0.03	1.5
Aspect ratio [length/diameter]	59 - 64	59	1.68	2.9

As presented in Table 2, the average of all the geometric features evaluated are in accordance with the product data sheet. The exception is determined diameter of glass macrofibre which was 4.3% larger than the declared dimension. The result is an average equivalent diameter. This difference could be justified by the fact that the diameter was calculated by the density method which is not affected by the pressure employed by the calliper load claws or the position of the fibre [15] as regularly used for this kind of determination.

The low coefficient of variation of all the features analysed must be noted because these parameters have an important influence in the AR-glass macrofibre mechanical properties determination.

– 3.2 Tensile strength and elastic modulus

The load-extension and stress-strain curves are shown in Fig. 10. The lighter colour curves represent the individual results and the darker one represents the average curves. The synthesis of the results is presented in Table 3, including the product data sheet provide by the manufacturer.

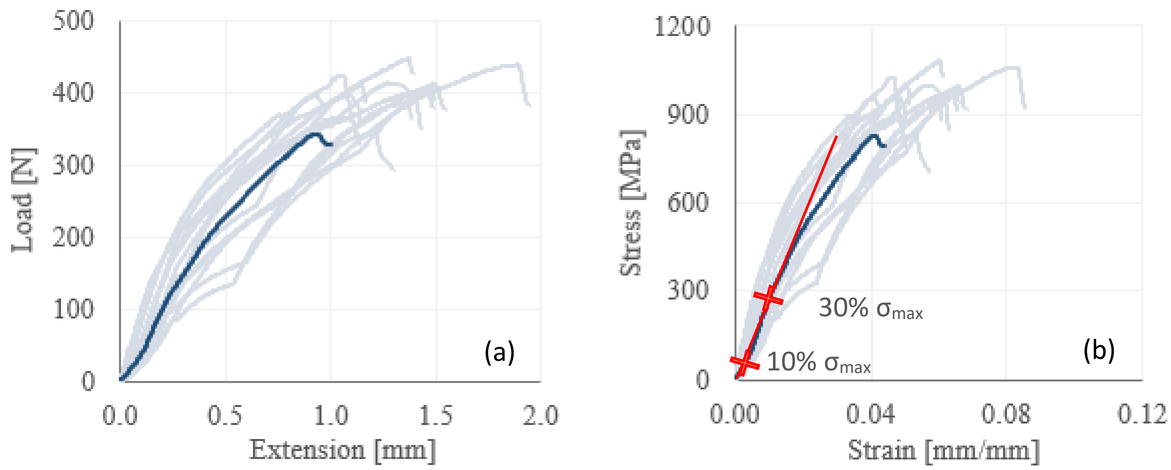


Figure 10: Curves of composite AR-glass macrofibre: (a) Load – Extension (b) Stress-Strain

Table 3: Mechanical characterization of composite AR-glass macrofibre

Parameter	Product data sheet	Number of samples	Average	Standard deviation	CV (%)
Load [N]	385		403	30	7
Tensile strength [MPa]	> 1000	14	973	72	7
Elastic modulus [GPa]	42		17	4	27

Considering the scatter of the results, the average value obtained for the maximum load was in accordance with the product data sheet. However, the average tensile strength was below the minimum value presented by the manufacturer. This condition could be explained by the fact that the fibre´s diameter presented by the producer is inferior the diameter measured in this study (Table 2), which was used to calculate the section area and the tensile stress consequently.

The average value obtained for the Young´s modulus was significantly less than the value informed by the manufacturer. Partially, this result can be explained by the previously observed reduction of the stress measured by this method in relation to the values presented by the producer. In addition, the measurement of the strain of the fibre considering the total displacement between claws is an approximation that tends to overestimate the strain. Therefore, the Young´s modulus measured here is underestimated in relation to the actual values. An alternative for future works is the use of a high-speed camera to measure fibre deformation in order to maximize the test precision.

3.3 FRC characterization

The basic mechanical characterization of the composites is presented in Table 4.

Table 4: Basic mechanical characterization of the composites

	Compressive strength [MPa]			Young´s modulus [GPa]		
Fibre content (kg/m³)	**3.8**	**7.6**	**11.5**	**3.8**	**7.6**	**11.5**
Average	47.4	47.8	47.2	27.7	29.2	28.1
Standard deviation	3.2	1.4	0.0	-	0.1	0.8
CV	7%	3%	0.0%	-	0.4%	2.7%

. The results showed very similar compressive strength and elastic modulus for the different macrofibre contents used. It is also notice that the scatter of the results is very low.

3.4 Three-point bending test

The results presented in Fig. 11 show the 3PBT load-CMOD curves obtained for all mixtures. The lighter colour curves represent individual results and the darker one represents the average curve.

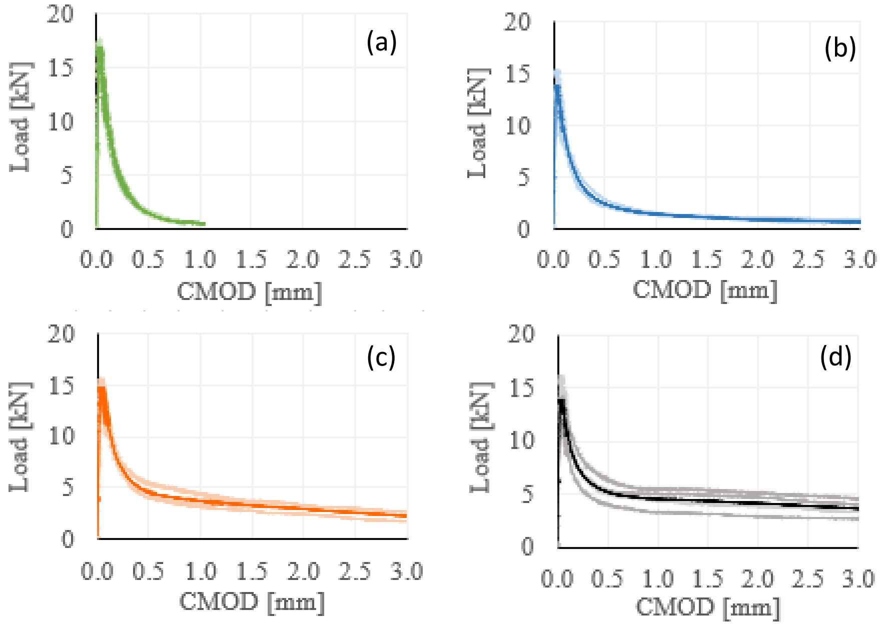


Figure 11: 3PBT load-CMOD curves: (a) Plain concrete (b) 3.8 kg/m³ (c) 7.6 kg/m³ (d) 11.5 kg/m³

The 3PBT results showed low variability, as can it be seen in Fig. 11. The three fibre contents tested exhibited the same tendency, reducing the load capacity with the development of the crack opening. In other words, the results showed a clear softening behaviour. For the plain concrete (Fig. 11a), the experiment was interrupted with a 1 mm crack opening in order to guarantee the safety of the equipment avoiding the collapse of the specimen over the clip gauge. It is also possible to notice that the limit of proportionality (F_L) was approximately 15 kN for all fibre contents and for the reference concrete. These results were considered statistically equal in the ANOVA test performed with 0.05 of significance (p-value of 0.214).

To classify the post-cracking strength of FRC, characteristic flexural residual strength values must be analysed for serviceability (F_{R1k}, CMOD = 0.5 mm) and ultimate (F_{R3k}, CMOD = 2.5 mm) conditions [1]. The characteristics flexural strength for crack opening, F_{R1k} and F_{R3k} and their respective variations are presented in Table 5.

Table 3 : Characteristics flexural strength of composite AR-glass macrofibre

Fibre content	**Parameter**	**Characteristic flexural strength**	**Standard Deviation**	**CV (%)**
Plain concrete	F_L	4.73	0.06	1
	F_{R1}	0.47	0.00	0
3.8 kg/m³	F_L	3.62	0.47	11
	F_{R1}	0.67	0.09	12
	F_{R3}	0.19	0.05	19
7.6	F_L	4.22	0.32	7

kg/m³	F_{R1}	1.27	0.17	11
	F_{R3}	0.67	0.14	17
11.5 kg/m³	F_L	3.76	0.58	13
	F_{R1}	1.54	0.22	12
	F_{R3}	1.14	0.20	14

It is shown in Fig. 12 the linear correlation between the characteristic flexural strength measured at 0.5 and 2.5 mm crack openings with the fibre content. For both cases, the obtained coefficients of determination (R^2) were higher than 0.93. As can be seen in Fig. 11a, the plain concrete presented some residual strength for 0.5 mm crack opening ($F_{R1k} = 0.47$), but not at all for 2.5 mm. Consequently, the curve referring to f_{R3k} intercept the origin, while for f_{R1k} the value for plain concrete was included (Fig. 12). This consideration allows to estimate the residual strength for CMOD of 0.5 mm when fibre contents are under 3.8 kg/m³.

Furthermore, according to [1], the minimum requirement performance to consider a FRC as a structural material must to obey the following conditions: $F_{R1k}/F_{Lk} > 0.4$ and $F_{R3k}/F_{R1k} > 0.5$, where F_{Lk} is the characteristic value for the limit of proportionality. As can be seen in Fig. 13 and Fig. 14, linear trendlines were obtained when comparing the mentioned parameters with the tested fibre contents. Although, the contents of 7.6 and 11.5 kg/m³ presented F_{R3k}/F_{R1k} relations higher than 0.5, a fibre content of at least 12 kg/m³ was required to ensure $F_{R1k}/F_{Lk} > 0.4$. In order words, for the concrete matrix used in this study, it is necessary the minimum fibre content of 12 kg/m³ to substitute conventional reinforcement. This will ensure a FRC in 1.5b classification of *fib* Model Code 2010 [1].

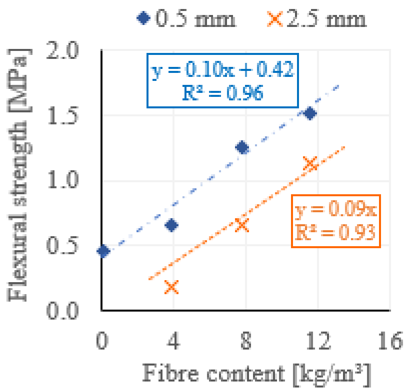


Figure 12: Characteristic flexural residual strength *versus* fibre content

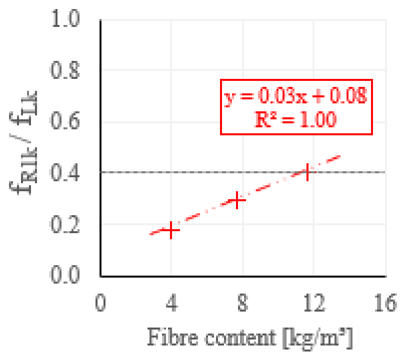


Figure 13: f_{R1k} / f_{Lk} *versus* fibre content

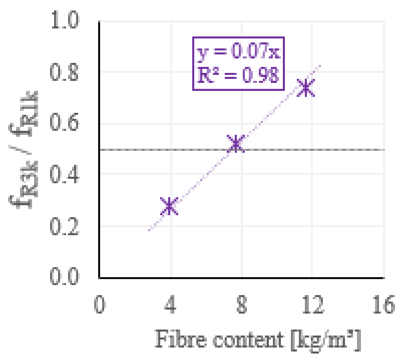
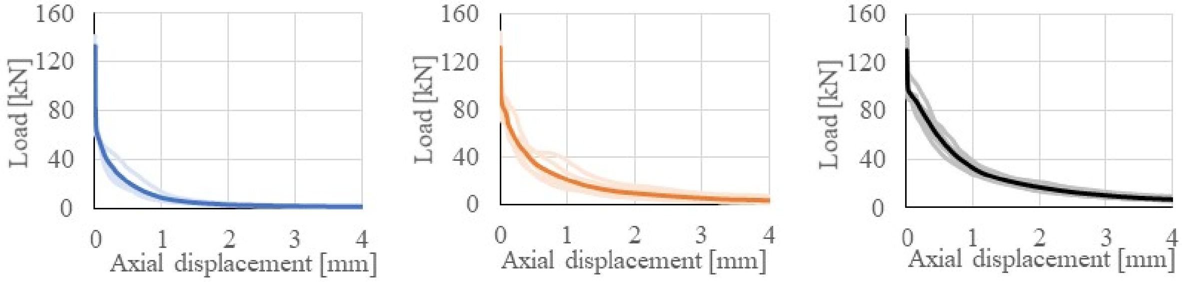


Figure 14: f_{R3k} / f_{R1k} *versus* fibre content

3.5 Double punch test

The results presented in Fig. 15 show the DPT residual load-axial displacement curves obtained for all FRC evaluated in this study. The lighter colour curves represent the individual results and the darker one represents the average curve. In order to better evaluate the results, the average relevant loads are presented in Table 6 together with standard deviation and coefficient of variation. The results permit to affirm that the cracking load (F_{cr}) is not influenced by the fibre content. The ANOVA test result a p-value of 0.827 for the effect of fibre content, greater than 0.05, indicating not significant influence of this parameter. On the opposite, the post-cracking behaviour increases proportionally to the fibre content, and the ANOVA test results a p-value of 0.001, lower than 0.05, indicating significant effect.



(a) (b) (c)

Figure 15: Residual load-axial displacement curves in DPT (a) 3.8 kg/m³, (b) 7.6 kg/m³ and (c) 11.5 kg/m³

Table 4 : Characteristics flexural strength of composite AR-glass macrofibre

Fibre content		Relevant loads (kN)				
		F_{cr}	$F_{R,0.5}$	$F_{R,1.5}$	$F_{R,2.5}$	$F_{R,3.5}$
3.8 kg/m³	Average	126.7	19.9	4.7	2.3	1.5
	Standard deviation	13.0	7.1	1.0	0.5	0.5
	CV	10%	36%	22%	21%	31%
7.6 kg/m³	Average	125.5	35.7	13.2	7.3	4.3
	Standard deviation	15.0	8.3	5.4	3.6	2.6
	CV	12%	23%	41%	49%	61%
11.5 kg/m³	Average	129.9	57.0	22.3	12.7	8.1
	Standard deviation	9.4	7.9	2.9	2.5	1.5
	CV	7%	14%	13%	20%	18%

Table 6 shows that lowest coefficients of variation (CV) were obtained for the F_{cr} results, between 7% and 12%. The residual loads present coefficient of variation between 13% and 61%, and the highest CV values are associated to higher crack openings ($f_{R,2.5}$ and $f_{R,3.5}$).

The correlation between the DPT and the 3PBT was determined in two ways. First, the experimental results of residual loads obtained from both tests were correlated, considering the axial displacement for DPT and CMOD for 3PBT (Fig. 16). The results presented in Fig. 16 express the excellent correlation between the experimental results of residual loads measured with the 3PBT and DPT. The coefficients of determination (R^2) are higher than 0.89, for values of *i* corresponding to 0.5 mm. This may be attributed to the differences in terms of crack formation in both tests, whose influence is evident for low displacements [9].

Fig. 17 shows a second correlation between the results obtained from 3PBT and the corresponding result estimated with Eq. (2) from the results of the DPT for the displacements *i* of 1.5, 2.5 and 3.5 mm. The predictions made with Eq. (2) really approaches the results from the 3PBT, with a R^2 of 0.97, confirming the potential of DPT use as an alternative test method to quality control of FRC.

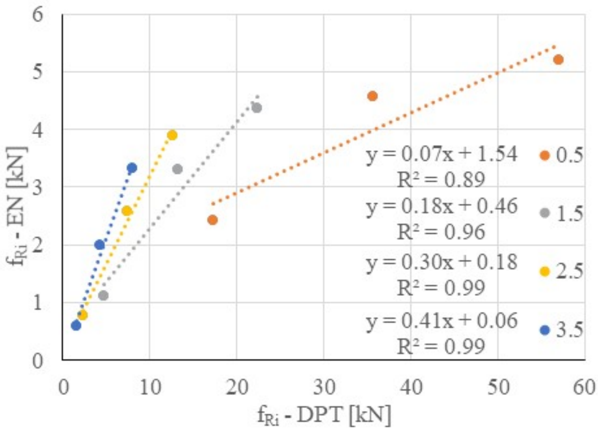


Figure 16: Correlation with experimental results of 3PBT and DPT

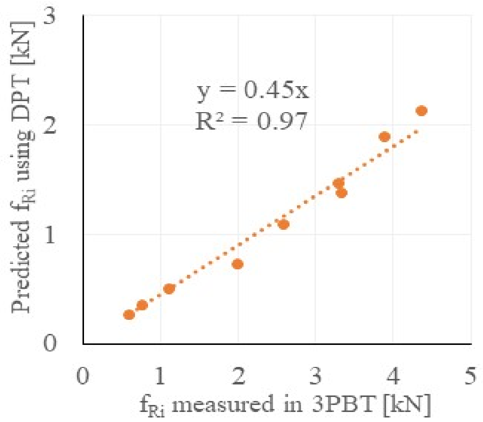


Figure 17: Correlation between experimental and predicted 3PBT loads

4. CONCLUSIONS

This paper proposes an experimental investigation using composed AR-glass macrofibre, performing the fibre characterization directly in the macrofibre and measuring the post-cracking behaviour with 3PBT and the DPT. The following conclusions may be derived from the results of this study.

- The geometric characterization presents very low coefficient of variation of the results, which indicates high-quality control in the production of these composed macrofibre. Only the diameter measurement presented a significant difference in relation to the producer declared dimension. However, the diameter measurement procedure used in this study was more reliable because is less susceptible to be underestimate due to the effect of the pressure of the calliper claws on the macrofibre.
- The tensile strength results demonstrate the feasibility of direct tensile testing method made directly in the composed AR-glass macrofibre. It is a meaningful contribution for this material consumers that do not have access to yarn samples. Conversely, the test method was not effective to the Young´s modulus determination because presented a tendency to underestimate the measured value. Nonetheless, a high-speed camera may be used to measure fibre deformation in future works in order to improve the accuracy of the test.
- The 3PBT results showed low variability and the three fibre contents tested exhibited a softening behaviour. The influence of the contents is depicted in the linear trendlines obtained in characteristic flexural strength versus fibre content for 0.5 and 2.5 mm CMOD. This kind of correlations could be a very useful tool for FRC mix-design.
- In the present study, the requirements of the fib Model Code for the definition of minimum FRC behavior as structural material were only fully met when the glass fibre content of 12kg/m^3 was used. This content ensured the classification of the material in the category 1.5b classification of fib Model Code 2010.
- The DPT results also exhibited a softening behaviour but presenting higher dispersion in comparison to 3PBT. The cracking load (F_{cr}) is not influenced by the fibre content and the post-cracking behaviour increases as the fibre content increases, as expected. The results of DPT and 3PBT were exceptionally well correlated. The coefficient of

determination (R^2) is 0.89, for values of *i* corresponding to 0.5 mm, and higher than 0.96 for other values of *i*. Also, a very good correlation ($R^2 = 0.97$) was obtained between the experimental 3PBT results and the corresponding result estimated from the results of the DPT. This fact confirms the potential DPT use as an alternative test method to perform the regular quality control procedure of the FRC, even if composite AR-glass macrofibre was used.

ACKNOWLEDGEMENTS

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