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Evaluation of steel fibre reinforced sprayed concrete by energy absorption tests

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Abstract

Steel fibre reinforced sprayed concrete (SFRSC) is widely used for ground support in underground works. The panel test, as in EN 14488-5, is one of the most common procedures for the quality control of the energy absorption capacity of SFRSC. The test entails the deployment of large equipment to manipulate and characterise heavy specimens that cannot be easily extracted from the structure in case a direct assessment of the material in place is needed. Alternative procedures such as the Barcelona test (BCN) have been used to assess the energy absorption of cast fibre-reinforced concrete in smaller-scale cylindrical specimens that can be extracted from the structure and are considerably less demanding in terms of equipment and payload. The objective of this study is to evaluate the use of the BCN in substitution of the traditional square panel test to assess the energy absorption of SFRSC. Both tests were conducted in parallel in combination with the quantification of the incorporated fibre content trough the inductive test. Hence, the analysis reflects the actual control conditions of the SFRSC under the influence of the spraying process. Results indicate a possible reliable correlation between the BCN and panel test if the cracked area is considered. Different sizes of cores were tested to understand the influence of this parameter in the energy absorption by the BCN test. The reduction of specimen size demands an increase in the number of determinations per batch to ensure representative results. The study suggests that the BCN can be considered a viable method to evaluate the energy absorption of SFRSC in cores extracted from test panels or actual tunnel linings.

Keywords*: Steel fibre, sprayed concrete, Barcelona test (BCN), square panel test, inductive test, energy absorption.*

1. Introduction

Steel fibres are used in sprayed concrete to provide post-cracking reinforcement to enhance toughnesss avoiding the typical brittle behavior of this material (Bernard and Thomas 2020) and enhancing dynamic mechanical properties (Chen *et al*. 2020). Steel fibre reinforced sprayed concrete (SFRSC) is widely used in a variety of applications including, construction of slope stabilization, excavation support, structure recovery, refractory lining, tunnel lining, mining operations, etc. (Pfeuffer and Kusterle 2001; Cengiz and Turanli 2004; Bernard 2008; Ginouse and Jolin 2015; Galobardes *et al*. 2019; Liu *et al*. 2020). One of the most traditional applications of SFRSC is tunnel lining by the New Austrian Tunneling Method (NATM). Specifications (e.g. EFNARC 1996, EN 14487-1 2005) classify the SFRSC in this application according to the material energy absorption capacity measured in flexural tests of square panels. The results obtained in the test are used both in the design and systematic quality control. For instance, the Australian Institute of Concrete (2010) takes the energy absorption class measured in the square panel test and the rock formation as input parameters for the tunnel lining design.

The square panel test is currently defined by the standard EN 14488-5 (2006). Modifications in the specimen shape and test procedure proposed to facilitate execution and improve the results include the three-point bending test of square panels with a notch (EFNARC 2011) and round panel test (ASTM C 1550-12 2012). Previous studies have addressed the correlation between different panel shapes (Bernard 2002; Myren and Bjøntegaard 2010) and proposed the use of even larger round panels for increased reliability (Bernard 2013). These methods, however, entail a significant degree of complexity and imply the use of sizeable testing equipment and specimens challenging to produce and manipulate. Possibly the main drawback of these tests lays in the impossibility to extract flat specimens from the curved lining in case a direct verification is needed. Differences in the boundary conditions during the execution of the structure and the panel can lead to different material consolidation and fibre rebound that could compromise the representativeness of the test results (Figueiredo and Helene 1993; Austin *et al*. 1997; Jolin 1999; Armelin and Banthia 2002; Kaufmann *et al*. 2013).

Figueiredo (1997), Bernard (2002), Myren and Bjøntegaard (2010) highlight a significant variability in the panel test results. Papworth (2002) suggests that the non-uniform moulding procedure of panels can lead to inconsistencies in the test results. The production of sufficiently flat, regular specimens is one of the major challenges towards ensuring adequate contact with the support during the test, which might have a significant influence on the results (Bernard 2002). Visual observations reveal that frictional forces between the panel and the supports have a direct impact on the energy absorbed (Myren and Bjøntegaard 2010).

Alternative procedures, such as the Barcelona test (BCN) defined in UNE 83515 (2010), have been used to assess the energy absorption in smaller-scale cast fibre-reinforced concrete (FRC) cylindrical specimens, that can be extracted from the structure and are considerably less demanding in terms of equipment and payload. In the BCN, cylinder punches concentrically placed above and below the specimen produce internal tensile stresses that induce the crack formation and opening. The UNE 83515 (2010) specifies that the increment in specimen perimenter due to cracking should be measured with a circumferential extensometer.

Pujadas *et al*. (2013) demonstrate that the increment in perimeter can be calculated from the vertical displacement of the press, thus avoiding the use of the expensive circumferential extensometer not found in most quality control laboratories (Monte *et al*. 2014). The use of this simplified BCN has proved to be an adequate method for the FRC quality control (Simão *et al*. 2019). Its application for the assessment of the energy absorption of sprayed FRC and the potential correlation of the results with those obtained through traditional panel tests still lack further research.

Carmona *et al*. (2020) correlated the absorbed energy of macro-syntetic fibre reinforced sprayed concrete by means of the BCN test, using a circumferential extensometer, and the square panel test, obtaining good correlation of results. However, the correlation equations were obtained using cast concrete, which differs from sprayed concrete due to the spraying conditions. It was proved by Banthia *et al*. (1994) and Leung *et al*. (2005) that there is no perfect parallelism between the mechanical properties of cast and sprayed FRC in the same dosage.

In order to know the actual fibre content incorporated in the structure, a new methodology was developed, the inductive test (Torrents *et al*. 2012; Cavalaro *et al*. 2015). This test can be applied to cylindrical cores (Cavalaro *et al*. 2016) and has been previously used to quantify the fibre content in SFRSC cores (Silva *et al*. 2015; Galobardes *et al*. 2019). Still few studies have been developed considering this method in the evaluation of SFRSC.

The objective of this study is to clarify these issues and to evaluate the potential use and implications of the simplified BCN together with the inductive test in substitution of the traditional square panel test. The analysis reflects the real control conditions of the material under the influence of the spraying process. The energy absorption results of two sizes of cylinders tested through the BCN test were correlated with those obtained from the square panel test. Findings derived from this study might support alternative approaches for the quality control of sprayed FRC and enable more straightforward verification of both properties of already built linings and the spraying process conditions.

2. Methodology

2.1 Spraying process

The mix composition of the concrete is shown in Table 1. The dry materials chosen for the experimental program are commonly used in tunnel linings production in the region of Sao Paulo, Brazil. A polyfunctional admixture based on lignosulphonate solution, a superplasticiser based on a polycarboxilate solution and a hydration stabiliser composed by a sucrose derivate were added to the composition to ensure adequate fresh state properties. The concrete was supplied in a concrete mixer truck.

The steel fibre used as reinforcement was classified as type C-II according to the Brazilian standard ABNT NBR 15530: 2007 (2007), with 39 mm length with and aspect ratio of 25 (Figure 1a). This fibre with low aspect-ratio was selected in order to evaluate one of the most critical conditions of SFRSC. Fibres were added in 3 nominal contents (approximately 30, 60 and 90 kg/m^3) directly to the truck and mixed thoroughly before the concrete was placed in the pump CP 10-SU (Figure 1b). This equipment has a nominal capacity of spraying of 10 cubic meters per hour and is mainly applied in tunnel linings with cross-sectional area bigger than 40 m^2. The mixture was sprayed on wood moulds positioned at 20° to the vertical axis (Figure 1c). An accelerator admixture based on aluminium sulphate solution (approximately 24 kg/m^3) was used to ensure adequate material consolidation over the surface. The wet spraying process replicates that typically found in ground support applications.

Once the production of a test panel series related to lower fibre content was completed, the volume of the remaining concrete was estimated and an extra amount of fibre was added to the concrete truck to achieve the intermediate fibre content. Once the intermediate fibre content test panels were cast, the remaining volume of concrete was again estimated and a last portion of fibres was added to the mix to produce the last series of test panels with the highest fibre content. Notice that ensuring the exact fibre contents of 30, 60 and 90 kg/m^3 is not essential for conducting this study as the actual average content was assessed in all cylindrical cores. These nominal fibre contents were chosen aiming to cover the three levels of energy absorption (500, 700, 1000 J) considered in the EN 14487-1 standard, according to the methodology of Figueiredo (1997). The average sprayed concrete compressive strength for each nominal fibre content at 5 months was: 39.1, 38.5 and 37.2 MPa, respectively. The results meet the compressive strength requirements for permanent sprayed concrete (30 MPa or greater) (Thomas 2020).

The sprayed specimens were square pyramidal truncated panels of two sizes: small panels of 600 mm × 600 mm at the base, 800 mm × 800 mm at the top, and thickness of 100 mm; and large panels of 600 mm × 600 mm at the base, 1000 mm × 1000 mm at the top, and thickness 200 mm. 4 small panels and 1 large panel were sprayed with each nominal fibre content. An additional small panel was produced for the nominal contents of 60 kg/m^3 and 90 kg/m^3.

2.2 Square panel test – EN 14488-5

At the age of 5 months since production, 14 small panels (4 for the concrete with the lowest nominal fibre content and 5 for each of the others) were tested according to the EN 14488-5 using a 200 tf Shimadzu machine, as shown in Figure 2. A square metal plate (100×100×5 mm) was cast with mortar at the central part of the panels to mitigate irregularities in the spraying surface and ensure uniform load application. The surface of the panel in contact with the mould was positioned on a square steel support, leaving a free square area in the central part of 500 mm side. In some cases, steel thin sheets had to be placed on the edges to obtain a continuous contact between the test panels and the support. The tests were performed at a constant rate of 1 ± 0.1 mm/min. LVDTs were used to measure the displacement, positioned at a yoke fixed at the frame, in order to reduce external deformations. An analysis of the absorbed energy in Joules was made by calculating the area under the load-displacement curve obtained in the tests.

2.3 Extraction of cores

Cylindrical cores were extracted from the panels using a diamond crown cup saw. Large cylinders of nominal size of Ø150 mm × 150 mm (diameter × height) were extracted from large panels (Figure 3a). Small cylinders of Ø100 mm × 100 mm were extracted from small panels after the flexural test (Figure 3b). This process was performed carefully, avoiding extracting cylinders from cracked regions. The rough end of the core was cut to ensure the same height across all specimens. The specimens were used in the tests described in the next items.

2.4 Barcelona test

The test was performed on a 200 tf Shimadzu universal machine following the procedure proposed by Pujadas *et al*. (2013). 18 large cylinders (Ø150 mm × 150 mm) and 83 small ones (Ø100 mm × 100 mm) were tested at 5 and 7 months since production, respectively. The large cylinders are dived in 6 per panel from each fibre content; the small cylinders are divided in 23 from the concrete with lower fibre content (6 per panel minus 1 cylinder that was discarded), 30 from the concrete with the intermediate and higher fibre content, respectively (6 per panel). A constant piston displacement rate of 0.5 ± 0.05 mm/min was used in all cases. The cylinders were kept in the same position, that is, the face in contact with the mould at the base of the test machine. The punching load was applied using Ø25 mm × 20 mm steel cylinders for the small specimens and Ø37.5 mm × 30 mm for the large ones to comply with the specimen-metallic punch diameter ration of 1/4 defined in UNE 83515 (2010). The steel cylinders were concentrically placed on the upper and lower faces of the specimen (Figure 4). The absorbed energy was calculated as the area under the load-displacement curve in Joules.

2.5 Inductive test

The fibre content was determined by the inductive test (Torrents *et al*. 2012; Cavalaro *et al*. 2015). Initially, calibration procedure was performed with styrofoam cylinders, three of Ø100 mm × 100 mm (785.40 cm^3) and three of Ø150 mm × 150 mm (2650.72 cm^3) in which fibres were inserted manually in a random manner to achieve contents of 30, 60 and 90 kg/m^3. The inductance change measured can be used to calculate the inductance coefficients for the fibre used, as described in Cavalaro *et al*. (2016). Figure 5 shows the correlations between the fibre content placed in the styrofoam cylinders and the summed inductance variation ΔL_T measured in the 3 orthogonal axes. A linear relationship is both cylinder sizes with intersect 0 (condition without fibre) and a slope β equal to 0.0109 and 0.0103 for large and small cylinders, respectively. The similar β despite the variation on specimens sizes highlights the accuracy of the method.

Equation 1 gives the fibre content (C_f) within the cores in kg/m^3, depending on slop coefficient β, the total inductance variation (ΔL_T) in mH and volume (V) in m^3. Since the inductance change produced by concrete and styrofoam is negligible in comparison to that induced by the steel fibres, the same equation and coefficients apply to the cores extracted in the experimental programme.

$$C_f = \beta \times \frac{\Delta L_T}{V} \tag{1}$$

The inductive test was perfomed on the same cylinders used in the BCN test, before undergoing this test. The notations used to present the results are M1, M2 and M3, corresponding to the concretes with nominal fibre contents of 30, 60 and 90 kg/m^3, respectively. The letters L and S are added at the beginning of the notation refer to the large and small cylinders, respectively. For example, L_M3 refers to the large cylinders with 90 kg/m^3 nominal fibre content.

3. Results and analysis

3.1 Inductive test

Table 2 shows the fibre content assessed in the large and small cylinders, including mean values, standard deviation (*SD*), coefficient of variation (*CV*), number of specimens of the sample (*N*), maximum values (*max*) and minimum (*min*). The average fibre content found in specimens L_M1 is 46.98 ± 2.19 kg/m^3, which is considerably higher than the nominal fibre content of 30 kg/m^3. The L_M2 and L_M3 cylinders have similar fibre contents of (79.60 ± 5.96 and 76.85 ± 8.58 kg/m^3, respectively) despite the difference in the nominal fibre content (60 and 90 kg/m^3, respectively).

Small cylinders S_M1 and S_M2 with the lower and intermediate fibre contents (33.88 ± 4.32 and 63.02 ± 7.31 kg/m^3, respectively) show results close to the nominal contents (30 and 60 kg/m^3, respectively), while small cylinders S_M3 with the highest fibre content (74.92 ± 10.24 kg/m^3) display results lower than the nominal value (90 kg/m^3). Small cylinders presented a high *CV* associated to the smaller total weight of fibre within the specimen in comparison with the total weight found in larger cylinders. This can be intensified by the fact that a fibre with low aspect ratio was used, which implies a more significant weight variation due to the changes in the number of fibres in the sample.

For subsequent analysis, the average fibre content measured for the cylinders, determined by the inductive test, will be used. The fibre contents obtained in the small cylinders also correspond to the small panels from which they were extracted, and will be used in the evaluation of the square panel test EN 14488-5.

3.2 Square panel test – EN 14488-5

Figure 6 shows the mean load (*P*) versus displacement (δ) and absorbed energy (*E*) versus displacement (δ) curves. Table 3 summarises the energy absorption for a displacement of 25 mm (E_{25}), the panel thickness (*h*) and the number of cracks (N_c) after the test, considering the major and minor cracks. The mean values, standard deviation (*SD*), coefficient of variation (*CV*), sample size (*N*), and maximum (*max*) and minimum (*min*) values are also provided.

Both fibre content and panel thickness influence the energy absorption results in Table 3. The panels with higher fibre content (74.92 kg/m^3) and higher thickness (121.25 mm) show the highest average energy absorption value (976.18 ± 174.51 J), followed by the panels with fibre contents of 63.02 and 33.88 kg/m^3, which have energy absorption values of 578.18 ± 47.22 and 488.85 ± 50.38 J, respectively. The cracking pattern was generally 4 cross-shaped major cracks in panels with fibre contents of 33.88 and 63.02 kg/m^3 (Figure 7a). The number of cracks tends to increase for the content of 74.92 kg/m^3. For example, the panel with the highest energy absorption value of 1176.07 J presented 5 major and 2 minor cracks (Figure 7b). Panels with lower and medium fibre contents show a smaller number of cracks because a simple biaxial flexion occurs. As fibre content increases, the degree of redundancy in the test increases (Myren and Bjøntegaard 2010; Salehian *et al*. 2014; Juhasz *et al*. 2017); this in addition to the friction forces in the supports cause punching shear failure (Carmona *et al*. 2020), therefore the number of cracks increases. Cracking close to the edge of the panel could be highly affected by the support. Future studies focusing on that matter are needed.

The influence of the panel thicknesses on the absorbed energy was also reported by Bjøntegaard (2009), Myren and Bjøntegaard (2010), Sandbakk (2011). A correction factor, based on the study of Thorenfeldt (2009) *apud* Myren and Bjøntegaard (2010) was applied to compensate for this influence. The procedure is as follows: firstly, a corrected displacement must be found ($\Delta = 25\ mm \times k$, $k = 100/h$); then, the corrected energy (E_C) is the energy corresponding to the corrected displacement (E_Δ) multiplied by the factor k ($E_C = E_\Delta \times k$).

From Table 3 the corrected energy absorption results (E_C) are: 397.85 ± 30.31, 494.18 ± 37.12, 758.88 ± 147.15 J, for the panels with fibre contents of 33.88, 63.02 and 74.92 kg/m^3, respectively. These results will be used for further analysis in following sections. Similar *CVs* were found for the two lowest fibre contents. The considerably higher *CV* observed for specimens with the highest fibre content is probably due to the more pronounced variation in thickness and number of cracks in these panels. Microcraks or internal cracks could also influence differently the *CV* of tested panels with high and low fibre content. However, the presence of such microcracks was not assessable in the study.

3.3 Barcelona test

Figure 8 shows the mean load (*P*) and absorbed energy (*E*) versus displacement (δ) curves of the cylinders extracted from the panels of each mixture, of the two days of spraying. The curves were considered only from the displacement relative to the peak load reached in the test.

The results of energy absorption by displacement of the extracted cylinders are presented in Table 4. The results are evaluated up to the post-peak displacement of 5.0 mm, following the same criteria of previous studies that assess the absorbed energy in regular displacements in FRC (Galobardes and Figueiredo 2015; Liu *et al*. 2018) and SFRSC (Silva 2017; Galobardes *et al*. 2019) through the BCN test.

The load results are not considered in the analysis since they are not part of the study. The mean values, the standard deviation (*SD*), coefficient of variation (*CV*), sample size (*N*), maximum (*max*) and minimum (*min*) values are presented in Table 4.

From Table 4 analyzing the energy absorption results of the large cylinders in the displacement of 5 mm, the absorbed energies in increasing order are: 79.07 ± 17.61, 154.67 ± 26.64, 189.24 ± 39.81 J , for the cylinders with fibre contents of 46.98, 79.60 and 76.85 kg/m^3, respectively. It is observed that the cylinders with fibre content of 76.85 kg/m^3 show a higher level of energy absorption in relation to the cylinders of 79.60 kg/m^3, despite having lower fibre content. This may also be due to a better orientation in relation to the crack surface which may occurs randomly.

Analyzing the average absorption results of the small cylinders, the absorbed energies at 5 mm are: 34.18 ± 12.36, 60.35 ± 16.41 and 69.91 ± 15.04 J, for the cylinders with fibre contents of 33.88, 63.02 and 74.92 kg/m^3, respectively. The increasing order in energy absorption is related to the fibre content. The *CVs* were generally higher for the small cylinders, following the trend observed in the fibre content, as expected and better discussed in the next section.

3.4 Comparison of coefficients of variation

Figure 9 shows the *CVs* of the energy absorption results obtained from the square panel tests EN 14488-5 (Table 3) and BCN tests (Table 4). It can be seen that the higher *CVs* correspond to the small cylinders of the BCN test, with a mean *CV* of 28.29%. In an intermediate situation are the large cylinders of the BCN test, with mean *CV* of 20.18%. The panels have the smallest variation, with a mean *CV* of 11.51%.

In general, the *CV* of the absorbed energies is higher for small specimens. The *CVs* obtained with small cylinders were higher than those of the large ones, although they have lower amplitude of results. Similar trend was found by Aire *et al*. (2007), who evaluated the FRC in different sizes of cylinders, using the BCN test. This behavior can also be associated with the size of the specimen that defines the area of the fractured section. The larger this area, the smaller the coefficient of variation as observed in the study by Cavalaro and Aguado (2015). And also, in the small cylinders the *CVs* decrease since the fibre content increase, while in the large remains practically constant in all mixtures. These facts show that the large cylinders maintain a more stable behavior during the BCN test.

The *CVs* obtained in the EN 14488-5 panel tests were lower than the *CVs* obtained with the BCN tests for each mixture. This fact may be due to having a larger fracture surface. Similarly, it may be due to the fact that great care was taken before the test, by placing metal plates to ensure a continuous contact between the panels and the support; and during spraying, avoiding buckling on the panels. Several authors report that *CV* decreases with enhancing the fracture surface (Carmona *et al*. 2018). Nonetheless, the *CV* increases in the mixture with higher fibre content. This may be due to the fact that panels of 74.92 kg/m^3, besides the higher fibre content, have the greatest thickness and number of cracks variation, resulting in a greater variation of energy absorption results.

3.5 Mix design correlations and comparative analysis

The comparative analysis of the absorbed energy of the SFRSC is based on the analysis of mix design correlations. These correlations are focused on the average energy absorption results, between the square panel tests EN 14488-5 and BCN tests (Tables 3 and 4, respectively). The R^2 resulting for the correlations between the square panel test EN 14488-5 and BCN tests on small and large cylinders are almost similar, with values of 0.9809 and 0.9798, respectively (Figure 10). The good correlations indicate that any of the cylinders can be used in the evaluation of the energy absorption of the SFRSC, replacing the panels.

The comparative analysis is also based on the correlation of the energy absorption results of the square panel test EN 14488-5 and BCN tests on both size of cylinders with the fibre content, in each evaluated element (individual results that generated Tables 2-4). These correlations are shown in Figure 11a. The best correlation corresponds to the square panel test ($R^2 = 0.9714$), with sample size of 14 panels. The correlations obtained in the BCN tests on small and large cylinders were 0.9538 and 0.9568, with sample sizes of 83 and 18 cylinders, respectively.

The experimental design generated the difference in the number of parameters points of the tests in the linear fittings in Figure 11. In the case of the square panel test, the sample type and number respond to those typically adopted for the quality control of shotcrete. Since the BCN is an alternative test without the support of specific standards for shotcrete, the number of specimens was increased to evaluate the significance of the test variability.

To further verify the correspondence between the test methods, the absorbed energy results were divided by the crack area of each specimen tested. In the BCN tests, the absorbed energy was divided by the area of the rectangle that forms the cylinder, multiplied by three, since this is the number of cracks that commonly appear in this test (Pujadas 2013). In the panels, the absorbed energy was divided by the cross-sectional area multiplied by two, since the cracking pattern was generally 4 cross-shaped major cracks. The correlations between energy absorbed per area and fibre content are shown in Figure 11b. It can be seen that the three tests have similar trend lines. Grouping into a single correlation, the trend line equation is: $y = 63.584\,x$, with an R^2 value of 0.9562. This fact reinforces the concept that the tests are correlated with each other. It is also noteworthy that the absorbed energy results have an almost constant range as the fibre content increases.

From Figure 11a it is possible to determine which energy level corresponds to each test for a given fibre content. This can be used to evaluate the SFRSC by the BCN test, according to design methods based on square panel tests results, such as the EN 14487-1 (2005) standard.

According to the EN 14487-1, in the square panel test, to evaluate the SFRSC, three energy absorption levels are considered, in 25 mm of displacement. This type of classification can be associated with empirical tunnel sizing methods, which define the application of SFRSC according to the competence of the rock mass (Barton 2002; Shotcreting in Australia: Recommended Practice 2010; Rehman *et al*. 2019). The energy requirements are: class E 500, E 700, and E 1000 of 500 J, 700 J, and 1000 J, respectively. From Figure 11a, the energy absorption levels of the BCN test, on large and small cylinders, that correspond to these energy requirements and the average fibre content to achieve these energies, are shown in Table 5. Because all regressions in Figure 11a are linear, there may be a linear relationship between the values obtained. However, specific studies need to be done to obtain correlations of energy absorption with other types of fibres.

The energy requirements for each test and average fibre content were calculated considering the confidence intervals of linear regression, at 90% of confidence level, obtained from individual results that generated Tables 2, 3 and 4, according to the method of Freund and Simon (2002). The confidence intervals are presented in brackets in Table 5 and are also shown with dashed lines in Figure 11a.

3.6 Sample size analysis

A very common question for tunnel designers and builders is about the representative sample size in order to evaluate a structure. For this, according to the results, the reliable sample size was determined using the method of Bussab and Moretin (2002), through Equation 2, where the statistical values are: the sample size (n); the t-distribution (t) according to the confidence level (α); standard deviation (SD); and the acceptable error. In the present case, it was considered an average value according to the CVs evaluated, i.e. 20% of the mean value (e). Table 6 shows the comparison of sample sizes obtained for BCN tests on small and large cylinders and for the square panel test EN 14488-5, according to the results of Tables 4 and 3, respectively.

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

Evaluating sample sizes at 95% of confidence level, for the BCN test on large cylinders, the sample is almost constant for all mixtures, ranging from 5 to 9 cylinders. The BCN test on small cylinders needs a larger sample of 15 cylinders for lower fibre content (33.88 kg/m^3). For larger fibre contents (63.02 and 74.92 kg/m^3) the sample decreases to 8 and 5 cylinders, respectively. In the case of the square panel test, only 2 samples are required for mixtures of 33.88 and 63.02 kg/m^3. However, for the mixture with higher fibre content (74.92 kg/m^3), 8 panels are required. The increase in the number of specimens demanded for the EN 14488-5 test with the highest fibre content was due to the increase in *CV* of this serie, which was generated by the variation of panel thickness and number of cracks. This tendency of increasing number of specimens associate to the highest fibre content was not so evident for the BCN tests that presented higher uniformity on geometry and crack pattern characteristics.

This high number of specimens can also be attributed to the fact that the fibre used has a low aspect ratio. As a result, the reinforcement capacity is more susceptible to variations in the number of fibres present in the cracking area. Therefore, this evaluation can be considered as critical and the number of specimens indicated must meet the confidence level for sprayed concretes reinforced with fibre with higher aspect ratio. Considering that the number of specimens in the sample show to be below the desired for a few test conditions, the findings represent a valid contribution to the literature.

Although the cylinders for the BCN tests need a larger number of samples, they can easily be handled and transported, as the small cylinder weighs around 2 kg and the large 6.5 kg, much less compared to the small panels for the square panel test, which weighs around 110 kg. This fact would evidently improve the technology control process both on site and in the laboratory, besides the advantage of being able to extract cores directly from the structure in different locations. However, in cases of evaluation of existing structures it may be necessary to extract a larger number of specimens to obtain representative results.

4. Conclusions

The study showed the possibility of correlation between the results obtained of energy absorption in the BCN tests in small and large extracted cylinders and the square panel test EN 14488-5. The main conclusions were:

- It was confirmed that the level of energy absorption is directly related to the actual fibre content of the SFRSC, being able to determine which energy level corresponds to each test for a given fibre content. By dividing the energy absorption by the fracture area observed in the specimens of each test they practically maintain the same trend line, showing the correspondency between all tests.
- The *CV* of energy absorption associate to the small cylinders is higher than those of the large ones. In the small cylinders the *CVs* decrease since the fibre content enhance, while in the large remains almost constant. This shows that the large cylinders provide more uniform results from the BCN test due to the larger crack area. The panel tests have the smallest *CV* which could be associated to the even larger fracture surface. However, the *CV* increases at higher fibre contents due to variations in the number of the cracks together with the panel´s thickness in this particular case. Thus, the production of specimens for this type of test should be careful to minimize the variation of their final thickness.
- The largest *CV* of the BCN test is clearly disadvantageous, in order to obtain representative results. Nonetheless, the BCN test can be used for routine control and, especially for existing SFRSC structures evaluation once it becomes possible to perform the test with extracted cores. Also, the BCN test has the advantage of using smaller equipment and the smaller specimens produce much better working conditions for operators in the laboratory.
- The good correlations of the absorbed energy results of the square panel test and BCN in extracted cylinders, justify the use of any of the cylinders in the evaluation of the absorbed energy of the SFRSC. The BCN test can be considered as representative to evaluate the values of absorbed energy in underground works of SFRSC, as long as the correspondence of absorbed energy is established in previous studies.
- Cylindrical cores can be extracted *in situ* allowing evaluate the tunnel lining real conditions. The fact that the specimens can be used for two determinations (fibre content effectively incorporated into the structure and determination of the mechanical behavior of the SFRSC) expands the quality control potential of the tunnel lining construction, providing greater reliability in the process. However, the obtained correlations could not

be extrapolated and, in consequence they must be determined for each project in the previous qualification studies of the SFRSC.

Data availability

All data, models, and code generated or used during the study appear in the submitted article.

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TABLES

Table 1 *– Concrete mix composition.*

Materials	*Content (kg/m^3)*
Cement (70% CEM I 52.5R and 30% blast-furnace slag)	400
Fine quartz sand (0 - 0.6 mm)	574
Crushed granitic sand (0 - 4.8 mm)	315
Crushed granite coarse aggregate (4.8 - 12.5 mm)	840
Water	200
Polyfunctional admixture	1.44
Superplasticiser	0.84
Hydration stabilizer	1.12

Table 2*: Fibre content (C_f) in kg/m^3 of the extracted cylinders.*

Cylinders of Ø150 mm × 150 mm				***Cylinders of Ø100 mm × 100 mm***			
	L_M1	***L_M2***	***L_M3***		***S_M1***	***S_M2***	***S_M3***
Mean	46.98	79.60	76.85	***Mean***	33.88	63.02	74.92
SD	2.19	5.96	8.58	***SD***	4.32	7.31	10.24
CV (%)	4.67	7.48	11.16	***CV (%)***	12.75	11.60	13.66
N	6	6	6	***N***	23	30	30
max	49.45	89.38	86.46	***max***	47.05	82.27	93.48
min	44.28	71.23	63.55	***min***	24.66	51.80	54.02

Table 3*: Absorbed energy in 25 mm (E_{25}) in J for smaller panels according to EN 14488-5, panel thickness (h) in mm, number of cracks on the panels (N_c) after being tested, factor of correction (k), modified displacement (Δ) in mm, corrected absorbed energy (E_c) in J.*

Panels (C_f = 33.88 kg/m³)						
	E_{25}	***h***	***N_c***	***k***	**Δ = 25.k**	***E_c = K. E_Δ***
Mean	488.85	117.61	3.75	0.85	21.28	397.85
SD	50.38	4.02	0.50	0.03	0.72	30.31
CV (%)	10.31	3.42	13.33	3.37	3.37	7.62
N	4	4	4	4	4	4
max	538.51	122.99	4.00	0.88	21.93	422.11
min	424.94	113.98	3.00	0.81	20.33	354.17

Panels (C_f = 63.02 kg/m³)						
	E_{25}	***h***	***N_c***	***k***	**Δ = 25.k**	***E_c = K. E_Δ***
Mean	578.18	112.05	4.40	0.89	22.31	494.18
SD	47.22	1.51	0.55	0.01	0.30	37.12
CV (%)	8.17	1.35	12.45	1.34	1.34	7.51
N	5	5	5	5	5	5
max	629.05	114.29	5.00	0.90	22.57	542.63
min	505.37	110.77	4.00	0.87	21.87	440.22

Panels (C_f = 74.92 kg/m³)						
	E_{25}	***h***	***N_c***	***k***	**Δ = 25.k**	***E_c = K. E_Δ***
Mean	976.18	121.25	5.00	0.83	20.65	758.88
SD	174.51	5.17	1.22	0.04	0.89	147.15
CV (%)	17.88	4.26	24.49	4.31	4.31	19.39
N	5	5	5	5	5	5
max	1176.07	126.28	7.00	0.87	21.70	978.13
min	707.44	115.22	4.00	0.79	19.80	578.39

***Table 4**: Absorbed energy in 5.0 mm (E_5) in J, for cylinders of Ø150 mm × 150 mm and Ø100 mm × 100 mm, according to the BCN test.*

Cylinders of Ø150 mm × 150 mm				***Cylinders of Ø100 mm × 100 mm***			
C_f (kg/m^3)	***46.98***	***79.60***	***76.85***	***C_f (kg/m^3)***	***33.88***	***63.02***	***74.92***
Mean	79.07	154.67	189.24	***Mean***	34.18	60.35	69.91
SD	17.61	26.64	39.81	***SD***	12.36	16.41	15.04
CV (%)	22.27	17.22	21.04	***CV (%)***	36.17	27.18	21.51
N	6	6	6	***N***	23	30	30
max	92.65	186.08	241.24	***max***	54.52	86.12	102.06
min	52.27	118.93	129.54	***min***	16.08	22.69	40.98

***Table 5**: Correlation for energy levels required by EN 14487-1 (2005) and BCN tests ($E_{Panel, 25}$ and $E_{BCN, 5.0, \delta (mm)}$) in J, and average fibre content C_f in kg/m^3.*

EN 14487-1	***EN 14488-5***	***BCN (L)***	***BCN (S)***	
Class	***E_{25}***	***$E_{5.0}$***	***$E_{5.0}$***	***C_f***
E 500	500 (± 54)	112 (± 19)	50 (± 2)	53
E 700	700 (± 68)	157 (± 15)	70 (± 3)	74
E 1000	1000 (± 148)	224 (± 36)	100 (± 7)	106

***Table 6**: Sample size (n) according to the statistical measurement values.*

1 - α	***90%***	***95%***	***1 - α***	***90%***	***95%***	***1 - α***	***90%***	***95%***
C_f (kg/m^3)	***BCN (L)***		***C_f (kg/m^3)***	***BCN (S)***		***C_f (kg/m^3)***	***EN 14488-5***	
46.98	6	9	***33.88***	10	15	***33.88***	1	2
79.60	4	5	***63.02***	6	8	***63.02***	1	2
76.85	5	8	***74.92***	4	5	***74.92***	5	8

FIGURES

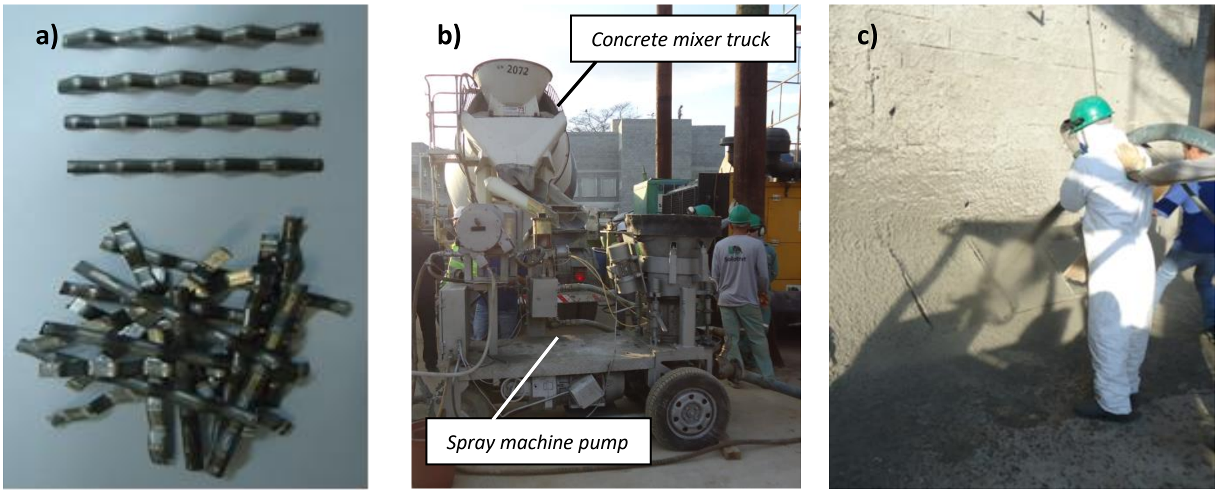

Figure 1*: Steel fibre used (a); concrete truck and pump (b); spraying process (c).*

Figure 2*: Square panel test according to EN 14488-5.*

Figure 3*: Cylinders extraction from large panels (a) and small panels (b).*

***Figure 4**: Barcelona test (BCN).*

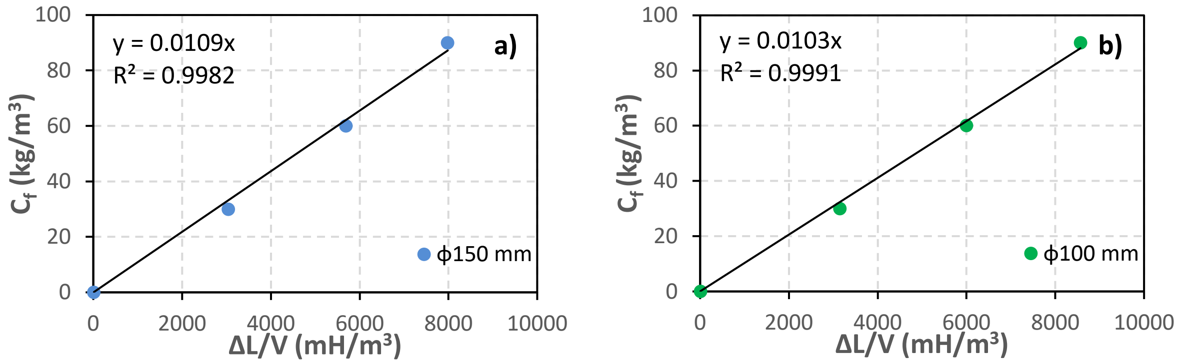

***Figure 5**: Inductive method calibration in styrofoam cylinders of Ø150 mm × 150 mm (a) and Ø100 mm × 100 mm (b).*

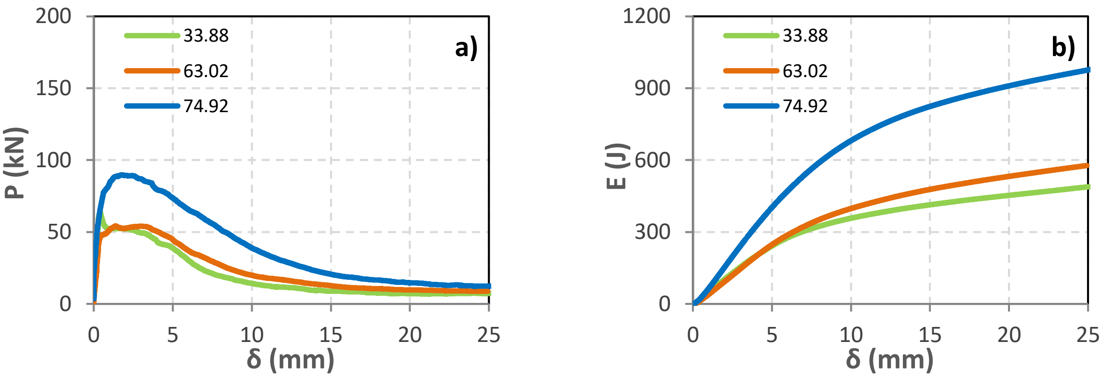

***Figure 6**: Average curves of load (a) and energy absorption (b) versus displacement, according to the EN 14488-5 test on small panels with fibre contents of 33.88, 63.02 and 74.92 kg/m^3.*

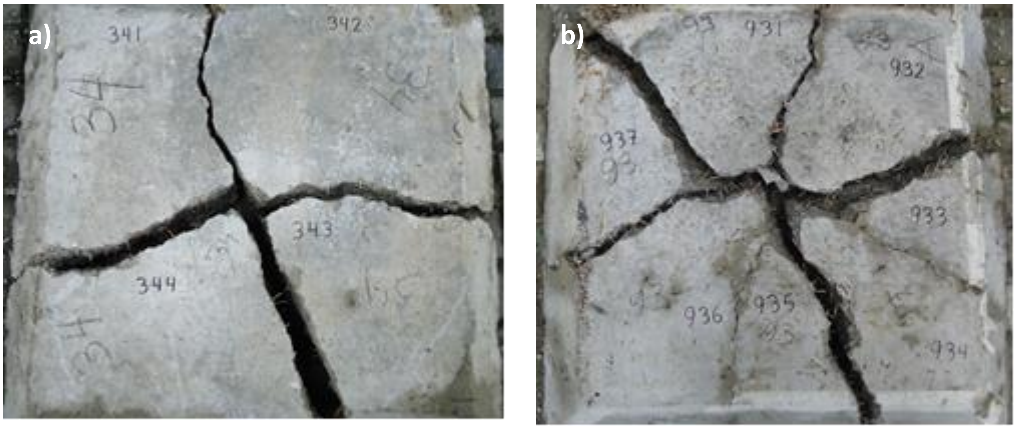

Figure 7: *Typical crack pattern including 4 major cracks for medium and lower fibre contents (a). Multiple cracks observed in panel with highest energy absorption for higher fibre contents (b).*

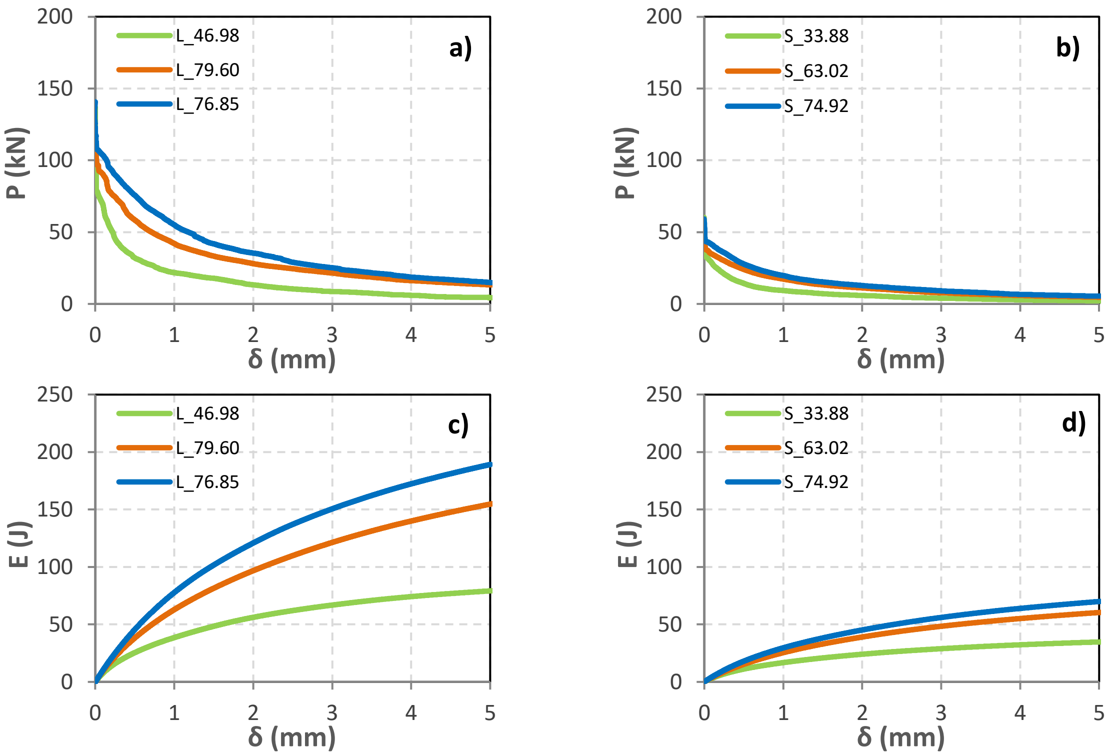

Figure 8: *Average curves of load by displacement in cylinders of Ø150 mm × 150 mm (fibre contents of 46.98, 79.60 and 76.85 kg/m^3) (a) and Ø100 mm × 100 mm (fibre contents of 33.88, 63.02 and 74.92 kg/m^3) (b); and of energy absorption by displacement in cylinders of Ø150 mm × 150 mm (c) and Ø100 mm × 100 mm (d) by the BCN test.*

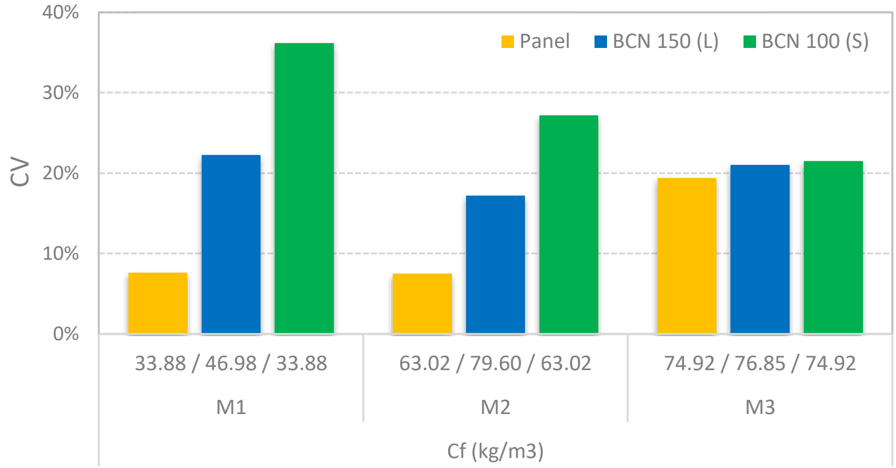

Figure 9: *Comparison of the CVs of the energy absorption results of the EN 14488-5 test and BCN tests.*

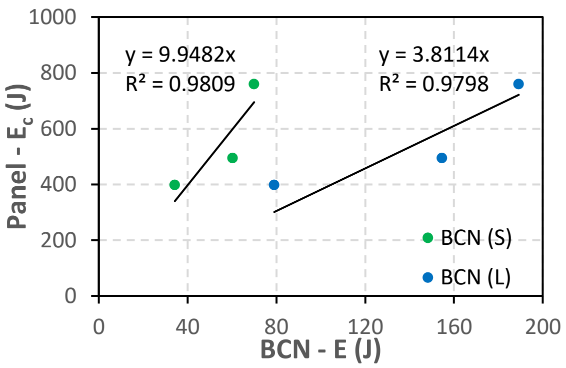

Figure 10: *Correlation of average energy absorption results between the square panel test EN 14488-5 and BCN tests.*

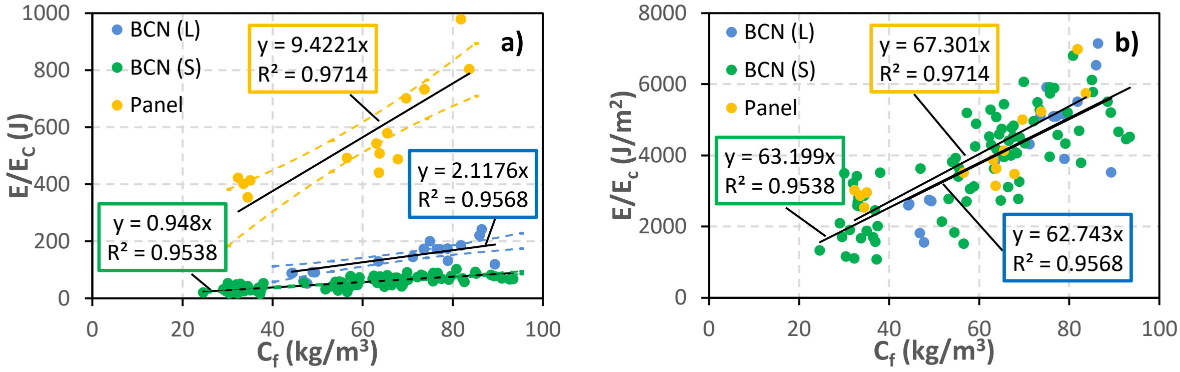

Figure 11: *Correlation between energy absorption results from the square panel test EN 14488-5 and BCN tests with fibre content, in J – kg/m³ (a) and J/m² - kg/m³ (b).*

FIGURE CAPTION LIST

Figure 1: Steel fibre used (a); concrete truck and pump (b); spraying process (c).

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