Alternative quality control of steel fibre reinforced sprayed concrete (SFRSC)

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https://doi.org/10.1016/j.conbuildmat.2019.08.003

PUBLISHER

Elsevier

VERSION

AM (Accepted Manuscript)

PUBLISHER STATEMENT

This paper was accepted for publication in the journal Construction and Building Materials and the definitive published version is available at https://doi.org/10.1016/j.conbuildmat.2019.08.003

REPOSITORY RECORD

Galobardes, Isaac, Cesar L. Silva, Antonio Figueiredo, Sergio Pialarissi-Cavalaro, and Chris Goodier. 2019. “Alternative Quality Control of Steel Fibre Reinforced Sprayed Concrete (SFRSC)”. Loughborough University. https://hdl.handle.net/2134/23938044.v1.

ALTERNATIVE QUALITY CONTROL OF SPRAYED CONCRETE REINFORCED WITH STEEL FIBRES

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Abstract

Steel fibre reinforced sprayed concrete (SFRSC) is used in applications with high structural responsibility. The quality control of SFRSC typically includes the assessment of toughness-related properties and of the fibre content. The toughness may be measured with the beam test presented in the standard EN 14488-3:2006, whereas the fibre content is generally measured by manual methods collecting and weighting the fibres. Both procedures are time-consuming, difficult to perform and difficult to apply in specimens extracted from the structure. These difficulties limit the frequency of the characterization and compromise the reliability of the information obtained, thus hindering the capacity of technicians to detect problems and optimize the material. The objective of this work is to explore a simpler quality control system for the assessment of the toughness and the fibre content of SFRSC that includes the inductive method for the assessment of the fibre content and the Barcelona test for the assessment of the toughness. Dry-mix SFRSC with five fibre contents were produced and tested with beam, Barcelona and inductive tests. Results confirm the higher sensibility of the Barcelona test and the advantages of combining it with the inductive method for an optimized quality control. Besides, equations were proposed to predict the beam test results using the Barcelona test. These equations provided good fit ($R^2 = 0.97$) regardless of the fibre content in the mix, thus confirming the robustness of the approach both for the classification and for the quality control of SFRSC.

Keywords: sprayed concrete, fibres, post-cracking strength, characterization, inductive method, beam test, Barcelona test

1. INTRODUCTION

Recent studies have highlighted the advantages of steel fibre reinforced sprayed concrete (SFRSC) as a structural material for construction of tunnel linings, slope stabilization, among other applications [1-3]. During the construction process, concrete is delivered through a pipe and exits the nozzle towards a surface. Part of the sprayed concrete impacts and remains at the surface forming the structure whereas another part rebounds. The tendency of the components of concrete to rebound depends on their particle size, shape and elastic properties. Consequently, a change in the initial composition of concrete takes place due to the differential rebound of components. This phenomenon also affects the final fibre content of the in-situ concrete [4-6] and, hence, the toughness of the SFRSC [7], introducing uncertainty about the characteristics of the sprayed concrete.

The quality control of SFRSC typically includes the assessment of toughness-related properties and of the fibre content. The evaluation of the fibre content can be made by washing fresh sprayed concrete and counting or weighting the fibres as presented in EN 14488-7:2006 [8] or crushing hardened specimens extracted from panels, manually collecting and weighting the fibres [9]. These procedures are time-consuming, difficult to perform and highly operator dependent. Alternative semi-non-destructive methods, such as the proposed by [10-12], have been developed and extensively validated for the assessment of fibre content in conventionally cast fibre reinforced concrete. Nevertheless, their use to SFRC is still incipient.

According the European standard EN 14487-1:2008 [13], the toughness of fibre reinforced sprayed concrete may be specified either by residual strength or by energy absorption class depending on the test considered to characterize the material. For instance, four classes of residual strength (Class S1 to Class S4) are defined based on the results from flexural tests of beams sawn from sprayed panels with standardized dimensions of 75x125x500 mm and defined by the standard EN 14488-3:2006 [14] (similar to the American ASTM 1609/C1609M:2012 [15]). This procedure is time-consuming, cumbersome, and practically unfeasible in cores extracted from the structure. Other tests, such as the slab specimen test described in EN 14488-5:2006 [16], also rely on production of test panels, which must sprayed separately and could hardly be extracted from the structure. This is an important drawback because the rebound in the panel may be very different from the real structure. Consequently, the composition and the performance in the test panel may be different from that found in the structure.

Furthermore, in countries with few qualified laboratories and technicians, the characterization of SFRSC tends to be performed in opened-loop test machines. Problems to control the residual strength at small crack widths have been reported in such cases [6]. In this context, the use of simpler test methods - like the described by [17, 18] - could mitigate current problems and provide a less labour-intensive evaluation of the quality of in-situ sprayed concrete.

SFRSC is prone to high scatter in properties due to the variability induced by the spraying process and the influence from the operator. Appropriate structural design and quality control during execution are key points to optimize material consumption and properties, as well as to reduce the risk of failure. Difficulties regarding the testing procedures currently used for the control of SFRSC limit the frequency of the characterization and compromise the reliability of the information obtained, thus hindering the capacity of technicians to detect problems and optimize the material.

The main objective of this work is to explore an alternative quality control system for the assessment of the toughness and the fibre content of SFRSC in a simpler way, more compatible with the intrinsic characteristics of the production process and could be performed on both, structure and test panels. This quality control includes the inductive method [9-11] for the assessment of the fibre content and the Barcelona test [17] for the valuation of the toughness of cylindrical extracted cores.

2. METHODOLOGY

An experimental program is conducted using specimens obtained from the dry-mix spraying process of SFRSC with different fibre contents. First, the fibre content is evaluated using the inductive method. Then, the toughness is assessed by means of the beam test and the Barcelona test. Their sensibility to the variations of the actual fibre content is evaluated and a correlation between results obtained in both procedures is established. This correlation is used to classify the SFRSC based on the Barcelona test results according to the European standard residual strength classification. Notice that the possibility of correlation between the Barcelona test and the flexural beam test with open loop systems has been already demonstrated for normally cast concrete [19-23]. However, the transpositions of the knowledge obtained from experiments carried out with conventionally cast concrete and the sprayed concrete have long been considered very doubtful due to the specificities of the sprayed concrete such as the variation of the fibre content by the rebound effect [24] and the specific fibre orientation forced during the spraying process [25]. For this reason, as this experimental work was carried out under actual construction conditions with the sprayed concrete, has an important contribution to the state of knowledge of the SFRSC. Conclusions derived from this study might promote a change in the typical quality control methodology adopted to evaluate the performance of SFRSC towards a more economic, environmentally friendly and reliable alternative.

2.1. Materials and concrete mix

A dry mix concrete composition was defined in accordance to the ranges recommended by [5, 26, 27] and with previous projects using SFRSC. It was made of 435 kg/m^3 of cement CP III 40 RS, 925 kg/m^3 of limestone sand (0-4 mm) and 810 kg/m^3 of limestone gravel (4-12 mm). The cement contained a high proportion of blast furnace slag (35-70% by weight according to the Brazilian specific standard) and was resistant to sulphates (RS). Aggregates complied with NBR 7211:2009 [28], being selected to ensure good sprayability and to enhance optimization of the concrete packing [5, 26].

The reference concrete mix was produced with five different fibres contents: 20, 30, 35, 45 and 55 kg/m^3, typical quantities for sprayed concrete [1, 4, 29]. The fibres were steel Wirand® type FSN3(R) produced by Maccaferri do Brasil and recommended for sprayed concrete, with a length of 33 mm and an aspect ratio of 44. The geometric and mechanical characteristics of the fibres were evaluated considering the standard NBR 15530:2007 [30]. The five mix compositions sprayed in this study were named as SCX, where X is the fibre content in kg/m^3.

Potable water following the requirements defined by the standard NBR 15900:2009 [31] was added at the nozzle of the spraying system. Care was taken to guarantee the same delivery speed and volume of water throughout the experimental program, thus maintaining approximately the same water-to-cement ratio in all mixes.

2.2. Spraying process and specimen preparation

The spraying process followed the standard EN 14487-2:2008 [26]. A compact dry-mix rotor barrel spraying machine was used with a constant air pressure of 2.8 kPa. Wooden test panels with 500x500x120 mm, complying with the standard NBR 13070:2012 [32], were positioned on the floor at an angle of 20° with the vertical, as recommended (Figure 1.a). Two panels were sprayed per mix.

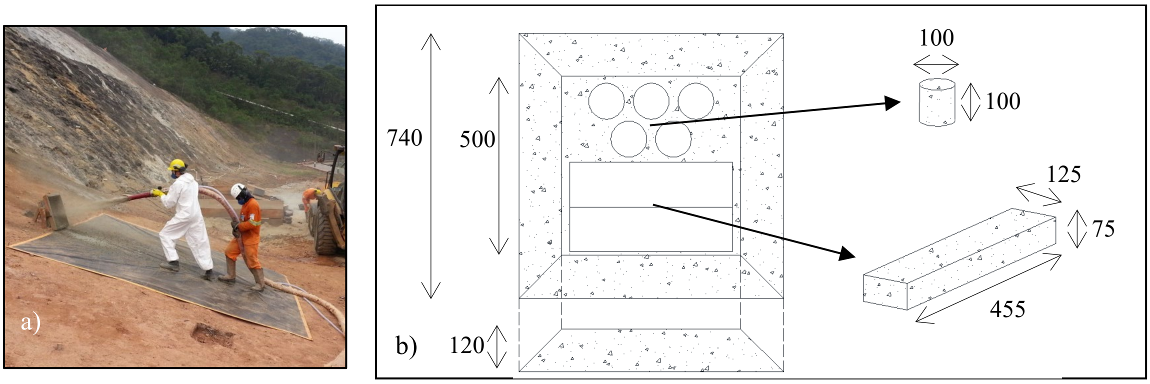

Figure 1- Spraying of a panel (a) and detail of specimen extracted from each panel (b)

Then, 5 cylindrical cores with 100 mm diameter were extracted from each test panel, according to the requirements of EN 14488-1:2005 [33] (Figure 1.b). Subsequently, the roughest face of the core was sawn using a radial disc-cutter in order to obtain cylindrical specimens with height equal to 100 mm. Moreover, two 75x125x455 mm prismatic specimens were sawn from each panel (Figure 1.b), and their rough faces were removed (sawn).

Due to limitation in the moulds available, the length of the beams (455 mm) is smaller than the described in EN 14488-3:2006 (500 mm). This should not affect the results as the characterization is limited to a 375-mm-long region at the central part of the specimens, which is effectively subjected to bending forces and cracking during the flexural test detailed in EN 14488-3:2006. In total, 50 cylindrical specimens (10 per mix) were characterized with the inductive method, 30 cylindrical specimens (6 per mix) were characterized with the inductive method and 20 prismatic specimens (4 per mix) were characterized with the beam test.

2.3. Test methods

2.3.1. Inductive method

The inductive method [9-12] relies on the assessment of inductance variation (ΔL) observed when a SFRC specimen is placed inside a coil that generates an electromagnetic field. The inductance variation of each specimen was measured in three directions: one parallel to the spraying direction (ΔL_z) and two orthogonal to this direction (ΔL_x and ΔL_y). The sum of inductances in the three directions ($\Delta L_T = \Delta L_Z + \Delta L_0 + \Delta L_{90}$) is related to the total fibre content. The individual values are used to calculate the orientation number parallel to a certain direction. The orientation number is defined as the average cosine formed by all fibres in the sample and a direction. High values of ΔL indicate a preferential orientation parallel to this axis.

The calibration of the inductive method for the type of fibre was performed in accordance with the procedure described by [9-12] and considered a valid alternative to the calibration through crushing and weighting of fibres in hardened concrete specimens. Three ϕ100x100 mm cylindrical expanded polystyrene specimens with the same geometry as the SFRSC cores were produced. Next, different amounts of fibre (10, 20 and 30 g equivalent to fibre contents of respectively 12.7, 25.5 and 38.2 kg/m^3) were introduced in the polystyrene specimens.. Then, the total inductance change (ΔL_T) of each specimen was assessed as the sum of the inductance measurement taken in 3 directions:1 along the axis and 2 perpendicular within the circumferential plane. Figure 2 presents the relationship between the known fibres content and their ΔL_T considering the volume of each specimen (V). As observed, the relationship is linear and shows a good fit ($R^2 = 0.997$). Since concrete and polystyrene produce negligible inductance variations in comparison with that produced by the steel fibres, the same correlation is also valid for SFRSC. Therefore, Equation 1 was used to estimate the fibre content ($C_{f,i}$) of SFRSC specimens using the inductive method. The fibre orientation number in different directions was also assessed with the inductance results of SFRSC specimens as described by [9-12]. Notice that this assessment does not require a preliminary calibration.

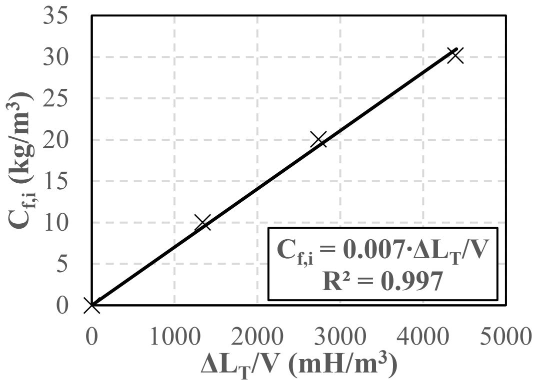

Figure 2- Inductive method: calibration equation

$$C_{f,i}(kg/m^3) = 0.007 \cdot \frac{\Delta L_T(mH)}{V(m^3)} \qquad (1)$$

2.3.2. Beam test

The EN 14488-3:2006 defines a four-point bending beam test that is widely accepted across Europe for characterizing the SFRSC residual strength [14]. During the test, the load (*F*) is controlled and the vertical displacement (δ) measured. In this study, the δ was measured with two LVDTs, one at either side of the beam in order to minimize variation of the results.

The residual tensile strength of the SFRSC (f_{Rim}) is calculated considering the load, the cross section of the specimen and the distance between load applications. The standard recommends the determination of the residual strength for four vertical displacements: 0.5, 1.0, 2.0 and 4.0 mm (f_{R1m}, f_{R2m}, f_{R3m} and f_{R4m}, respectively) corresponding to a rocky low, normal and high deformation classes D_1, D_2 and D_3, respectively, defined by [13]. These residual strengths are used to classify the SFRSC in four classes (from S1 to S4) according to Figure 3. In this study, 20 specimens (five per mix) were tested in an opened-loop press following the European standard recommendations.

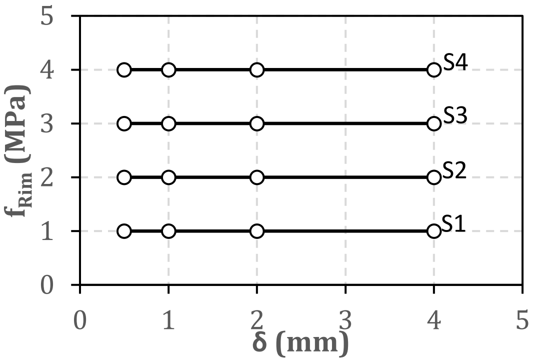

Figure 3- Residual strength classes for the SFRC defined by EN 14487-1:2008 [13]

The beam test defined by the standard is a relatively straightforward method, although labour intensive due to the time and material required for testing. It generally involves prismatic specimens (75x125x500 mm) that weight approximately 10 kg each. Considering that a minimum of three specimens are required to obtain reliable results, 30 kg of concrete is therefore required to perform a single evaluation of SFRSC. Moreover, the specimens are generally extracted from a sprayed test panel, weighting around 90 kg. The difficulties are greater if there is a need to evaluate the in-situ material within the real structure where the extraction of the prismatic specimens is highly difficult and sometimes unfeasible.

2.3.3. Barcelona test

The Barcelona test is an alternative method to assess the residual strength of fibre reinforced concrete. It was developed at the Universitat Politècnica de Catalunya in Spain, based on the double punch test proposed by Chen (1970) [34]. It is now a standardized method according to UNE 83515:2010 [17] and may be used for characterization of the residual response of SFRSC, as demonstrated by [35, 36].

During the test, the ϕ100x100 mm cylindrical core is placed between two steel cylindrical rod punches located at the centre of the top and the bottom surfaces (Figure 3.a). The piston of the press moves with a constant displacement rate, producing a compression of the punches and the specimens. Radial cracks appear during the test (from two to four), activating the fibres (Figure 3.b).

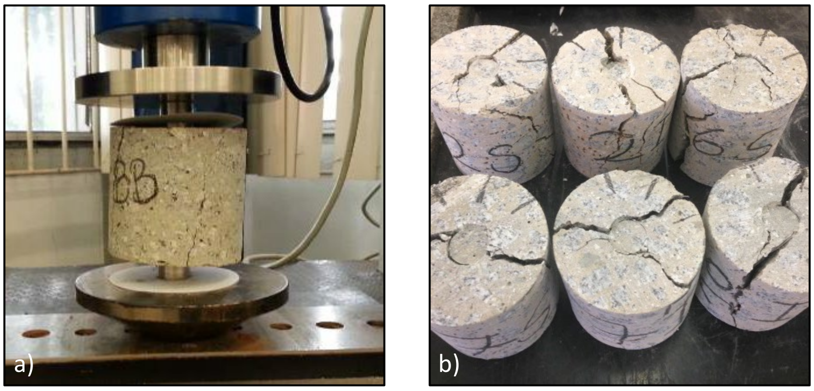

Figure 4- 100 mm x 100 mm Barcelona test specimen a) and cracked samples b)

In its origin, the total crack opening displacement (TCOD) was measured with a circumferential extensometer placed at half-height of the specimen, as described in the Spanish standard. The requirement of a circumferential extensometer to measure the TCOD restricted the wider uptake of the test. To overcome this, an analytical correlation between the axial displacement of the press and the TCOD was proposed [37]. Currently, only the axial displacement is required. This change simplified the test procedure, increasing its potential use in regular quality control programs of fibre reinforced concretes in general and for SFRSC specifically. Hence, a curve of load (F) versus vertical displacement (δ) was obtained for each one of them.

The Barcelona test may be performed in the same cylindrical specimens used in the inductive test. Due to their smaller size and weight, a bigger number of specimens may be extracted from the test panels, leading to a larger data set and a more robust evaluation of the average results. This is important for SFRSC due to the inherit variability of the mechanical properties of the material [1, 2]. Furthermore, the Barcelona test allows testing cores extracted from real structural elements such as tunnel linings, which could be necessary in some cases.

3. EXPERIMENTAL RESULTS

3.1. Fibre content and orientation

Figure 5.a presents the average fibre content estimated per panel (thin bars with dotted shade) and the average fibre content for each mix composition (thick bars with continuous shade) after spraying. These values were obtained by means of Equation 1. The straight horizontal lines indicate the nominal fibre content prior to spraying. The content measured after spraying is 44%, 59%, 36%, 42%

and 33% smaller than the nominal content of mixes with 20, 30, 35, 45 and 55 kg/m³, respectively. This implies that a significant proportion of fibres, around 40%, is lost during the spraying process possibly due to the rebound at the surface.

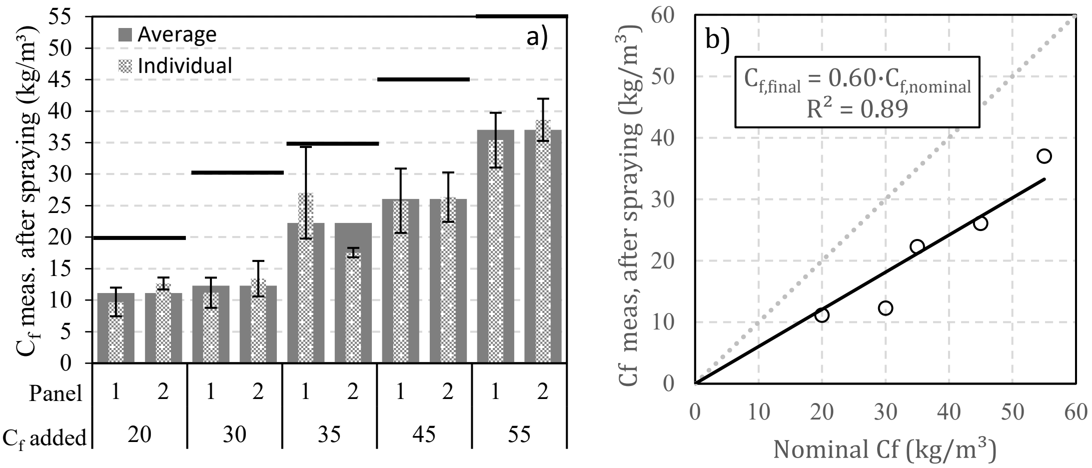

Figure 5- Fibre content measured (a) and relation between nominal and final fibre content after spraying (b)

The authors consider that the values of incorporated fibres are within an expected range since the spraying process is the main responsible for the drastic reductions (difference between $C_{f,nominal}$ and $C_{f,final}$) observed by [7]. In fact, the rebound is significantly higher in the dry-mix process as opposed to that found in the wet-mix spraying process. Notice that Robbins et al. [38] found a reduction below 15% on the steel fibre content of concrete sprayed with the wet-mix process. This value is between 2 to 4 times smaller than the ones observed in the present experimental program.

Figure 5.b shows the relation between the nominal and the final fibre content after spraying. The relationship between both parameters may be approximated through a linear regression passing thought the origin, with a slope of 0.6 and a R^2 of 0.89. This indicates that the initial fibre content tends to be reduced by 40% due to the spraying process. In other words, to guarantee a target fibre content after spraying, the nominal content should be approximately 67% bigger than the target.

Figure 6 shows the average orientation numbers measured in the directions parallel to spraying (Z) and orthogonal to spraying (0° and 90°). Approximately the same values are found for all mixes. The orientation numbers perpendicular to the spraying direction are three times higher than that found parallel to the spraying direction. These results are consistent with the observed by Robbins et al.

[38], who concluded that the shearing condition induced by spraying process favour a fibre alignment perpendicular to the spraying direction.

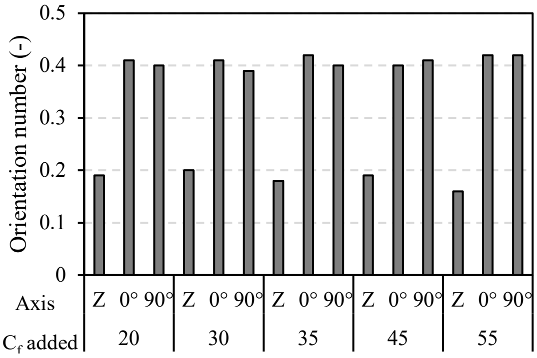

Figure 6- Orientation number estimated for each SFRSC mix

3.2. *Residual strength: beam test*

Figure 7 shows, the load (*F*) – vertical displacement (*δ*) curves obtained from beam tests. Each curve is the average of results obtained for four specimens tested per mix. The load peak values (kN) and its variation (in brackets) obtained are 10.66 (4.75%), 9.88 (2.78%), 9.48 (7.53%), 8.44 (11.09%) and 9.46 (5.94%), for mixes SC20, SC30, SC35, SC45 and SC55, respectively.

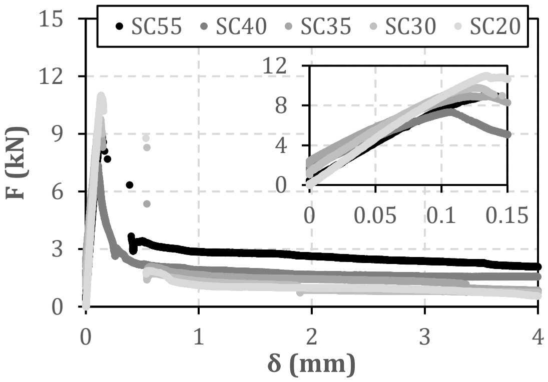

Figure 7- F- δ curves obtained with the beam test

The experimental curves present three different zones: an elastic zone from the beginning of the load application to the start of cracking (first peak of the curve), a post-peak zone, and a stable post-cracking zone. In general, the peak load decreases with the increase of the nominal fibre content. This is possibly due to the compacting process of the concrete matrix during the dry-mix spraying, which is higher when the fibre content is lower [1, 4]. Moreover, the post-peak instability, which is an interval of rapid uncontrolled deformation of the specimen [39] that normally occurs in the post-peak region of a load-deformation response, is bigger for mixes with lower fibre content, as reported in [40]. Notice that a slight instability is observed in post-peak zone probably due to the open loop system used to gather the results. The authors could not avoid this issue arising from the lack of equipment with the closed-loop refinement needed to capture the crack formation in the flexural test of FRC. This is a common problem faced in many countries under development such as Brazil [20] and is an additional reason in favour of the application of the Barcelona test that shows no instability for the same equipment and material characterized.

Table 1 shows average values of the residual flexural tensile strength (f_{Rim}) estimated for reference vertical displacements defined by EN14488-3. The table also presents the coefficient of variation of the results in parenthesis.

Table 1- Residual tensile strength in MPa (f_{Rim})

Residual strength	**Reference displacement (δ)**	**Concrete mix**				
		SC20	**SC30**	**SC35**	**SC45**	**SC55**
f_{R1m}	0.5 mm	4.15 (19.5%)	3.99 (13.0%)	3.35 (15.2%)	2.25 (17.3%)	2.55 (10.6%)
f_{R2m}	1.0 mm	1.08 (43.5%)	1.17 (35.0%)	1.63 (18.4%)	2.32 (21.6%)	2.20 (15.0%)
f_{R3m}	2.0 mm	1.00 (51.0%)	0.87 (46.0%)	1.33 (19.5%)	2.22 (23.9%)	2.10 (17.1%)
f_{R4m}	4.0 mm	0.64 (93.8%)	0.43 (41.9%)	0.93 (38.7%)	1.97 (22.3%)	1.63 (26.4%)

Based on the analysis of Table 1, one might erroneously conclude that f_{R1m} reduces with the fibre content. This behaviour contradicts the expected according to the literature [19, 40]. The trend observed in the experimental results is highly influenced by the instability found just after crack initiation. Such phenomenon is more pronounced in the case of lower fibre contents, affecting a wider range of vertical displacements and entailing an overestimation of the residual strength for low crack openings. This gives a false impression that higher f_{R1m} are measured for mixes with smaller fibre contents. As the crack opening increases, the control and the stability of the test is recovered, leading to residual tensile strengths that tend to increase with the fibre content, although several exceptions are still found due to the high scatter of the results.

The coefficient of variation ranges from 13.0% to 93.8%. Most of the values are around 25%, which is consistent with the reported in the literature for the flexural post-cracking response of conventionally cast fibre reinforced concrete beams [19]. Despite that, values above 40% are found in several cases – especially for the larger displacements in case of mixes with low fibre content. This unusually high coefficient of variation may be attributed to the small cross-sectional area of the beam characterized in the flexural test for SFRSC (75x125 mm) as opposed to the cross-sectional area of specimens characterized with the traditional flexural test of cast FRC beams (150x150 mm). In fact, Cavalaro and Aguado [41] demonstrated that a reduction of the cross-sectional area induces an increase in the scatter of the residual flexural response of the material. The authors also suggest that such phenomenon should become more evident as the fibre content decreases. Both observations are found in this experimental programme with SFRSC.

3.2. Barcelona test

Figure 8 shows the curves that relate the load (*F*) and the energy (*E*) with the vertical displacement (*δ*) in the Barcelona test. Each curve is the average of results obtained for five specimens tested per mix.

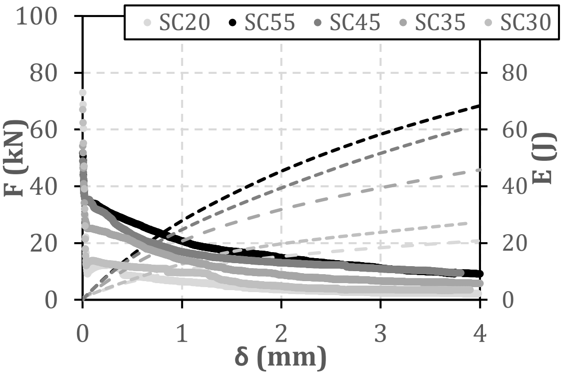

Figure 8- F – δ (continuous) and E – δ (discontinuous) curves obtained with the Barcelona test

For comparative purposes, following the approach described in [19], only the post-cracking zone of the curves are depicted. As observed for the beam test results, the peak load is higher for lower fibre content. Conversely, the magnitude of the instability identified in all beam tests does not occur in the Barcelona test. Notice that this presents as well instabilities, but much smaller than the ones observed for the beam test results with almost no influence in the residual strength at low level of crack opening [42, 43].

Table 2 presents load ($F_{BCN,\delta}$) and the energy ($E_{BCN,\delta}$) for reference values of vertical displacement (δ) in the Barcelona test. The coefficient of variation of the results appear in parenthesis. Notice that the residual load and energy increase with the fibre content for all displacements. Due to the absence of instability after cracking, this trend is observed even for low displacement levels.

Table 2- Load ($F_{BCN,\delta}$) in kN and energy ($E_{BCN,\delta}$) in J for different vertical displacements

Parameter	**Reference displacement (δ)**	**Concrete mix**				
		SC20	**SC30**	**SC35**	**SC45**	**SC55**
$F_{BCN,max}$	0.0 mm	73.06 (11.67%)	62.78 (10.01%)	54.31 (15.78%)	47.33 (10.84%)	51.80 (8.49%)
$F_{BCN,0.5}$	0.5 mm	8.51 (3.6%)	8.53 (4.2%)	20.74 (1.5%)	24.59 (0.8%)	27.43 (0.4%)
$F_{BCN,1.0}$	1.0 mm	6.53 (3.8%)	6.9 (6.2%)	14.18 (2.1%)	16.72 (1.3%)	20.84 (0.9%)
$F_{BCN,1.5}$	1.5 mm	4.84 (8.3%)	5.48 (7.5%)	10.6 (1.7%)	12.96 (2.4%)	17.22 (1.4%)
$F_{BCN,2.0}$	2.0 mm	3.69 (12.5%)	4.49 (12.2%)	8.91 (2.2%)	11.31 (3.1%)	14.96 (1.8%)
$F_{BCN,2.5}$	2.5 mm	3.15 (16.8%)	3.87 (14.2%)	7.51 (3.9%)	10.13 (3.7%)	12.9 (2.2%)
$F_{BCN,3.0}$	3.0 mm	2.56 (29.3%)	3.46 (16.5%)	6.74 (4.9%)	8.99 (3.7%)	11.26 (3%)
$F_{BCN,3.5}$	3.5 mm	2.48 (32.3%)	3.23 (17.6%)	6.31 (5.5%)	8.02 (4.1%)	10.04 (3.8%)
$E_{BCN,0.5}$	0.5 mm	6.51 (6.1%)	5.46 (10.3%)	12.1 (4.5%)	13.49 (2.6%)	15.79 (1.1%)
$E_{BCN,1.0}$	1.0 mm	10.26 (1.6%)	9.27 (3.5%)	20.66 (1%)	23.94 (0.6%)	27.79 (0.5%)
$E_{BCN,1.5}$	1.5 mm	13.16 (1.1%)	12.33 (1.5%)	26.89 (0.3%)	31.25 (0.4%)	37.16 (0.3%)
$E_{BCN,2.0}$	2.0 mm	15.26 (0.7%)	14.85 (1.1%)	31.8 (0.2%)	37.24 (0.3%)	45.28 (0.2%)
$E_{BCN,2.5}$	2.5 mm	16.94 (0.6%)	16.91 (0.8%)	35.88 (0.2%)	42.59 (0.2%)	52.22 (0.1%)
$E_{BCN,3.0}$	3.0 mm	18.35 (0.5%)	18.74 (0.5%)	39.45 (0.2%)	47.34 (0.1%)	58.29 (0.1%)
$E_{BCN,3.5}$	3.5 mm	19.61 (0.5%)	20.42 (0.4%)	42.7 (0.1%)	51.52 (0.1%)	63.56 (0.1%)

The coefficient of variation of the load in the Barcelona test ranges from 0.1% to 32.3%, with most values being around 8.0%. The variability is smaller than the observed by [19] for conventionally cast specimens. One of the reasons for the smaller variation in comparison with the literature might be the preferential orientation of the fibres in the SFRSC specimens, which tend to align perpendicular to the spraying direction. Consequently, a bigger number of fibres cross the cracking planes in the SFRSC specimen in comparison with what occurs in a conventionally cast specimen. According to Cavalaro and Aguado [41], as more fibres contribute to the mechanical response, the variability tends to reduce. Because of that and due to the bigger cracking surface characterized, the scatter of the Barcelona test was considerably smaller than that of the beam test.

In general, results reveal a significant increment of $F_{BCN,i}$ and of $E_{BCN,i}$ with the increase of the theoretical fibre content. The only exception to this trend was found in the comparison of results from mixes SC20 and SC30 that - despite the increment in the theoretical fibre content from 20 to 30 kg/m³ - showed similar results for of $F_{BCN,i}$ and of $E_{BCN,i}$. This is justified by the actual fibre content left in the concrete after spraying, which shows clear increments in mixes SC30, SC35, SC45 and SC50 following the theoretical content but are nearly the same for mixes SC20 and SC30 (11.26 and 12.30 kg/m^3, respectively).

4. SENSIBILITY OF MECHANICAL TESTS TO VARIATIONS IN FIBRE CONTENT AFTER SPRAYING

The toughness of the sprayed concrete at the post-cracking stage is directly linked to the fibre content since fibres are the responsible for bridging the cracks and providing residual mechanical response. By the same token, tests used to assess the toughness of the material should sensible to the variations in the fibre content. This brings the question: which of the two tests evaluated here (beam test or Barcelona test) is more sensible to the variation of the fibre content after spraying?

This was assessed through the coefficient of determination (R^2) between the results of each test and the average fibre content estimated with the inductive method. The determination was performed for different values of displacement for the beam test and the Barcelona test. High values of R^2 indicate a high correlation between both parameters and a higher capacity of the mechanical test to detect the influence of the variation of the fibre content. Figure 9 summarizes the result of this analysis.

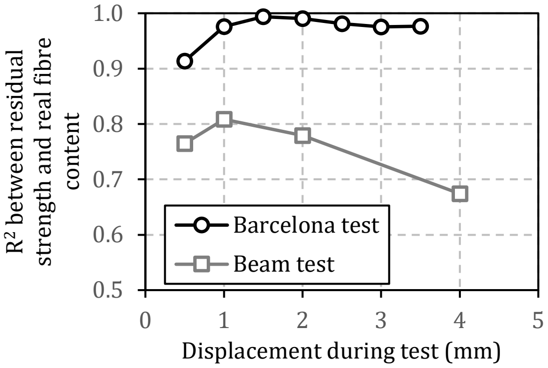

Figure 9- Sensibility of toughness tests to variation in the final fibre content for different levels of displacement

The R^2 in the beam test reduces from around 0.81 to 0.67 as the displacement increases. This suggests that, at least in the present experimental program, the sensibility of the test to discriminate variations in fibre content reduces with the crack opening. The R^2 in the case of the Barcelona test goes from 0.91 to 0.98 with the increase of the displacement. Consequently, in the present experimental program, the Barcelona test was considerably more sensible to the variation of the fibre content than the beam test.

Such outcome might be the result of the several cracks observed during the Barcelona test without a predefined position as opposed to the single localized crack observed in the beam test. Therefore, the former is capable of capturing the influence of different directions whereas the latter only characterizes a predefined plane localized in the region between the load actuators. Consequently, the correlations obtained in this study take into account the sensitivity of the tests to the typical changes in the proportion of fibers originated in the application of SFRSC.

5. CORRELATION BETWEEN TESTS

To correlate the loads ($F_{BCN.\delta}$) and the energies ($E_{BCN.\delta}$) obtained in the Barcelona test and the residual tensile strength of the beam test (f_{Rim}), a multi-parametric analysis was performed following the procedure described by [19-21]. The aim of this stage was increasing the R^2 values of the correlation performing a multivariable regression considering that the correlation equation outcome should be a residual tensile strength of the beam test (f_{Rim}) and the inputs a result of both, load ($F_{BCN.\delta}$) and energy ($E_{BCN.\delta}$), obtained in the Barcelona test. Then, the Barcelona test parameters that showed better correlation with the beam test parameters were the load and the energy for a displacement of 2.5 mm ($F_{BCN,2.5}$ and $E_{BCN,2.5}$). The R^2 of these parameters were 0.93 and 0.92, respectively.

The free-access curve fitting software LAB Fit was used to determine the equation that best reproduces the relation between tests. The best fit was obtained with Equation 2. The proposed equation contains two parameters (A and B) that depend on the vertical displacement (δ). To calibrate both parameters, a Levenberg-Marquardt algorithm was used [44]. Equation 3 and 4 were obtained for the best fit of the correlation. Results of the f_{R1m} obtained in the beam test were not considered in the analysis to avoid introducing the effect of the instability observed in the initial post-cracking displacements in this test.

$$f_{Rim} = A \cdot E_{BCN,2.5}{}^{\left({}^{B}/_{F_{BCN,2.5}}\right)} \tag{2}$$

$$A_i = 0.142 \cdot \delta + 3.416 \tag{3}$$

$$B_i = -(0.376 \cdot \delta + 1.037) \tag{4}$$

Figure 10 shows the comparison between the experimental residual strength estimated from the beam test and the residual strength estimated by applying the Barcelona test results in the correlation. The ideal equality line is also depicted in the graph. The R^2 obtained between measured and estimated residual strengths is 0.97, considering f_{R2m}, f_{R3m} and $f_{R4m.}$ Notice that f_{R1m} results do not follow the same tendency due to the instabilities observed in the bending test, corrected in the correlation equation.

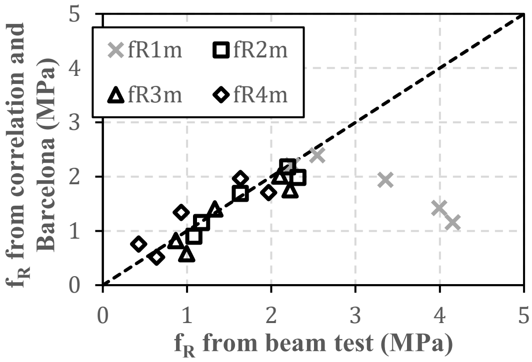

Figure 10- Comparison between residual strength estimated with the beam test and residual strength estimated with Barcelona test and correlation

To evaluate the influence of the methods used for the assessment of the residual strength in the classification of the SFRSC, mixes with the lowest (SC 20 with 20 kg/m^3) and the highest (SC55 with 55 kg/m^3) fibre contents were classified. Curves for other mixes remained between these extreme curves, being omitted here to facilitate the visualization and the analysis. Figure 11 presents the results obtained performing the beam test (SC25_A and SC55_A) and the ones with the Barcelona test results and the correlation (SC25_B and SC55_B). These results are compared with the residual strength classes defined in EN 14487-1:2008.

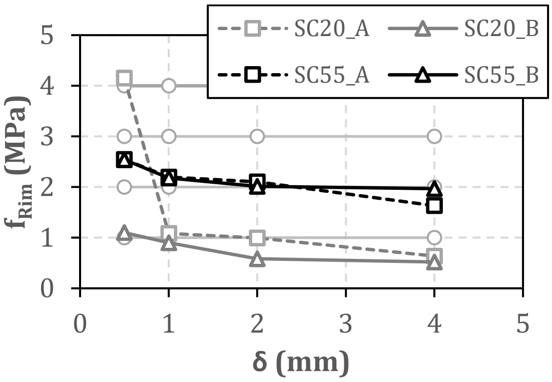

Figure 11- Classification of mixes SC20 and SC55 using beam and Barcelona test results

SC55 presents a residual flexural strength class D1S2 (or D2S2 and D3S1), whereas SC20 presents a class lower than S1. The same applies regardless of the approach used to estimate the residual strength, although an overestimation of the f_{R1} in the results of the beam test could suggest that SC20 is S4 for a vertical displacement of 0.5 mm.

6. CONCLUSIONS

This study shows that the combination of the inductive method and the Barcelona test is a suitable alternative for controlling the fibre content and the post-cracking behaviour of the SFRSC. This may imply an improvement on the reliability of the quality control as more determinations may be performed per panel or even in a tunnel lining. This also brings a reduction of the time and manpower required for the assessment, opening up the possibility of characterizing material extracted directly from the structure. The following conclusions may be derived based on the experimental program and the analysis performed here.

- A reduction of 40% in the nominal fibre content was observed because of the rebound of the fibres during the dry-mix spraying process, which remained approximately the same regardless of the nominal fibre content. Such reduction was expected considering previous research, however it is around two times bigger than that found in other studies from the literature with wet-mix sprayed concrete, suggesting that the dry-mix spraying process is the responsible for the enhanced reduction. Therefore, the use of dry-mix process to spray steel fibre concrete mixes should be evaluated in light of the potential waste of fibre and consequent loss in performance it might imply.
- The Barcelona test was more sensible to the variation of the actual fibre content than the beam test. This suggests that the former is more capable of detecting changes in the mechanical performance induced by variations in the fibre content. The scatter observed in the Barcelona test (8%) is also smaller than that observed in the beam test (25%). This is the consequence of the bigger cracked cross-section and multiple cracking planes in the former test, which provided more reliable average results.
- The open-loop equipment induces instabilities in the results of the beam tests just after cracking, which entails an overestimation of the residual strength for low displacement levels (< 1 mm). The Barcelona test did not show instabilities under the same conditions, being more suitable for the quality control. This is especially evident in case of projects that rely on the control of f_{r1m} and where no closed-loop test machine is available.

- Equations were proposed to predict the beam test results using the Barcelona test results. These equations provided good fit regardless of the fibre content in the mix ($R^2 = 0.97$), thus confirming the robustness of the approach both for the classification and for the quality control of SFRSC. Specific correlations should be derived for different types of concrete and of fibres. The procedure described in this study could be replicated for obtaining new correlations that will allow the design and quality control of the sprayed concrete by means of the Inductive Method and the Barcelona test.

7. ACKNOWLEDGMENTS

The authors of the study would like to thank the company PETROBRAS for supplying the materials needed to perform the research. Furthermore, the first author thanks FAPESP for the economic support.

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