

ALAN RENATO ESTRADA CÁCERES

**NEW APPROACH TO EVALUATE FIBRE-REINFORCED SPRAYED
CONCRETE FOR STRUCTURAL TUNNEL LINING**

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CONCRETE FOR STRUCTURAL TUNNEL LINING**

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Engineering.

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Figueiredo.

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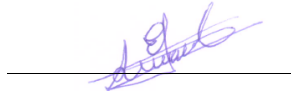
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ABSTRACT

Fibre-reinforced sprayed concrete (FRSC) has not followed the same evolution of conventional fibre-reinforced concrete (FRC) in terms of provisions for structural design and applications. Nearly all design codes either fail to mention or explicitly exclude sprayed concrete. Recent guidelines by the International Tunnelling and Underground Space Association propose an adaptation of the *FIB* Model Code provisions FRC to FRSC. Today, one of the innovative strategies to evaluate the FRSC is to control the material effectively incorporated into the tunnel lining by tests on small-scale specimens (small-scale tests) from extracted cores, avoiding basing the control process solely on traditional beam or panel tests. The main objective of this thesis is to demonstrate the viability of a modern approach to control the quality and derive structural design parameters of FRSC tunnels using small-scale tests, without the need for traditional empirical methods. Experimental and numerical studies were performed addressing the use of the double punch test (DPT) and the double-edge wedge splinting (DEWS) test to evaluate the mechanical behaviour of FRSC. These small-scale tests showed good correlations of toughness results with those of traditional beam (EN 14488-3) and panel tests (EN 14488-5, ASTM C1500). The possibility of obtaining constitutive models from both small-scale tests was demonstrated. This led to a quality control method to assess the energy absorption of FRSC that substitutes the panel test ASTM C1550 and an approach to derive constitutive models, both underpinned by simple small-scale tests. The suitability of the small-scale tests constitutive models was verified by numerically simulating the experimental post-cracking behaviour of the panel test ASTM C1550. Results confirm the viability of the approach proposed here.

Keywords: Fibre-reinforced sprayed concrete. Tunnel lining. Small-scale specimens. Panel tests. Numerical simulation.

RESUMO

O concreto projetado reforçado com fibras (CPRF) não seguiu a mesma evolução do concreto reforçado com fibras (CRF) convencional em termos de provisões para projeto estrutural e aplicações. Quase todos os códigos de projeto não mencionam ou excluem explicitamente o concreto projetado. Diretrizes recentes da Associação Internacional de Túneis e Espaço Subterrâneo propõem uma adaptação das disposições de CRF do *FIB Model Code* para CPRF. Hoje, uma das estratégias inovadoras para avaliar o CPRF é controlar o material efetivamente incorporado ao revestimento do túnel por meio de ensaios em corpos de prova de pequena escala (ensaios em menor escala) provenientes de núcleos extraídos, evitando basear o processo de controle apenas em ensaios tradicionais em vigas ou placas. O principal objetivo desta tese é demonstrar a viabilidade de uma abordagem moderna para controlar a qualidade e obter parâmetros de projeto estrutural de túneis de CPRF usando ensaios em menor escala, sem a necessidade de métodos empíricos tradicionais. Estudos experimentais e numéricos foram realizados abordando o uso do ensaio de duplo puncionamento DPT (do inglês: *double punch test*) e do ensaio de compressão de corpo de prova com duplo corte em cunha DEWS (do inglês: *double-edge wedge splitting*) para avaliar o comportamento mecânico do CPRF. Esses ensaios em menor escala mostraram boas correlações de resultados de tenacidade com os dos ensaios tradicionais em vigas (EN 14488-3) e placas (EN 14488-5, ASTM C1500). A possibilidade de obter modelos constitutivos de ambos os ensaios em menor escala foi demonstrada. Isso levou a um método de controle de qualidade para avaliar a absorção de energia do CPRF que substitui o ensaio de placa ASTM C1550 e uma abordagem para derivar modelos constitutivos, ambos sustentados por ensaios simples em menor escala. A adequação dos modelos constitutivos dos ensaios em menor escala foi verificada simulando numericamente o comportamento experimental pós-fissuração do ensaio de placa ASTM C1550. Os resultados confirmam a viabilidade da abordagem aqui proposta.

Palavras-chave: Concreto projetado reforçado com fibras. Revestimento de túneis. Corpos de prova de pequena escala. Ensaio em placas. Simulação numérica.

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...conduire par ordre mes pensées, en commençant par les objets le plus simples et le plus aisés à connaître, pour remonter peu à peu, comme par degrés, jusques à la connaissance des plus composés...

...to drive my thoughts in order, starting by the simplest objects, the easiest to know, so as to rise gradually, step by step, up to the knowledge of the most compound ones...

(René Descartes, *Discours de la méthode*, 1637).

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1 INTRODUCTION

1.1 Justification

Composite materials are widely used in construction. In conventional concrete, the use of fibres provides a series of benefits. Concrete is characterized by being a fragile material which can be improved by fibres addition, generating fibre-reinforced concrete (FRC) (CHEN, 1995; FIGUEIREDO, 1997; NAAMAN, 2003; BENTUR; MINDESS, 2007; JOHNSTON, 2010; SINGH, 2017). Fibres bridge the cracks, increasing the ductility and the post-cracking behaviour of concrete (BENTUR; MINDESS, 2007; di PRISCO; COLOMBO; DOZIO, 2013).

One of the most common uses of FRC is in structural elements produced through spraying systems. The material produced with this approach is called fibre-reinforced sprayed concrete (FRSC). Since the first experimental work on FRSC in the early 1970s, the material has been the subject of study and application in many fields (MORGAN *et al.*, 1989; ACI, 1998; CENGIZ; TURANLI, 2004; di PRISCO; COLOMBO; DOZIO, 2013). Tunnel linings are characterized by a high degree of hyperstaticity and represent the type of application where FRSC is most effective (di PRISCO; PLIZZARI; VANDEWALLE, 2009; de MONTAIGNAC; MASSICOTTE; CHARRON, 2012; SALEHIAN; BARROS; TAHERI, 2014).

Fibre reinforcement is increasingly popular for sprayed concrete lining tunnels in hard and soft ground (THOMAS, 2020). Tunnels made with FRSC reach stability at lower stress levels due to a redistribution of loads without loss of structural competency as deformation occurs within the limits of the ground and the lining (FIGUEIREDO, 2011; BERNARD; THOMAS, 2020; THOMAS, 2020). The most efficient lining is one that mobilizes the massif to guarantee lower stress levels for the lining (VANDEWALLE, 1997).

The use of FRSC has increased in tandem with improvements in spray machines, tests, and concrete dosage methods (use of admixtures, chemical additives, and types of fibres) (YOGGY, 2002; NGUYEN, 2003; DUFOUR; O'DONNELL; BALLOU, 2003; ZHANG; MORGAN, 2015). FRSC is used as total or partial reinforcement in all tunnel linings because of its economic competitiveness and

improvements in structural performance (BERNARD, 2002). According to John (1999) *apud* Nguyen (2003), more than 90% of underground mine roadways are suitable for FRSC or FRSC and bolts. The size of the global market of sprayed concrete is projected to reach USD 10.9 billion by 2030, at an annual growth rate of 6.91% between 2021 and 2030¹.

Further studies should accompany this high demand for sprayed concrete. This does not occur due to the methodological difficulty of producing at a lab scale sprayed concrete samples, which requires spraying machines and high volumes (PRUDÊNCIO Jr., 1993; FIGUEIREDO, 1997; ARMELIN, 1997; NGUYEN, 2003; de RIVAZ, 2011; GARCIA; BLANCO; CAVALARO, 2016; SALVADOR, 2016). The lack of studies is one of the problems that delay the development of more current approaches to assess the structural behaviour of FRSC if compared with conventional FRC.

FRC with structural responsibility has experienced significant technological development since the 1990s (di PRISCO, PLIZZARI, VANDEWALLE, 2009). The *FIB* Model Code (FIB, 2010) considers FRC as a material with a structural purpose. FRSC did not follow this evolution. The *FIB* Model Code explicitly excludes sprayed concrete. This is a clear demonstration of the specificity of FRSC. The direct transfer of results obtained in FRC is not sufficient to justify the use and determine the properties of FRSC as a structural material (BANTHIA; TROTTIER; BEAUPRÉ, 1994; LEUNG; LAI; LEE, 2005). FRSC still lacks developments to guarantee its reliability in terms of structural application.

Over the years, there have been attempts to approximate the design philosophy of *FIB* Model Code to FRSC, such as the use of the three-point bending test of square panel with a notch proposed by EFNARC (2011). This test resembles the three-point flexural test on a beam with a notch EN 14651 (CEN, 2007), which is recommended by the *FIB* Model Code to obtain FRC residual strength parameters. However, this panel test shows great difficulty in its execution (CÁCERES; SANTOS; FIGUEIREDO, 2017).

Recent guidelines such as those of ITA Working Group No. 12 and ITAtech (ITA, 2020) propose the EN 14651 test to obtain post-cracking design parameters for FRSC according to *FIB* Model Code. Recent studies propose an adaptation of the design philosophy of FRC to FRSC structures (LARIVE *et al.* 2020; THOMAS, 2020).

¹ <https://www.alliedmarketresearch.com>

However, further work is required to evaluate the potential use of FRSC as a structural material in line with *FIB* Model Code definition.

The post-cracking performance of FRSC is traditionally evaluated in terms of residual strength through the flexural tests of beams according to JSCE SF-4 (JSCE, 1984), EN 14488-3 (CEN, 2006) and ASTM C1399 (ASTM, 2015); or energy absorbed through the flexure tests of panels according to EN 14488-5 (CEN, 2006) and ASTM C1550 (ASTM, 2020). The JSCE SF-4 test is not compatible with the quantification of residual strength parameters for the service and ultimate limit state design (FIGUEIREDO, 1997; SALVADOR, 2013). The ASTM C1399 test demands the use of a steel plate at the base of the beam, which makes it difficult to accurately identify the fracture load of the matrix and associate residual strengths with precise values of crack-openings (TIGUMAN; FIGUEIREDO, 2005; SALVADOR, 2013).

The EN 14488-3 test is based on the flexural beam test proposed by EFNARC (1996). This test is compatible with the approaches to derive design parameters (CÁCERES; SANTOS; FIGUEIREDO, 2017). Nonetheless, it requires more sophisticated equipment, with a closed-loop system to avoid post-peak instability. Additionally, to perform flexural beam tests (e.g. JSCE-F4, ASTM C1399, EN 14488-3, EN 14651), large panels are first sprayed and beams are extracted, which involves an arduous and difficult cutting process.

One of the most traditional approaches to link the FRSC with the traditional methods of construction of tunnels is the Q-System (PALMSTROM; BROCH, 2006). This empirical method of tunnel lining design associates the ground stability with minimum absorbed energy requirements (BARTON; GRIMSTAD, 1994; PALMSTROM; BROCH, 2006). In Q-system the FRSC absorbed energy should be assessed using the square panel test EN 14488-5 that was proposed by EFNARC (1996), or the round panel test ASTM C1550 (BERNARD; THOMAS, 2020).

National guidelines such as the Australian Institute of Concrete (CONCRETE INSTITUTE OF AUSTRALIA, 2010), Norwegian Concrete Association (NCA, 2011) or Norwegian Geotechnical Institute (NGI, 2013) continue to use the Q-system for tunnel lining design. Nonetheless, the use of empirical methods linked to energy absorption panel tests cannot certify the quality of the material actually in the tunnel, only of specimens sprayed separately.

The square panel test EN 14488-5 requires heavy specimens of up to 110 kg, and of large dimensions (600 mm side at the base, 800 mm side at the top, and

thickness of 100 mm), which are difficult to produce, manipulate and transport. The test involves a significant degree of complexity and imply the use of large test machines (FIGUEIREDO; HELENE, 1997; CARMONA; MOLINS; GARCÍA, 2020).

To facilitate the execution and improve the results, modifications in the procedure and panel shape were proposed. Examples are the three-point bending test of square panels with a notch (600 mm side $\times$ 100 mm) (EFNARC, 2011); flexure of round panels ($\varnothing$ 800 mm $\times$ 75 mm) supported on three points (ASTM C1550, 2020); flexure of triangular panels (600 mm side $\times$ 100 mm) supported on three points (ALMEIDA, 1999). To increase the reliability of results, studies proposed the use of much larger panels, such as the flexure of a large round ($\varnothing$ 1200 mm $\times$ 150 mm) (BERNARD, 2013) or square panel (1600 mm side $\times$ 80 mm) (KIRSTEN, 1997 *apud* NGUYEN, 2003).

From these tests, the round panel test ASTM C1550 (weighting around 91 kg) has great acceptance for the evaluation of sprayed concrete due to greater within-batch repeatability (TRAN; BERNARD; BEASLEY, 2005; BERNARD; XU, 2008; BERNARD; XU; CARINO, 2010). The round panel test experiences bi-axial flexure in response to a central point load and represents a mode of failure corresponding to the in-situ behaviour of tunnel lining structures (ASTM C1550, 2020).

Comparative studies found a linear correlation between the energy absorption results from the round panel test ASTM C1550 and square panel test EN 14488-5 (BERNARD, 2002; PAPWORTH, 2002; MYREN, BJØNTEGAARD, 2010). Despite the better representation of the volume of concrete and bi-axial flexural capacity, both panel tests give no explicit information about the tensile post-cracking response of FRC (NOUR *et al.*, 2011; SALEHIAN; BARROS; TAHERI, 2014) and do not have a direct link to modern design approaches.

One of the major drawbacks of panel tests lies in their inability to assess the behaviour of the material placed in the lining. This is relevant as spraying application factors such as rebound produce significant fibre content variation between the panel and the lining (ARMELIN, 1997; AUSTIN; PEASTON; ROBINS, 1997; KAUFFMAN *et al.*, 2013). The point loading test was recently proposed by Bernard; Oliveira; Forrest (2022) to evaluate the FRSC tunnel lining in situ. This evaluation method can be considered a load test under real conditions to evaluate the actual structural response of the lining. However, this large-scale load test implies a high cost and is destructive, covering only a restricted tunnel area.

Tests on small-scale specimens (henceforth called small-scale tests) have been developed to evaluate the FRC. Examples are the double punching test (DPT or Barcelona test) and the double-edge wedge splitting (DEWS) test. Due to the smaller dimensions and lower specimen weight (up to 2 kg), these tests can characterize core samples extracted from the lining. This enables the assessment of the material in the lining (ZHANG; MORGAN, 2015). Smaller specimens are easy to handle and allow more tests (GALOBARDES; FIGUEIREDO, 2015), making it possible to map large areas of the tunnel lining. These are also simple procedures suited for most quality control laboratories (FIGUEIREDO, 2014).

The DPT is supported by several research papers and has been increasingly used for the quality control of FRC in projects. This test provides results of residual strength and energy absorption (MOLINS; AGUADO; SALUDES, 2009; PUJADAS, 2013), having the potential to replace both the flexural beam test EN 14488-3 and the square panel test EN 14488-5 (CÁCERES; SANTOS; FIGUEIREDO, 2017; CÁCERES *et al.*, 2021b). Due to the geometry of DEWS specimen, the uniaxial tensile stress produced in the cross-section leads to a type I fracture (di PRISCO; FERRARA; LAMPERTI, 2013), which allows for determining the residual FRC strength directly.

As mentioned above, the current trend in designing and controlling FRSC as a structural material for tunnel linings is being directed towards the *FIB* Model Code, which is characterized by focusing exclusively on establishing constitutive models. This thesis proposes a new approach for characterizing FRSC for tunnel lining structural design purposes by means of constitutive models of small-scale tests (DPT, DEWS), without the need for traditional energy absorption empirical methods. This proposal aligns with recent recommendations of ITA Working Group N° 12 and ITAtech (ITA, 2020) to obtain new design parameterization according to *FIB* Model Code. It also lays the foundation for transitioning from the traditional energy absorption approach based on panel tests to a modern approach based on obtaining constitutive models for FRSC tunnel lining structural behaviour qualification.

Many tunnels are still designed and controlled according to the traditional empirical approach. In this sense, the DPT energy absorption results will be correlated with those of the square panel test EN 14488-5. The residual strength results of the DPT and DEWS tests will also be correlated with those of the flexural beam test EN 14488-3. The aspiration is to verify the capacity of both small-scale tests to derive

constitutive models according to the *FIB* Model Code for the design of FRSC tunnel linings.

A method based on both small-scale tests (DPT, DEWS) will be proposed, allowing the integration of the traditional energy absorption approach of the round panel test ASTM C1550 for FRSC quality control, and the new approach that includes obtaining constitutive models. The suitability of the constitutive models of both small-scale tests will be verified through a numerical simulation of the round panel test ASTM C1550 post-cracking behaviour. The simulation results will be contrasted with experimental ones.

The thesis seeks to improve the process of control and assessment of design parameters for FRSC tunnel linings. Optimized control systems for tunnel linings can minimize fibre consumption and consequently reduce environmental impact. Tunnel works are used in sanitation systems, power generation, infrastructure transport, and, which are very important for social, economic, and environmental development. Thus, the thesis is in direct accordance with SDG (Sustainable Development Goal of United Nations)² numbers 6, 7, 11, and specially, number 9, linked with infrastructures. However, as it has already been demonstrated that investment in infrastructure contributes to the reduction of social inequality (KLENERT *et al.*, 2019; JOSA *et al.*, 2019), it is also possible to link to SDG number 10.

1.2 Objectives

The general objective of the thesis is to demonstrate the validate a novel approach for quality control and assessment of design parameters for FRSC using small-scale tests (DPT, DEWS). To accomplish the general objective, it is necessary to achieve the following specific objectives:

- Evaluate the potential use of the DPT test to control FRSC structures, replacing the traditional energy absorption panel test EN 14488-5 and deriving a correspondence in terms of energy absorption capacity.

² <https://sdgs.un.org/goals>

- Evaluate the correlation between the residual strength results of the traditional flexural beam test EN 14488-3 and those of DPT and DEWS tests. Verify the possibility of obtaining constitutive models for FRSC from both small-scale tests, in line with current trends to obtain design parameters for FRSC according to *FIB Model Code*.
- Propose a unique method that allows the integration of the traditional approach which includes the characterization of FRSC by the energy absorption panel test ASTM C1550 and the new approach that comprises obtaining constitutive models for structural design purposes of FRSC by means of small-scale tests. Verify the suitability of the small-scale tests constitutive models by numerically simulating the post-cracking behaviour of the round panel test ASTM C1550.

2 THESIS ORGANIZATION

2.1 Chapters description

The doctoral thesis was organized in 7 chapters, as shown in Figure 2.1. The main body of the thesis is organized in a collection of articles format.

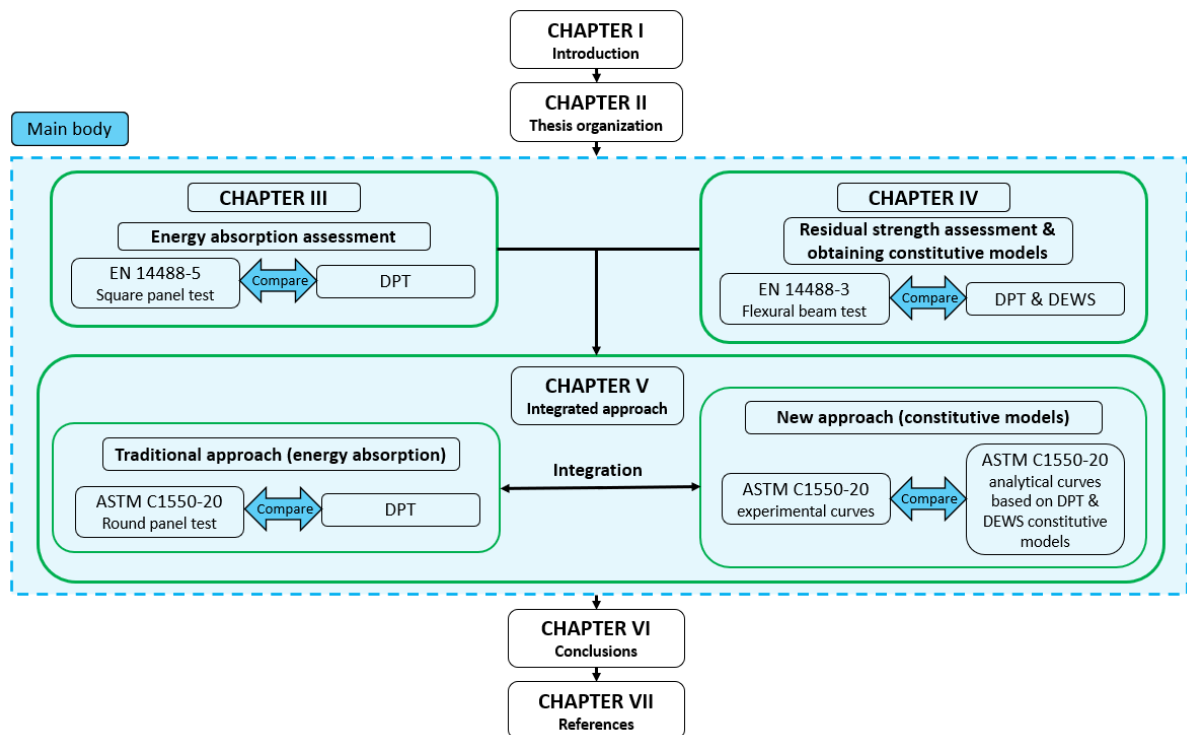


Figure 2.1 – Thesis organization.

The chapters presented in this doctoral thesis deal with the following issues:

- Chapter 1: Introduction, justification, and objectives of the thesis. It presents the contextualization and motivations for the thesis.
- Chapter 2: Organization of the thesis.
- Chapter 3: Evaluation of absorbed energy. It describes a new methodology to characterize the energy absorption of steel fibre-reinforced sprayed concrete (SFRSC). The results of energy absorption from the square panel test EN 14488-5 are contrasted with those of DPT. This chapter is the faithful

reproduction of the article written by the author and collaborators in “Evaluation of steel fibre-reinforced sprayed concrete by energy absorption tests” (CÁCERES; CAVALARO; FIGUEIREDO, 2021).

- Chapter 4: Evaluation of residual strength and constitutive models. It describes a new methodology to characterize the residual strength of SFRSC. The results of residual strength from the flexural beam test EN 14488-3 are contrasted with those of small-scale tests (DPT, DEWS). The possibility of obtaining constitutive models for parameterizing the post-cracking behaviour of SFRSC in terms of stress by crack-opening in agreement to *FIB* Model Code from small-scale tests (DPT, DEWS) is verified. This chapter is the faithful reproduction of the article written by the author and collaborators in “Alternative small-scale tests to characterize the structural behaviour of steel fibre-reinforced sprayed concrete” (CÁCERES *et al.*, 2021a).
- Chapter 5. Integration of the traditional energy absorption control approach of SFRSC and the new approach based on constitutive models, thorough small-scale tests. The energy absorption results of the round panel test ASTM C1550 are contrasted with those of DPT. The study evaluates the suitability of the constitutive models of DPT and DEWS tests to simulate the post-cracking behaviour of the round panel test ASTM C1550. The numerical simulations are contrasted with experimental results of the round panel test ASTM C1550 in terms of load and energy absorption. This chapter is the faithful reproduction of the article written by the author and collaborators in “Integrated approach for quality control of fibre reinforced-sprayed concrete for tunnel lining” (CÁCERES; CAVALARO; FIGUEIREDO, 2023).
- Chapter 6: Conclusions. This chapter describes the study's conclusions based on the analysis of results. Suggestions for future works are also mentioned.
- Chapter 7: Bibliographic references.

2.2 Articles status description

The articles current status description that compound the main body of the thesis is presented below:

Article 1 (Chapter 3)

Title: Evaluation of steel fibre-reinforced sprayed concrete by energy absorption tests.

Published in: ASCE Journal of Materials in Civil Engineering.

Published date: 15/07/2021.

DOI: 10.1061/(ASCE)MT.1943-5533.0003865.

Article 2 (Chapter 4)

Title: Alternative small-scale tests to characterize the structural behaviour of steel fibre-reinforced sprayed concrete.

Published in: Construction & Building Materials.

Published date: 16/08/2021.

DOI: <https://doi.org/10.1016/j.conbuildmat.2021.123168>.

Article 3 (Chapter 5)

Title: Integrated approach for quality control of fibre reinforced-sprayed concrete for tunnel lining.

Published in: Tunnelling and Underground Space Technology.

Published date: 20/06/2023.

DOI: <https://doi.org/10.1016/j.tust.2023.105260>.

3 EVALUATION OF STEEL FIBRE-REINFORCED SPRAYED CONCRETE BY ENERGY ABSORPTION TESTS

3.1 Introduction

Steel fibres are used in sprayed concrete to provide post-cracking reinforcement to enhance toughness avoiding the typical brittle behaviour of this material (BERNARD; THOMAS, 2020) and enhancing dynamic mechanical properties (CHEN; ZHANG; LIU, 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; KUSTERLE, 2001; CENGIZ; TURANLI, 2004; BERNARD, 2008; GINOUSE; JOLIN, 2015; GALO BARDES *et al.*, 2019; LIU *et al.*, 2020). One of the most traditional applications of SFRSC is tunnel lining by the traditional methods of construction of tunnels. Specifications (e.g. EFNARC, 1996; EN 14487-1: 2005 (CEN, 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 (CONCRETE INSTITUTE OF AUSTRALIA, 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 (CEN, 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 C1550-2020 (ASTM, 2020)). Previous studies have addressed the correlation between different panel shapes (BERNARD, 2002; MYREN; 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; HELENE, 1993; AUSTIN; PEASTON; ROBINS, 1997; JOLIN, 1999; ARMELIN; BANTHIA, 2002; KAUFMANN *et al.*, 2013).

Figueiredo (1997), Bernard (2002) and Myren; 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; BJØNTEGAARD, 2010).

Alternative procedures, such as the Barcelona test (BCN) defined in UNE 83515 (AENOR, 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 (AENOR, 2010) specifies that the increment in specimen perimeter 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; TOALDO; FIGUEIREDO, 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; Molins; García (2020) correlated the absorbed energy of macro-synthetic 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 Bantia;

Trottier; Beaupré (1994) and Leung; Lai; Lee (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; GALO BARDES *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.

3.2 Methodology

3.2.1 Spraying process

The mix composition of the concrete is shown in Table 3.1. The dry materials chosen for the experimental program are commonly used in the construction of tunnel linings in the region of São Paulo, Brazil. A polyfunctional admixture based on lignosulphonate solution, a superplasticiser based on a polycarboxylate 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: 2019 (ABNT, 2019), with 39 mm length with and aspect-ratio of 25 (see Figure 3.1a). 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/m³) directly to the truck and mixed thoroughly before the concrete was placed in the pump CP 10-SU (see Figure 3.1b). 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 m². The mixture was sprayed on wood moulds positioned at 20° to the vertical axis (see Figure 3.1c). An accelerator admixture based on aluminium sulphate solution (approximately 24 kg/m³) was used to ensure adequate material consolidation over the surface. The wet spraying process replicates that typically found in ground support applications.

Table 3.1 – Concrete mix composition. Source: Cáceres; Cavalaro; Figueiredo (2021).

Materials	Content (kg/m³)
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 stabiliser	1.12

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/m³ 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/m³ and 90 kg/m³.

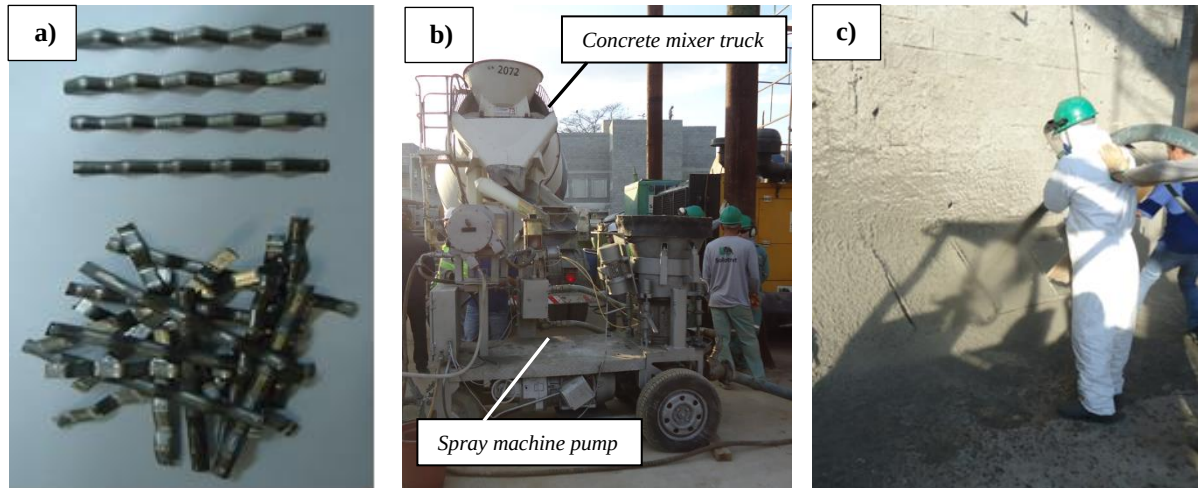


Figure 3.1 - Steel fibre used (a); concrete truck and pump (b); and spraying process (c). Source: Cáceres; Cavalaro; Figueiredo (2021).

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 3.2. 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.



Figure 3.2 - Square panel test according to EN 14488-5. Source: Cáceres; Cavalaro; Figueiredo (2021).

3.2.3 Extraction of cores

Cylindrical cores were extracted from the panels using a diamond crown cup saw. Large cylinders of nominal size of $\varnothing 150 \text{ mm} \times 150 \text{ mm}$ (diameter $\times$ height) were extracted from large panels (see Figure 3.3a). Small cylinders of $\varnothing 100 \text{ mm} \times 100 \text{ mm}$ were extracted from small panels after the flexural test (see Figure 3.3b). 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.

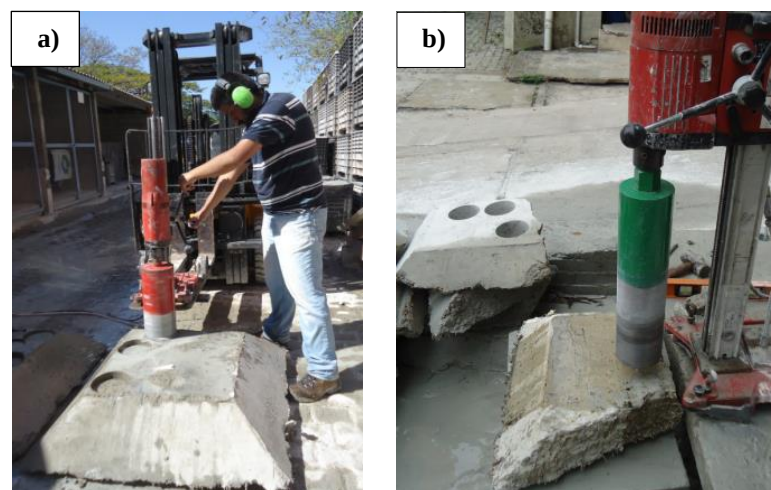


Figure 3.3 - Cylinders extraction from large panels (a); and small panels (b). Source: Cáceres; Cavalaro; Figueiredo (2021).

3.2.4 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 ($\varnothing 150 \text{ mm} \times 150 \text{ mm}$) and 83 small ones ($\varnothing 100 \text{ mm} \times 100 \text{ mm}$) were tested at 5 and 7 months since production, respectively. The large cylinders are divided 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 $0.5 \pm 0.05 \text{ mm/min}$ 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 $\varnothing 25 \text{ mm} \times 20 \text{ mm}$ steel cylinders for the small specimens and $\varnothing 37.5 \text{ mm} \times 30 \text{ mm}$ for the large ones to comply with the specimen-metallic punch diameter ration of 1/4 defined in UNE 83515 (AENOR, 2010). The steel cylinders were concentrically placed on the upper and lower faces of the specimen (see Figure 3.4). The absorbed energy was calculated as the area under the load-displacement curve in Joules.



Figure 3.4 - Barcelona test (BCN). Source: Cáceres; Cavalaro; Figueiredo (2021).

3.2.5 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 cm³) and three of Ø150 mm × 150 mm (2650.72 cm³) in which fibres were inserted manually in a random manner to achieve contents of 30, 60, and 90 kg/m³. The inductance change measured can be used to calculate the inductance coefficients for the fibre used, as described in Cavalaro *et al.* (2016). Figure 3.5 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 3.1 gives the fibre content (C_f) within the cores in kg/m³, depending on slope coefficient β , the total inductance variation (ΔL_T) in mH and volume (V) in m³. 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.

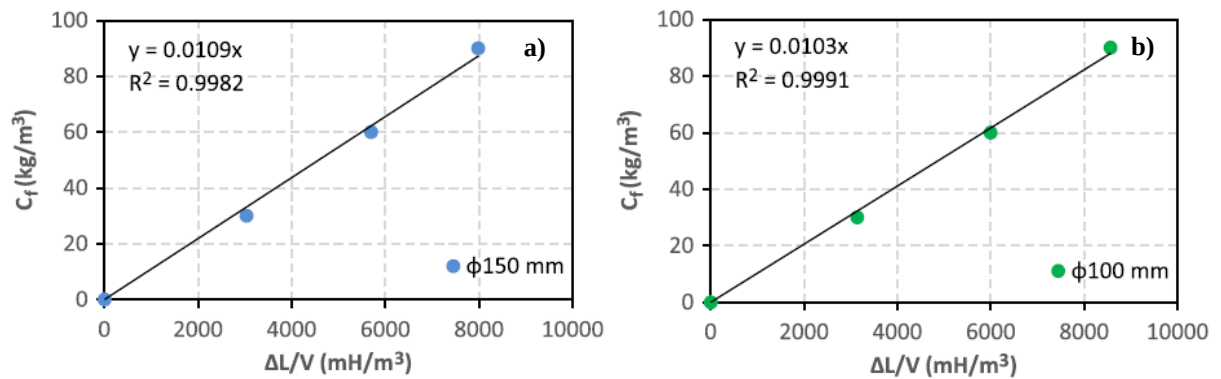


Figure 3.5 - Inductive method calibration in styrofoam cylinders of Ø150 mm × 150 mm (a); and Ø100 mm × 100 mm (b). Source: Cáceres; Cavalaro; Figueiredo (2021).

$$C_f = \beta \times \frac{\Delta L_T}{V} \quad (3.1)$$

The inductive test was performed 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/m³, 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/m³ nominal fibre content.

3.3 Results and analysis

3.3.1 Inductive test

Table 3.2 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 sample (*N*), maximum values (*max*), and minimum values (*min*). The average fibre content found in specimens L_M1 is 46.98 ± 2.19 kg/m³, which is considerably higher than the nominal fibre content of 30 kg/m³. The L_M2 and L_M3 cylinders have similar fibre contents of (79.60 ± 5.96 and 76.85 ± 8.58 kg/m³, respectively) despite the difference in the nominal fibre content (60 and 90 kg/m³, 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/m³, respectively) show results close to the nominal contents (30 and 60 kg/m³, respectively), while small cylinders S_M3 with the highest fibre content (74.92 ± 10.24 kg/m³) display results lower than the nominal value (90 kg/m³). 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.

Table 3.2 - Fibre content (C_f) in kg/m³ of extracted cylinders. Source: Cáceres; Cavalaro; Figueiredo (2021).

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

3.3.2 Square panel test – EN 14488-5

Figure 3.6 shows the mean load (P) and absorbed energy (E) versus displacement (δ) curves. Table 3.3 summarizes the energy absorption for a displacement of 25 mm (E_{25}), the panel thickness (h) and 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), maximum (max) and minimum (min) values are also provided.

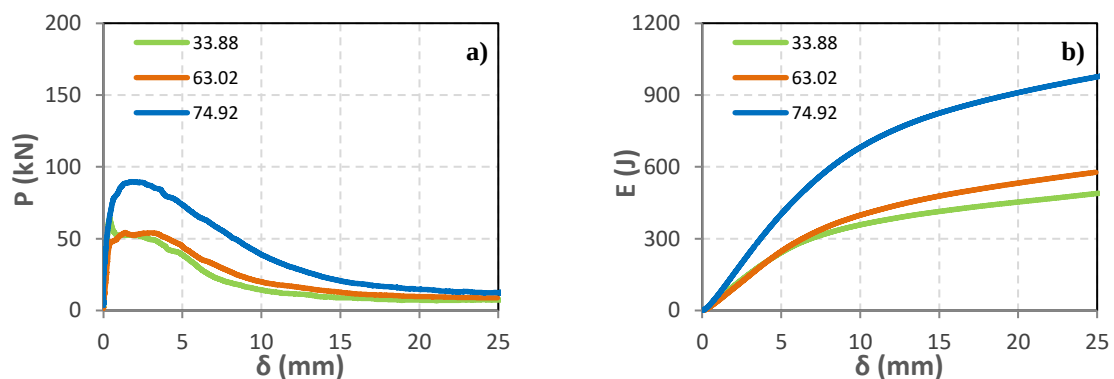


Figure 3.6 - Average curves of load (a); and energy absorption (b) versus displacement, based on EN 14488-5 test on small panels with fibre contents of 33.88, 63.02, and 74.92 kg/m³. Source: Cáceres; Cavalaro; Figueiredo (2021).

Both fibre content and panel thickness influence the energy absorption results in Table 3.3. The panels with higher fibre content (74.92 kg/m³) 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/m³, 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/m³ (see Figure 3.7a). The number of cracks tends to increase for the content of 74.92 kg/m³. For example, the panel with the highest energy absorption value of 1176.07 J presented five major and two minor cracks (see Figure 3.7b). 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; BJØNTEGAARD, 2010; SALEHIAN; BARROS; TAHERI, 2014; JUHASZ; NAGY; SCHAUL, 2017); this, in addition to the friction forces in the supports, causes punching shear failure (CARMONA; MOLINS; GARCÍA, 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.

Table 3.3 - 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. Source: Cáceres; Cavalaro; Figueiredo (2021).

Panels ($C_f = 33.88 \text{ kg/m}^3$)							Panels ($C_f = 63.02 \text{ kg/m}^3$)						
	E_{25}	h	N_c	k	$\Delta = 25.k$	$E_c = K. E_{25}$		E_{25}	h	N_c	k	$\Delta = 25.k$	$E_c = K. E_{25}$
Mean	488.85	117.61	3.75	0.85	21.28	397.85	Mean	578.18	112.05	4.40	0.89	22.31	494.18
SD	50.38	4.02	0.50	0.03	0.72	30.31	SD	47.22	1.51	0.55	0.01	0.30	37.12
CV (%)	10.31	3.42	13.33	3.37	3.37	7.62	CV (%)	8.17	1.35	12.45	1.34	1.34	7.51
N	4	4	4	4	4	4	N	5	5	5	5	5	5
max	538.51	122.99	4.00	0.88	21.93	422.11	max	629.05	114.29	5.00	0.90	22.57	542.63
min	424.94	113.98	3.00	0.81	20.33	354.17	min	505.37	110.77	4.00	0.87	21.87	440.22

Panels ($C_f = 74.92 \text{ kg/m}^3$)						
	E_{25}	h	N_c	k	$\Delta = 25.k$	$E_c = K. E_{25}$
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

The influence of the panel thicknesses on the absorbed energy was also reported by Bjøntegaard (2009), Myren; Bjøntegaard (2010), and Sandbakk (2011). A correction factor, based on the study of Thorenfeldt (2009) *apud* Myren; Bjøntegaard (2010) was applied to compensate for this influence. The procedure is as follows: first, a corrected displacement must be found ($\Delta = 25 \text{ mm} \times k$, $k = 100/h$); 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 3.3 the corrected energy absorption results (E_c) are as follows: 397.85 ± 30.31 , 494.18 ± 37.12 , and 758.88 ± 147.15 J, for panels with fibre contents of 33.88, 63.02, and 74.92 kg/m³, 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. Microcracks 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.

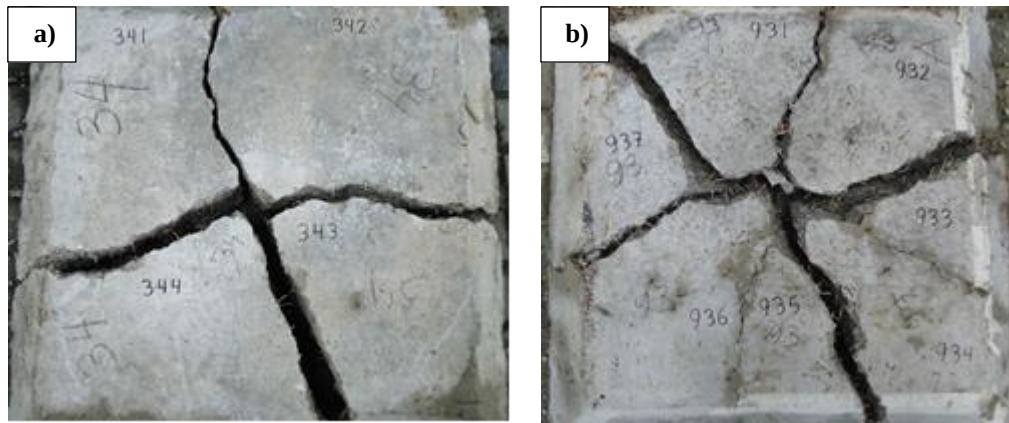


Figure 3.7 - Typical crack pattern including four major cracks for medium and lower fibre contents (a); and multiple cracks observed in panel with highest energy absorption for higher fibre contents (b). Source: Cáceres; Figueiredo; Cavalaro (2021).

3.3.3 Barcelona test

Figure 3.8 shows the mean load (P) and absorbed energy (E) versus displacement (δ) curves of the cylinders extracted from the panels of each mixture. 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 3.4. 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; 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) and sample size (N), maximum (*max*) and minimum (*min*) values are presented in Table 3.4.

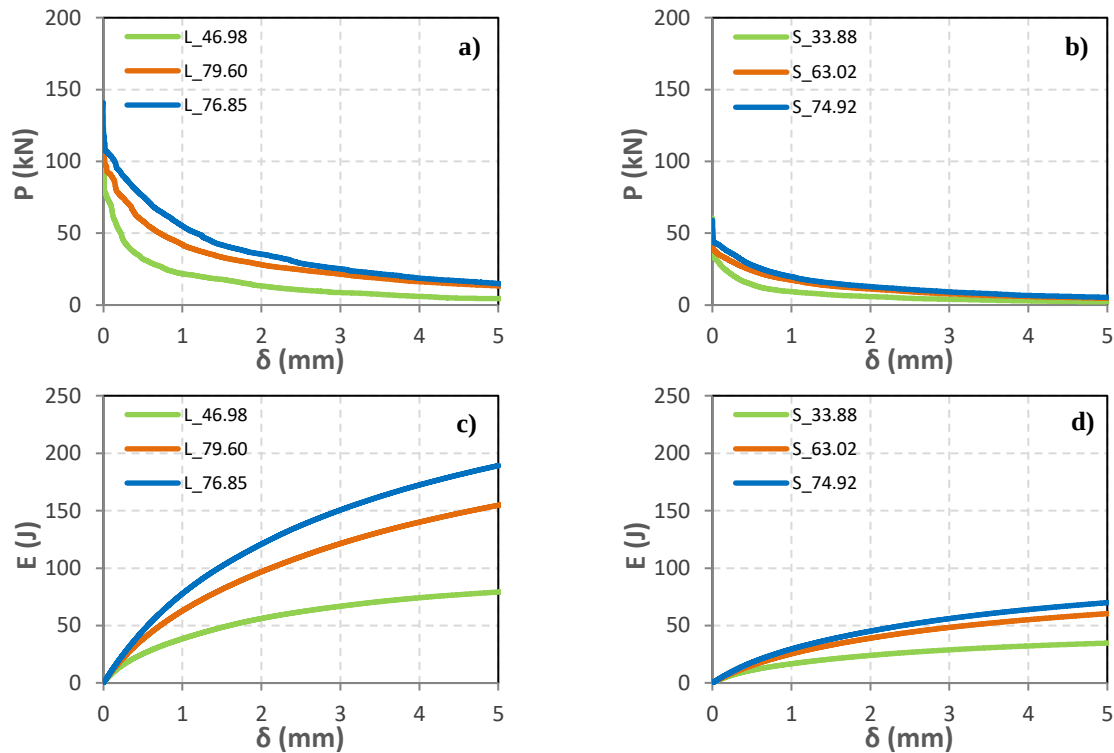


Figure 3.8 - Average curves of load by displacement in cylinders of Ø150 mm × 150 mm (fibre contents of 46.98, 79.60, and 76.85 kg/m³) (a); and Ø100 mm × 100 mm (fibre contents of 33.88, 63.02, and 74.92 kg/m³) (b); and of energy absorption by displacement in cylinders of Ø150 mm × 150 mm (c); and Ø100 mm × 100 mm (d) by BCN test. Source: Cáceres; Cavalaro; Figueiredo (2021).

Table 3.4 - Absorbed energy in 5.0 mm (E_5) in J, for cylinders of Ø150 mm × 150 mm and Ø100 mm × 100 mm, based on BCN test. Source: Cáceres; Cavalaro; Figueiredo (2021).

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 3.4 analysis of the energy absorption results of the large cylinders in the displacement of 5 mm shows the following absorbed energies, in increasing order: 79.07 ± 17.61 , 154.67 ± 26.64 , and 189.24 ± 39.81 J for cylinders with fibre contents of 46.98, 79.60, and 76.85 kg/m³, respectively. It is observed that the cylinders with fibre content of 76.85 kg/m³ show a higher level of energy absorption in relation to the cylinders of 79.60 kg/m³, despite having lower fibre content. This may also be due to a better orientation in relation to the crack surface which may occurs randomly.

Analysis of the average absorption results of the small cylinders shows the following absorbed energies at 5 mm: 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/m³, 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 as discussed in more depth in the next section.

3.3.4 Comparison of coefficients of variation

Figure 3.9 shows the CVs of the energy absorption results obtained from the square panel tests EN 14488-5 (see Table 3.3) and BCN tests (see Table 3.4). 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. A similar trend was found by Aire; Molins; Aguado (2013), who evaluated the FRC in different sizes of cylinders using the BCN test. This behaviour 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 CV, as observed in the study by Cavalaro; Aguado (2015). In addition, in the small cylinders the CVs decrease since the fibre content increases, while in the large remains practically constant in all mixtures. These facts show that the large cylinders maintain a more stable behaviour during the BCN test.

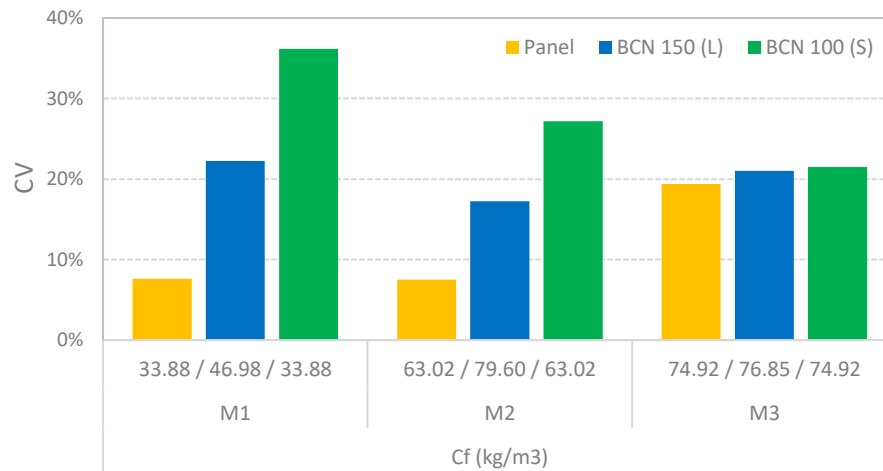


Figure 3.9 - Comparison of the CVs of energy absorption results of EN 14488-5 test and BCN tests. Source: Cáceres; Cavalaro; Figueiredo (2021).

The CVs obtained in the EN 14488-5 panel tests were lower than those 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 with placing metal plates to ensure continuous contact between the panels and the support and during spraying so as to avoid buckling on the panels. Several authors have reported that the CV decreases with enhancements to the fracture surface (CARMONA; MOLINS; AGUADO, 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/m³, besides having a higher fibre content, show the greatest variation in thickness and number of cracks, resulting in a greater variation of energy absorption results.

3.3.5 Mix design correlations and comparative analysis

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 (see Tables 3.3 and 3.4, respectively). The resulting R^2 values for the correlations between the square panel test EN 14488-5 and BCN tests on small and large cylinders are similar, with values of 0.9809 and 0.9798, respectively (see Figure 3.10). 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 fibre content in each evaluated element (individual results that generated Tables 3.2-3.4). These correlations are shown in Figure 3.11a. 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 3.11. In the case of the square panel test, the sample type and number respond to those typically adopted for the quality control of sprayed concrete. Since the BCN is an alternative test without the support of specific standards for sprayed concrete, the number of specimens was increased to evaluate the significance of the test variability.

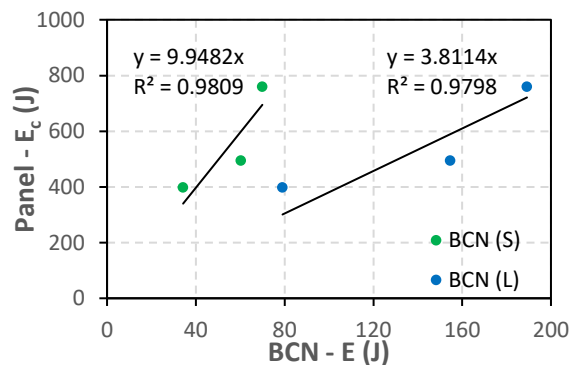


Figure 3.10 - Correlation of average energy absorption results between the square panel test EN 14488-5 and BCN tests. Source: Cáceres; Cavalaro; Figueiredo (2021).

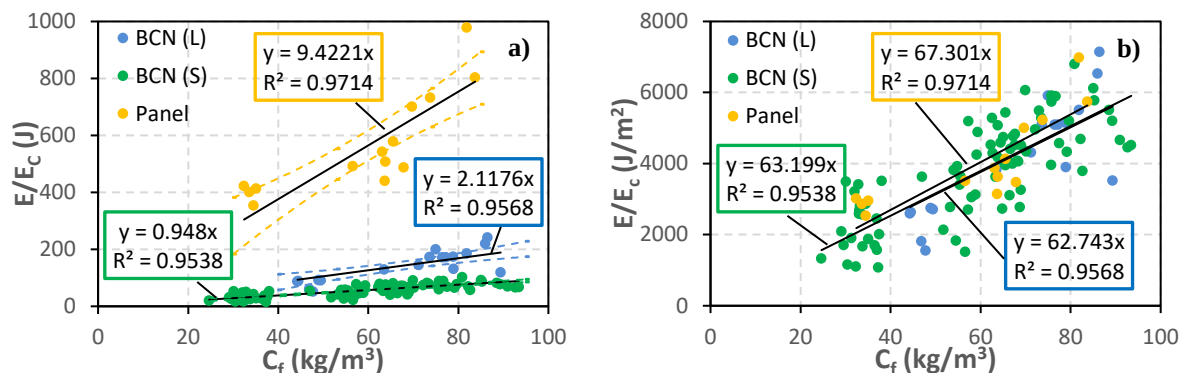


Figure 3.11 - Correlation between energy absorption results from the square panel test EN 14488-5 and BCN tests with fibre content, in J - kg/m^3 (a); and J/m^2 - kg/m^3 (b). Source: Cáceres; Cavalaro; Figueiredo (2021).

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 generally consisted of four cross-shaped major cracks. The correlations between energy absorbed per area and fibre content are shown in Figure 3.11b. It can be seen that the three tests have similar trend lines. Grouping into a single correlation, the trend line equation is $y = 63.584x$, 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 3.11a 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 (CEN, 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; CONCRETE INSTITUTE OF AUSTRALIA, 2010; REHMAN *et al.*, 2019). The energy requirements are: class E 500, E 700, and E 1000 of 500, 700 and 1000 J, respectively. From Figure 3.11a, 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 3.5. Because all regressions in Figure 3.11a 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% confidence level, obtained from individual results that generated Tables 3.2-3.4, according to the method of Freund; Simon (2002). The confidence intervals are presented in brackets in Table 3.5 and are also indicated by dashed lines in Figure 3.11a.

Table 3.5 - Correlation for energy levels required by EN 14487-1 (CEN, 2005) and BCN tests ($E_{Panel, 25}$ and $E_{BCN, 5.0}$, δ (mm)) in J, and average fibre content C_f in kg/m³. Source: Cáceres; Cavalaro; Figueiredo (2021).

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

3.3.6 Sample size analysis

A very common question for tunnel designers and builders concerns the representative sample size needed to evaluate a structure. For this, based on the results, the reliable sample size was determined using the method of Bussab; Moretin (2002), through Equation 3.2, where the statistical values are sample size (n), t-distribution (t) according to the confidence level (α), standard deviation (SD), and 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 3.6 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 3.3 and 3.4, respectively.

$$n = \frac{\tau_{n-1}^2 \cdot s^2}{e^2} \quad (3.2)$$

Table 3.6 - Sample size (n) according to the statistical measurement values. Source: Cáceres; Cavalaro; Figueiredo (2021).

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

Evaluating sample sizes at a 95% confidence level, for the BCN test on large cylinders, the sample is almost constant for all mixtures, ranging from five to nine cylinders. The BCN test on small cylinders requires a larger sample of 15 cylinders for lower fibre content (33.88 kg/m³). For larger fibre contents (63.02 and 74.92 kg/m³) the sample decreases to eight and five cylinders, respectively. In the case of the square

panel test, only two samples are required for mixtures of 33.88 and 63.02 kg/m³. However, for the mixture with higher fibre content (74.92 kg/m³), eight panels are required. The increase in the number of specimens required for the EN 14488-5 test with the highest fibre content was due to the increase in CV of this series, which was generated by the variation of panel thickness and number of cracks. This tendency of increasing number of specimens associated with the highest fibre content was not especially 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 a higher aspect-ratio. Considering that the number of specimens in the sample was shown to be below the desired for a few test conditions, the findings represent a valid contribution to the literature.

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

3.4 Conclusions

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

- The level of energy absorption is directly related to the actual fibre content of the SFRSC, which makes it possible to determine which energy level corresponds to each test for a given fibre content. When the energy absorption is divided by the fracture area observed in the specimens of each test, they maintain the same trend line, showing the correspondency between all tests.
- The CV of energy absorption associated with the small cylinders is higher than those of the large ones. In the small cylinders, the CVs decrease since the fibre content is enhanced, while in the large cylinders it remains almost constant. This shows that the large cylinders provide more uniform results in the BCN tests 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 because of variations in the number of the cracks together with the panel thickness in this particular case. Thus, specimens for this type of test should be produced with care to minimize the variation of their final thickness.
- The largest CV of the BCN test is clearly disadvantageous for obtaining representative results. Nonetheless, the BCN test can be used for routine control and especially for existing SFRSC structure 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, which creates 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 representative in terms of evaluating the values of absorbed energy in underground works of SFRSC, as long as the correspondence of absorbed energy is established from previous studies.
- Cylindrical cores can be extracted in situ, making it possible evaluate actual tunnel lining conditions. The fact that the specimens can be used for two determinations (fibre content effectively incorporated into the structure and the mechanical behaviour 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, as a consequence, they must be determined for each project in the previous qualification studies of the SFRSC.

4 ALTERNATIVE SMALL-SCALE TESTS TO CHARACTERIZE THE STRUCTURAL BEHAVIOUR OF STEEL FIBRE-REINFORCED SPRAYED CONCRETE

4.1 Introduction

One of the most common methods to characterize fibre-reinforced sprayed concrete (FRSC) is the four-point flexural beam test EN 14488-3 (BERNARD; THOMAS, 2020). Initially, this test was proposed by EFNARC (1996) and now is detailed in the standard EN 14488-3: 2006 (CEN, 2006). Recent guidelines such as those of ITA Working Group No. 12 and ITAtech (ITA, 2020) propose the three-point flexural test on a beam with a notch EN 14651 to obtain design parameters for FRSC structures according to the provisions in the *FIB* Model Code. This reflects the current aspiration of adopting the design philosophy of fibre-reinforced concrete (FRC) structures in sprayed concrete structures (LARIVE *et al.* 2020; THOMAS, 2020). However, due to the production process of FRSC elements, tests performed in beams need to be extracted from sprayed test panels. This implies a laborious cutting process and difficulties in handling heavy panels. Spraying process factors such as the effect of the spray direction (FIGUEIREDO, 1997; JOLIN, 1999; KAUFFMANN *et al.* 2013) and rebound (FIGUEIREDO, 1997; AUSTIN; PEASTON; ROBINS, 1997; ARMELIN, 1997; JOLIN, 1999; KAUFFMANN *et al.* 2013; GINOUSE; JOLIN, 2016) produce a significant variation in fibre content and orientation in the tunnel lining if compared with equivalent sprayed specimens.

Studies show high variability of results of the flexural characterization of FRSC beams in a range of 20 to 30% (MORGAN; MINDESS; CHEN, 1995; BERNARD, 2002; JUHASZ; NAGY; SHAUL, 2017; GALO BARDES *et al.*, 2019; HANKE; COLLIS; BERNARD, 2001 *apud* BERNARD; THOMAS, 2020). This phenomenon has been attributed to the small fracture surface of the specimen, which is prone to significant variation in the content and orientation of fibres crossing the cracked surface (TRAN; BERNARD; BEASLEY, 2005; BERNARD, 2013; CARMONA; MOLINS, 2019; GALO BARDES *et al.*, 2019). The uncertainty of results can also be exacerbated by the post-peak instability caused by the abrupt transfer of load from the matrix to the

fibres during cracking (NGUYEN, 2003; BERNARD, 2013). To lessen the effect of post-peak instability, flexural beam tests require high-quality testing machines with a closed-loop system (EN 14488-3: 2006 (CEN, 2006); BERNARD, 2009) that are not available in most technological control laboratories in Latin America (SILVA, 2017), for example.

Other tests were developed to evaluate FRC, such as the double punching test (DPT), also known as Barcelona and double-edge wedge splitting (DEWS) test. These tests procedures have the advantage of using smaller specimens, which can simplify the systematic quality control evaluation of existing FRSC structures through extracted samples or can be used for confirmation of design parameters. The common criteria considered when selecting the most appropriate test to evaluate structures are the reliability of the results, the cost of the tests and whether the sample is representative of the in-situ concrete (NGUYEN, 2003). Smaller-scale tests allow the evaluation of a larger number of samples, enabling a broader and more robust analysis of data (GALOBARDES; FIGUEIREDO, 2015), especially when it is desired to evaluate the behaviour of the material in FRSC structures that have great variability.

The DPT is supported by a large body of research and has been increasingly used for the quality control of FRC in real projects (CARMONA; AGUADO; MOLINS, 2013; BLANCO *et al.*, 2014; MONTE *et al.*, 2016; GALEOTE *et al.*, 2017; CARMONA; MOLINS; AGUADO, 2018; RAMBO *et al.*, 2018; CARMONA; MOLINS, 2019; SIMÃO *et al.*, 2019; SEGURA-CASTILLO *et al.*, 2019; NOGUEIRA *et al.*, 2020). Three cracks form during the test due to the internal stresses induced by cylinder punches located on the top and bottom of the specimens. The cracks usually evolve following a mix of types I and II fracture mode, which differs from the cracks in the bending test of beams that tend to display a type I fracture (GALEOTE *et al.*, 2017).

The DEWS test developed by di Prisco; Ferrara; Lamperti (2013) is also an indirect tensile test. Wedges placed in notches on two opposite faces of the specimen produce internal tensile forces that lead to crack formation and opening. The setup aims to create an approximately uniaxial tensile stress over the cross-section of the specimen, leading to a type I fracture mode. di Prisco; Ferrara; Lamperti (2013) recommend the use of six LVDTs (linear variable displacement transducers) and a very slow loading speed (displacement rate of 0.012 mm/min). Borges *et al.* (2019) proposed a simplified variation of the test with 10 times higher loading speed and only 2 extensometers, one at the centre of each face of the specimen to measure the crack-

opening, providing greater dynamism to the method, reducing the time and execution work.

Few studies have evaluated FRSC using the DPT. Silva (2017) evaluated the scatter of load results from the DPT, statistically proving that there is no significant difference in results of specimens extracted from different panels. Segura-Castillo *et al.* (2018) studied the anisotropy in the tensile response of FRSC through the DPT and inductive test. Galobardes *et al.* (2019) correlated the DPT using cylinders with a height and diameter of 100 mm with the flexural beam test EN 14488-3, obtaining good correlation ($R^2 = 0.97$) between the residual strength of both tests. Using the same cylinder size, Monteiro; Silva (2020) evaluated the influence of the machine stiffness on the DPT and correlated the results with those of the EN 14651 test, finding good correlations in terms of residual strength (mean R^2 0.96). The influence of the size of the cylindrical core of the DPT on the correlation of results with the EN 14488-3 test was not evaluated. To the authors' best knowledge, no study has applied the DEWS test to characterize FRSC recently. Consequently, no study has compared the post-cracking behaviour obtained with DPT, DEWS and the flexural bending tests in FRSC specimens or the constitutive models calculated from these test results in FRSC.

The objective of this study is to demonstrate the possibility to correlate the residual strength results of the flexural beam test EN 14488-3 with those of the DPT (in cylinders with 2 sizes) and DEWS test, in the evaluation of steel fibre-reinforced sprayed concrete (SFRSC). The possibility of obtaining and comparing constitutive models from these tests is verified in line with current trends to obtain design parameters for FRSC structures.

4.2 Methodology

4.2.1 Materials and spraying process

The concrete mixture was formulated with 400 kg/m³ of cement (70% CEM I 52.5 R and 30% blast furnace slag), 574 kg/m³ of fine quartz sand (0 - 0.6 mm), 315 kg/m³ of crushed granitic sand (0 - 4.8 mm), 840 kg/m³ of crushed granite coarse

aggregate (4.8 - 12.5 mm) and 200 l/m³ of water. The following admixtures were also added to the composition to ensure adequate fresh state properties: 1.44 kg/m³ of polyfunctional admixture, 0.84 kg/m³ of superplasticiser and 1.12 kg/m³ of hydration stabiliser. The materials were batched in a ready-mix plant and supplied in a concrete mixer truck.

A flat crimped steel fibre was used in the experimental program. This is a low-cost fibre, produced from the recycled steel wires and is commonly used in tunnel lining applications in Brazil. The dimensional characterization of length (L), equivalent diameter (d_e) and aspect-ratio (λ) of the fibre is presented in Table 4.1. The mean values, coefficient of variation (CV), standard deviation (SD) and sample size (N), are also provided.

Table 4.1 – Fibre dimensional characterization. Source: Cáceres *et al.* (2021a).

	L (mm)	d_e (mm)	$\lambda = L/d_e$
Mean	38.93*	1.56	25.03
SD	1.16	0.06	1.12
CV (%)	2.99	4.17	4.48
N	60	60	60

* This value is within the dimensional tolerances of Brazilian standard ABNT NBR 15530 (ABNT, 2019) as the deviation from nominal length ($L_n = 39$ mm) is less than $\pm 5\%$ and ± 1.5 mm. The other nominal values were not provided by the manufacturer.

The fibres were added directly to the mixer truck in three stages aiming to achieve three levels of fibre contents and mixed for at least 5 minutes in each stage. From the concrete mixer truck, the FRC was transferred to a wet-mix CP 10-SU pump and sprayed on wooden moulds positioned at 20° with the vertical axis. An accelerator admixture based on aluminium sulphate solution (approximately 24 kg/m³) was used to ensure appropriate setting times, seeking to replicate the wet-mix sprayed process normally found in tunnel linings.

The sprayed panels were 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. Five small panels and one large panel were sprayed with a lower nominal fibre content (30 kg/m³), and 6 small panels and one large panel with the intermediate and higher nominal fibre contents of, 60 and 80 kg/m³, respectively.

After the production of the first series of panels with the lower nominal fibre content, the volume of concrete remaining was estimated, and an extra amount of fibre was added to the mixer truck to reach the intermediate nominal fibre content. Once the

panels were sprayed, the remaining volume was estimated again, and fibres were added to the mixer truck to achieve the highest nominal fibre content. Material remaining from previous spraying on both the pump and the hose complicated the control of the fibre addition process in the sprayed specimens. However, ensuring previously the exact fibre content is not essential for conducting the study as long as the same conditions are applied to the batch of specimens subjected to the different tests. The actual average fibre content incorporated was determined through samples extracted from the panels and using the inductive test (TORRENTS *et al.* 2012; CAVALARO *et al.* 2015; CAVALARO *et al.* 2016) and crushing of specimens (KALIL; ESCARIZ; FIGUEIREDO, 2010), as described in section 4.2.3. After the spraying, the test panels were covered with plastic sheets, were periodically sprayed with water and demolded three days later.

4.2.2 Extraction of samples and preparation of specimens

18 cylinders with nominal dimensions $\varnothing 150 \text{ mm} \times 150 \text{ mm}$ and 84 of $\varnothing 100 \text{ mm} \times 100 \text{ mm}$ for the DPT were extracted from the large and small panels, respectively (see Figure 4.1a). To obtain the desired specimen height, the ends of the cylindrical cores were cut, removing the rough part. Twelve beams with nominal dimensions of 600 mm length, 125 mm wide and 75 mm high for the EN 14488-3 test were cut from the small panels, from which no cylinders had been extracted (see Figure 4.1b). After testing the beams, their ends were cut at the extremes far enough from the cracked plane, into smaller prisms, 125 mm length, 75 mm wide and 125 mm high used in the DEWS test (see Figure 4.1c). To induce cracking in these small prisms, a notch and wedges were made in the middle of the top and bottom faces of the specimens (see Figure 4.1d). Then, steel plates were glued over the wedges to ensure smoother metallic contact with the load application rollers.

All specimens were prepared and tested at an age greater than 5 months to ensure enough time for extraction and preparation of all specimens. This also contributes to a minimum impact of the evolution of strength over time in the test results. The notations used to present the results are LB, SB, F and D, corresponding to the large cylinders $\varnothing 150 \text{ mm} \times 150 \text{ mm}$ of the DPT, small cylinders $\varnothing 100 \text{ mm} \times 100$

mm of the DPT, beams of the EN 14488-3 test and prisms of the DEWS test, respectively. The numbers following the notation refer to the nominal fibre content. For example, F_60 are the beams of the EN 14488-3 test with a nominal fibre content of 60 kg/m³.

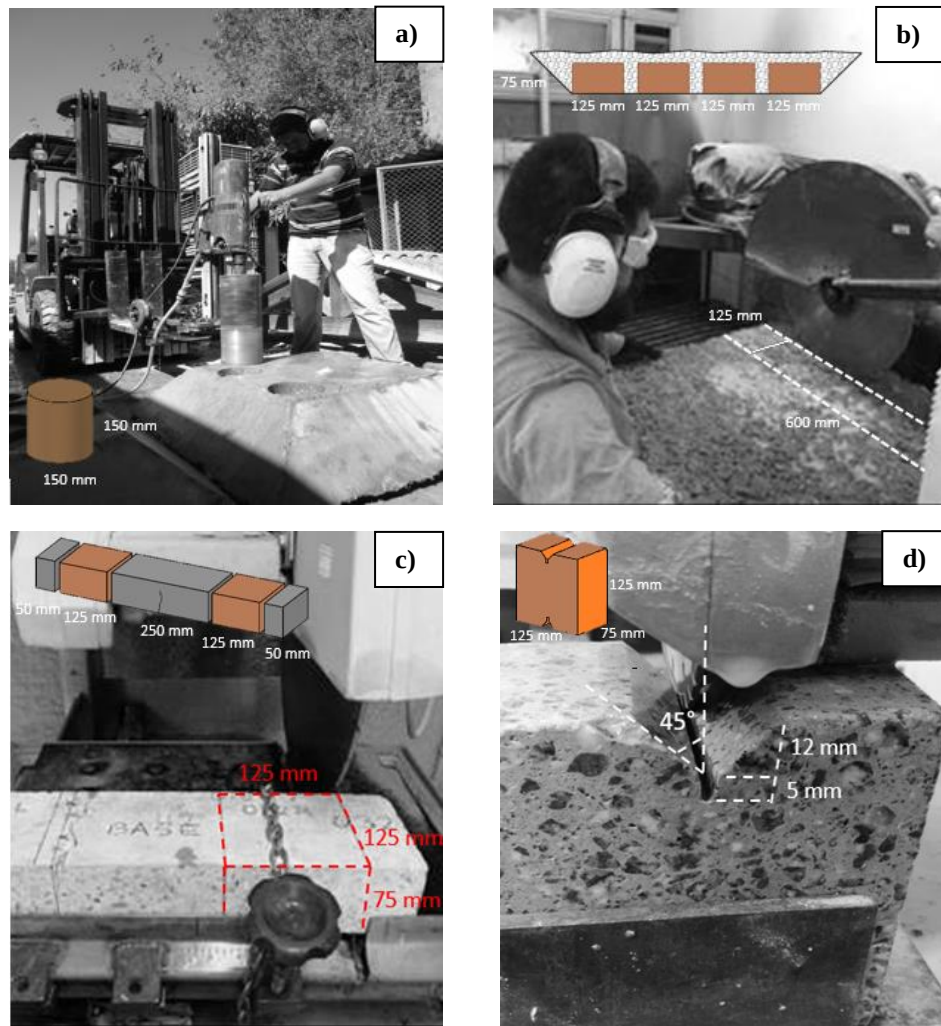


Figure 4.1 - Extraction of Ø150 mm × 150 mm cylinders from the large panels (a); cutting beams from the small panels (b); cutting smaller prisms for the DEWS test (c); and making the wedge and notch in the DEWS prism (d). Source: Cáceres *et al.* (2021a).

4.2.3 Determination of fibre content

The fibre content in the cylinders of the DPT was determined by the inductive test (TORRENTS *et al.* 2012; CAVALARO *et al.* 2015; CAVALARO *et al.* 2016). This methodology was previously used to quantify the fibre content in cores extracted from

FRSC in the studies by Segura-Castillo *et al.* (2018) and Galobardes *et al.* (2019). Initially, a calibration process was performed on styrofoam cylinders, three of Ø100 mm × 100 mm (785.40 cm³) and three of Ø150 mm × 150 mm (2650.72 cm³), in which the fibre contents of 30, 60 and 90 kg/m³ were inserted manually and randomly distributed in the volume of the cylinder. The inductance variation can be used to calculate the inductance coefficients of the fibre used, as described in Cavalaro *et al.* (2016). Figure 4.2 shows the correlations between the fibre content placed in the styrofoam cylinders and the sum of the inductance variation ΔL_T , measured in three orthogonal axes L_i .

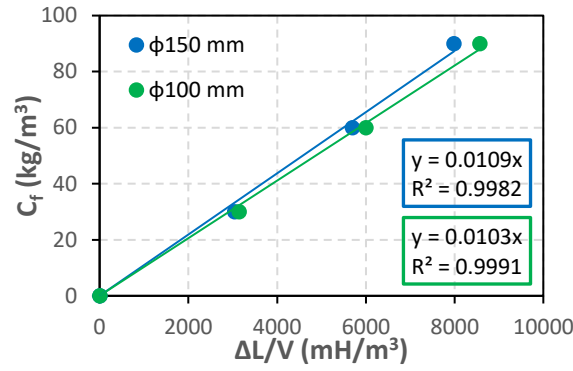


Figure 4.2 - Inductive method calibration in styrofoam cylinders of Ø150 mm × 150 mm and Ø100 mm × 100 mm. Source: Cáceres *et al.* (2021a).

Equation 4.1 provides the fibre content in the cylinders (C_f) in kg/m³, which depends on the coefficient β' (0.0109 and 0.0103 for the large and small cylinders, respectively), the total inductance variation (ΔL_T) in mH and volume of the cylinder (V) in m³. The inductive test was performed on the cylinders prior to the DPT tests.

$$C_f = \beta' \times \frac{\Delta L_T}{V} \quad (4.1)$$

The average orientation number n_i on each orthogonal axis was calculated using Equation 4.2, where: $B_{V,i}$ is a constant that depends on the magnetic field over the volume of the cylinder, $B_{V,x} = B_{V,y}$ is equal to 536 and 1789 for small and large cylinders, respectively; $B_{V,z}$ is equal to 538 and 1809 for small and large cylinders, respectively; γ is an inductance parameter that depends on the fibre aspect-ratio, which was assumed as 0.05 following the recommendation from Cavalaro *et al.* (2016); L_i is the inductance measurement on a specific axis; L_e is the sum of the ratio between each L_i measured in each of the orthogonal axis and the corresponding constant $B_{V,i}$.

The fibre contribution C_i in each axis was determined according to Cavalaro *et al.* (2016) and was calculated using Equation 4.3. This parameter measures the average cosine of the angle formed by the fibres with the axis analysed. Fibres present the highest contribution to the inductance variation when parallel to the magnetic field (CAVALARO *et al.*, 2016).

$$n_i = 1.03 \cdot \sqrt{\frac{L_{i \cdot (1+2\gamma)} - L_e \cdot B_{V,i} \cdot \gamma}{L_e \cdot B_{V,i} \cdot (1-\gamma)}} - 0.85 \quad (4.2)$$

$$C_i = \frac{n_i}{\sum_{i=x,y,z} n_i} \quad (4.3)$$

The fibre content in the prisms used in the DEWS test was determined by crushing the specimens and collecting fibres with a magnet after being tested, according to the procedure proposed by Kalil; Escaris; Figueiredo (2010). The actual fibre content of the beams was determined considering the average value obtained with the crushing of the two prisms cut from the end of the beams. The crushing method was adopted since the prisms have a different geometry than a cylinder or cube, which are considered in the inductive method by Cavalaro *et al.* (2016). Both methods have a good approximation of results in the determination of fibre content ($R^2 = 0.98$) (CAVALARO *et al.*, 2015).

4.2.4 Flexural beam test EN 14488-3

Ten beams were tested according to EN 14488-3 (three beams for each fibre content, plus one extra for the nominal content of 60 kg/m³). Two beams were lost due to rupture outside the central third, one in the nominal content of 30 and 80 kg/m³, respectively. The test was performed in a universal INTERMETRIC IM750SRV testing machine using a closed-loop system. All beams were positioned in the testing machine with the faces that were in contact with the mould in contact with the lower rollers. The load was applied using two upper rollers, positioned over the central third of the beam (see Figure 4.3). The displacement rate was 0.25 ± 0.05 mm/min until 0.5 mm when the rate was increased to 1.0 mm/min until the end of the test. The vertical

displacement measurements were made using two LVDTs located in the central part at the top on each side of the beam and fixed to a yoke.

The flexural strengths were obtained according to Equation 4.4, where: f_{Rim} is the residual strength; P_δ is the load related to several displacements; L is the test span (450 mm); b is the beam width; d is the height of the beam. The vertical displacement was transformed into a crack-opening displacement (COD) at the base of the beam, using Equation 4.5, which was proposed by Carmona; Molins (2019). Where: δ is the vertical displacement; h is the height of the beam; L is 450 mm; and e is the crack eccentricity of the tested beam concerning the middle of the span.

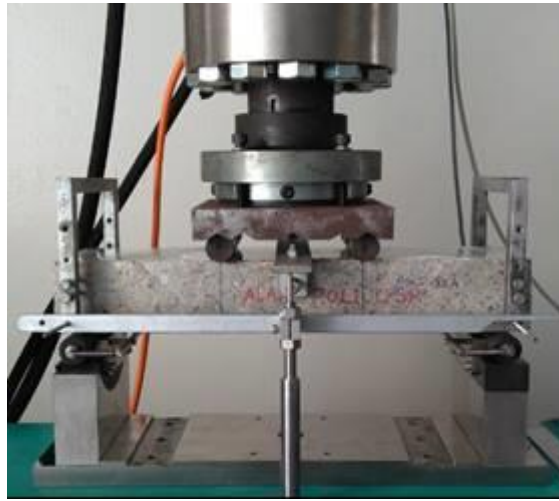


Figure 4.3 - Flexural beam test according to EN 14488-3. Source: Cáceres *et al.* (2021a).

$$f_{Rim} = \frac{P_\delta \cdot L}{b \cdot d^2} \quad (4.4)$$

$$COD = \frac{4 \cdot \delta \cdot h}{(L - 2 \cdot e)} \quad (4.5)$$

4.2.5 DPT

The DPT was performed on 18 large cylinders ($\varnothing 150$ mm $\times$ 150 mm) and 83 small ones ($\varnothing 100$ mm $\times$ 100 mm). Six large cylinders from each nominal content (six per panel). 23 small cylinders from the nominal content of 30 kg/m³ (six per panel, minus 1 that was discarded), 30 from the nominal contents of 60 and 80 kg/m³, respectively (six per panel). The test was carried out on a 200 tf universal Shimadzu

machine in an open-loop system, according to the recommendations of Pujadas *et al.* (2013).

The punching load was applied using steel discs, with a diameter of 25 mm and a height of 20 mm for the small cylinders, and a diameter of 37.5 mm and a height of 30 mm for the large cylinders (maintaining the proportion specimen-steel disc diameter 1:4), arranged on their upper and lower plane faces (see Figure 4.4). The load was applied uniformly with a constant displacement rate of 0.5 ± 0.05 mm/min. The cylinders were always kept in the same position, the faces that were in contact with the mould were placed on the base of the machine. The residual strength of the FRSC is calculated according to Equation 4.6, proposed by Saludes (2006), where: f_{R,δ_p} is the residual strength for a vertical displacement δ_p ; P_{δ_p} is the residual load for a vertical displacement δ_p ; a is the diameter of the steel disc; H is the height of the cylinder.



Figure 4.4 - DPT on a small cylinder with a height and diameter of 100 mm. Source: Cáceres *et al.* (2021a).

In the original test setup, the increment of the perimeter TCOD (total circumferential opening displacement) was measured by a circumferential extensometer positioned at half the height of the cylinder. To simplify the procedure and facilitate implementation in quality control, Pujadas *et al.* (2013) proposed a model that converts the vertical displacement of the testing machine into the TCOD without the need for the circumferential extensometer.

Residual strength was calculated in different circumferential deformations TCOD. To transform the vertical displacement of the machine (δ_p) into TCOD, Equations 4.7 and 4.8 proposed by Pujadas *et al.* (2013) were used. Where: n is the number of radial cracks formed in the test; a is the diameter of the steel disc; l is the

length of the wedge formed under the steel discs, 26.8 mm and 40.2 mm for the small and large cylinders, respectively; P is the load at the calculated point; P_{cr} and $\delta_{p,cr}$ are the load and vertical displacement at the maximum load point, respectively; $P_{R,0}$ and $\delta_{p,R,0}$ are the load and the vertical displacement at the starting point of the residual strength, respectively.

$$f_{R,\delta p} = \frac{4.P\delta p}{9.\pi.a.H} \quad (4.6)$$

$$TCOD = n.\frac{a.\delta_{p,R,0}}{2.l}.\sin\frac{\pi}{n}.\left(1 - \frac{P}{P_{cr}}\right), \quad \delta_{p,cr} < \delta_p < \delta_{p,R,0} \quad (4.7)$$

$$TCOD = n.\frac{a}{2.l}.\sin\frac{\pi}{n}.\left[\delta_p - \delta_{p,cr} + \delta_{p,R,0}.\left(1 - \frac{P}{P_{cr}}\right)\right], \quad \delta_p > \delta_{p,R,0} \quad (4.8)$$

4.2.6 DEWS test

The DEWS test was performed on six specimens per each nominal content. The nominal content of 60 kg/m³ was analyzed with five specimens as one was discarded. The test was performed on an EMIC DL 10000 universal machine with a capacity of 100 kN in an open-loop system, according to the recommendations of Borges *et al.* (2019). The loading speed was 0.12 mm/min until the matrix cracked, and 0.30 mm/min from the point of the first crack until the end of the test. The crack-opening displacement was measured by an LVDT positioned on each face of the specimen. The crack-opening w was the average of the measurements of the two LVDTs (see Figure 4.5).

The parameters provided by the machine were load versus crack-opening. The tensile strength was obtained according to di Prisco; Ferrara; Lamperti (2013). The effective load acting on the specimen P_{ef} was calculated using Equation 4.9, where: P is the load applied by the test machine; μ is the friction coefficient between the cylindrical rollers and the steel plates, the value adopted was 0.15; θ is the angle formed between the wedge surface and the notch centre line, that is 45°. The tensile strength σ was calculated using Equation 4.10, where: P_{ef} is the effective load; b is the

width of the cross-section of the specimen; h_{lig} is the distance between the ends of the two notches.



Figure 4.5 - DEWS test performed on a prismatic specimen extracted from the beams. Source: Cáceres *et al.* (2021a).

$$P_{ef} = P \cdot \frac{(\cos \theta - \mu \cdot \sin \theta)}{(\sin \theta + \mu \cdot \cos \theta)} \quad (4.9)$$

$$\sigma = \frac{P_{ef}}{b \cdot h_{lig}} \quad (4.10)$$

4.3 Results and analysis

4.3.1 Effective fibre content

Table 4.2 shows the results of average fibre content (C_f) obtained by the inductive test and crushing the specimens. Table 4.3 shows the average fibre incorporation in each axis (C_i) by the inductive test. The standard deviation (SD), coefficient of variation (CV), and sample size (N) are also provided in both tables.

Table 4.2 shows that there was a natural variation in the fibre content incorporated in the elements compared to the nominal content due to the spraying process and phenomenon of rebound. Despite that, for each nominal content, the fibre incorporated in the specimens remains nearly in the same range. However, the DPT

on large cylinders LB_30 and LB_60 show higher contents, due to the increase caused by the uncertainty around the remaining material in the machine pump and hose.

It is noted that the DPT in small cylinders has a higher CV compared to other specimens. This greater variation is associated with the small volume of the specimen and by the fact that the fibre used has a low aspect-ratio ($\lambda = 25$), which implies a smaller number of fibres present in the sample. The CV might also have increased because these cylinders were extracted from different panels.

Table 4.3 shows that the smallest fibre contribution is found in the plane parallel to the spraying direction (C_z), mean value 0.24. The fibre contribution in the x and y axes (C_x and C_y) are similar, both with mean value 0.38. The sum of C_x and C_y assesses the XY in-plane fibre contribution parallel to the surface equal to 0.76, that is consistent with those by Segura-Castillo *et al.* (2018) and Galobardes *et al.* (2019) who found 0.85 and 0.80, respectively. The high degree of anisotropy is caused by the effect of the spraying process, which tends to align fibres parallel to the spraying surface (BANTHIA; TROTTIER; BEAUPRÉ, 1994; ROBINS; AUSTIN; JONES, 2003; THOMAS, 2020).

Table 4.2 - Fibre content (C_f) in kg/m³ by the inductive test and crushing. Source. Cáceres *et al.* (2021a).

	C_f in kg/m ³ by the inductive test						C_f in kg/m ³ by crushing					
	DPT Ø100 × 100 mm			DPT Ø150 × 150 mm			EN 14488-3 beams			DEWS prisms		
	SB_30	SB_60	SB_80	LB_30	LB_60	LB_80	F_30	F_60	F_80	D_30	D_60	D_80
Mean	34	63	75	47	80	77	29	55	77	28	54	78
SD	4	7	10	2	6	9	3	3	5	3	4	4
CV (%)	13	12	14	5	7	11	12	6	7	10	8	5
N	23	30	30	6	6	6	3	4	3	6	5	6

Table 4.3 - Fibre incorporation on each axis (C_x , C_y , C_z) by the inductive method. Source: Cáceres *et al.* (2021a).

DPT Ø150 mm × 150 mm									
	LB_30			LB_60			LB_80		
	C_x	C_y	C_z	C_x	C_y	C_z	C_x	C_y	C_z
Mean	0.35	0.38	0.27	0.38	0.36	0.26	0.39	0.41	0.20
SD	0.02	0.02	0.03	0.03	0.02	0.02	0.02	0.04	0.02
CV (%)	6.65	4.26	10.86	7.46	4.31	8.18	5.88	9.30	7.79
N	6	6	6	6	6	6	6	6	6
DPT Ø100 mm × 100 mm									
	SB_30			SB_60			SB_80		
	C_x	C_y	C_z	C_x	C_y	C_z	C_x	C_y	C_z
Mean	0.39	0.37	0.24	0.38	0.37	0.25	0.40	0.40	0.20
SD	0.04	0.04	0.02	0.03	0.03	0.03	0.03	0.03	0.03
CV (%)	9.12	9.62	9.58	7.39	8.66	13.58	8.73	6.86	15.39
N	23	23	23	30	30	30	30	30	30

4.3.2 Strength results

The load-displacement curves of the EN 14488-3 test, DPT in large and small cylinder, and the load-crack opening curves of the DEWS test are shown in Figure 4.6. All curves were considered from the peak load using the same criteria adopted by Nogueira *et al.* (2020). These curves were converted into stress-crack opening curves utilizing Equations 4.4 to 4.10. The average stress-crack opening curves are shown in Figure 4.7. The mean values, the standard deviation (SD), the coefficient of variation (CV) and the sample size (N) of the maximum and residual strength results are provided in Table 4.4.

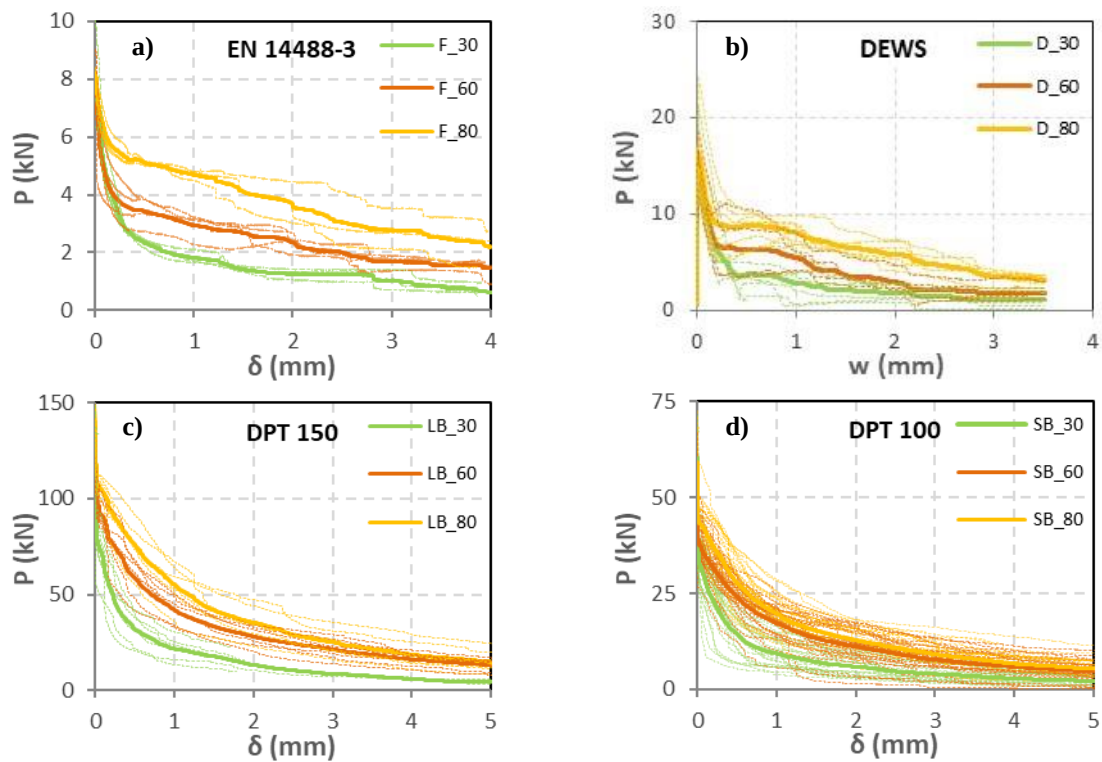


Figure 4.6 – Load-displacement curves by the flexural beam test EN 14488-3 (a); load-crack opening curves by the DEWS test (b); and load-displacement curves by the DPT in a large – DPT 150 (c) and small – DPT 100 (d) cylinder. The average curves are shown in continuous lines. Source: Cáceres *et al.* (2021a).

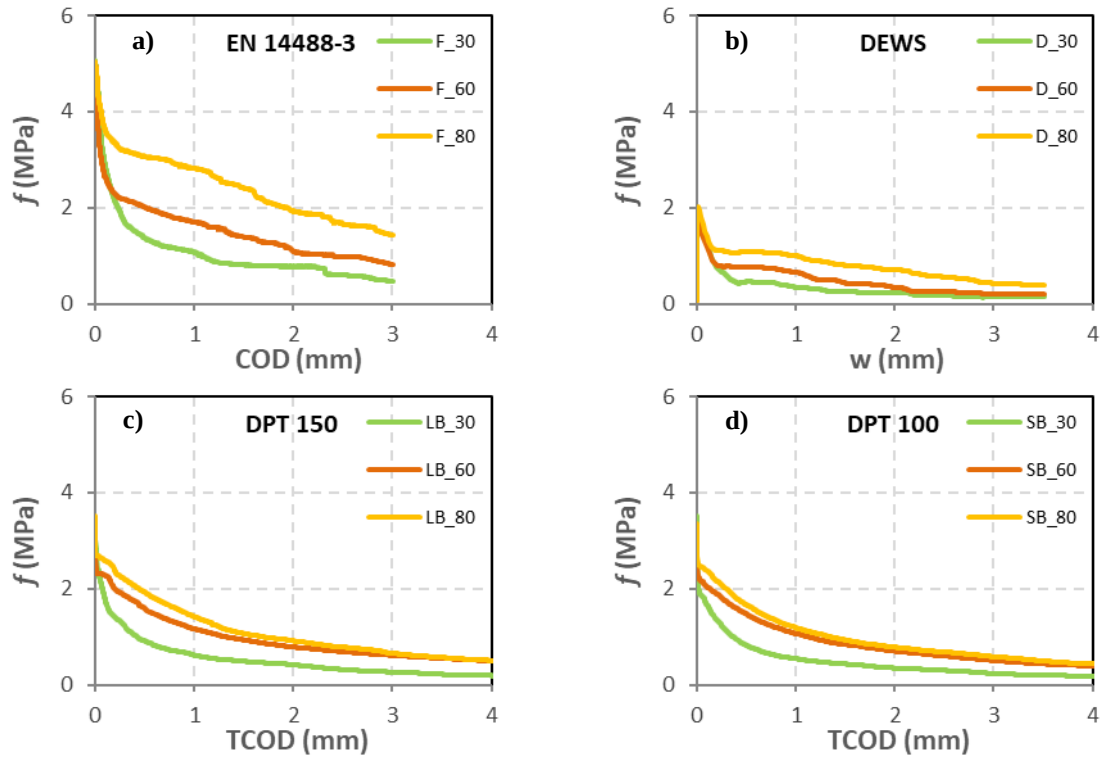


Figure 4.7 - Average strength-COD curves by the flexural beam test EN 14488-3 (a); average strength- w curves by the DEWS test (b); average strength-TCOD curves by the DPT in the large – DPT 150 (c) and small – DPT 100 (d) cylinder. Source: Cáceres *et al.* (2021a).

From Figures 4.6-4.7, all curves present strain-softening behaviour. In general, it appears that the residual strength increases with the fibre content, thus obeying a fundamental technological aspect of the FRC: the higher the fibre content, the greater the number of fibres acting as a stress transfer bridge at the crack (BENTUR; MINDESS, 2007). From Table 4.4, considering the peak-load strengths, the highest CV is presented in DEWS test (mean CV = 21%). The flexural beam test EN 14488-3 and DPT in small cylinder show nearly same variation (mean CV = 11%). The DPT in large cylinder has the lowest variation (mean CV = 6%). This can be attributed to the larger fracture surface and to the greater robustness of the cylinder in relation to the other specimens, having a greater capacity to absorb the rupture energy.

Greater cracking load tends to be achieved in larger specimens due to their bigger fracture surface. This should lead to bigger pre-cracking energy absorption in large cylinder as opposed to the observed in other specimens. As the cracking area increases, the number of fibres also increases, leading to bigger resistant load and energy absorption capacity. As observed by Cavalaro; Aguado (2015), the variability in the total number of fibres mobilised reduces with the increase of the cracked section.

Therefore, larger cracking area should lead to smaller coefficient of variation in terms of resistant load and energy absorption.

Table 4.4 - Maximum strength (f_{max}) and residual strengths results at crack-openings of 0.5, 1.5 and 2.5 mm ($f_{0.5}$, $f_{1.5}$, $f_{2.5}$) in MPa, for flexural beam test EN 14488-3, DEWS test, DPT in a large ($\varnothing$ 150 mm $\times$ 150 mm) and small ($\varnothing$ 100 mm $\times$ 100 mm) cylinder. Source: Cáceres *et al.* (2021a).

Flexural beam test EN 14488-3 - f (MPa)												
	F_30				F_60				F_80			
	f_{max}	$f_{0.5}$	$f_{1.5}$	$f_{2.5}$	f_{max}	$f_{0.5}$	$f_{1.5}$	$f_{2.5}$	f_{max}	$f_{0.5}$	$f_{1.5}$	$f_{2.5}$
Mean	5.1	1.4	0.8	0.6	5.0	2.0	1.4	1.0	5.0	3.1	2.4	1.7
SD	1.0	0.2	0.1	0.2	0.5	0.3	0.2	0.1	0.2	0.2	0.2	0.2
CV (%)	19	15	15	29	10	13	13	6	3	7	7	13
N	3	3	3	3	4	4	4	4	3	3	3	3
DEWS test - f (MPa)												
	D_30				D_60				D_80			
	f_{max}	$f_{0.5}$	$f_{1.5}$	$f_{2.5}$	f_{max}	$f_{0.5}$	$f_{1.5}$	$f_{2.5}$	f_{max}	$f_{0.5}$	$f_{1.5}$	$f_{2.5}$
Mean	1.8	0.5	0.3	0.2	1.7	0.8	0.4	0.3	2.0	1.1	0.8	0.6
SD	0.4	0.2	0.2	0.1	0.3	0.4	0.2	0.1	0.5	0.2	0.1	0.1
CV (%)	21	49	60	66	19	50	35	47	24	22	12	17
N	6	6	6	6	5	5	5	5	6	6	6	6
DPT $\varnothing$ 150 mm $\times$ 150 mm - f (MPa)												
	LB_30				LB_60				LB_80			
	f_{max}	$f_{0.5}$	$f_{1.5}$	$f_{2.5}$	f_{max}	$f_{0.5}$	$f_{1.5}$	$f_{2.5}$	f_{max}	$f_{0.5}$	$f_{1.5}$	$f_{2.5}$
Mean	3.4	0.9	0.5	0.3	2.9	1.6	0.9	0.7	3.5	1.9	1.1	0.8
SD	0.2	0.3	0.1	0.1	0.3	0.3	0.2	0.2	0.1	0.3	0.3	0.3
CV (%)	6	28	28	20	9	21	19	22	3	16	26	35
N	6	6	6	6	6	6	6	6	6	6	6	6
DPT $\varnothing$ 100 mm $\times$ 100 mm - f (MPa)												
	SB_30				SB_60				SB_80			
	f_{max}	$f_{0.5}$	$f_{1.5}$	$f_{2.5}$	f_{max}	$f_{0.5}$	$f_{1.5}$	$f_{2.5}$	f_{max}	$f_{0.5}$	$f_{1.5}$	$f_{2.5}$
Mean	3.5	0.9	0.5	0.3	3.1	1.5	0.8	0.6	3.4	1.7	0.9	0.7
SD	0.3	0.4	0.2	0.2	0.4	0.3	0.3	0.3	0.4	0.4	0.3	0.2
CV (%)	8	40	44	47	14	21	36	43	12	24	29	31
N	23	23	23	23	30	30	30	30	30	30	30	30

Considering the residual strengths in the crack-openings evaluated, the largest CVs are shown in the DEWS test (mean CV = 40%) and DPT in small cylinder (mean CV = 35%). This can be justified by the smaller fracture surface, exacerbated by the scarce number of fibres crossing the cracking sections, since the fibre has a low aspect-ratio ($\lambda = 25$). In an intermediate situation is found the DPT in large cylinder that has the larger fracture surface (mean CV = 24%). Even with small fracture surface, the lowest CV is shown in the flexural beam test EN 14488-3 (mean CV = 13%). This can be justified because this test was the only one performed on a machine with a closed-loop system, thus reducing the effect of post-cracking instability. In almost all tests, the CV decreases as the fibre content increases, except for the DPT in large cylinder,

which presents an almost constant CV in the evaluated mixtures, around 24%. The variation in the number of fibres could be one of the causes of the behaviour observed, albeit a conclusive answer could not be achieved based on data available.

4.3.3 Comparative analysis of strength results

As expected, there is no influence of the fibre content in the maximum strengths as the softening behaviour was observed (BENTUR; MINDESS, 2007). Figure 4.8a shows the comparison of individual results of maximum strengths obtained from different tests associated with the actual fibre content. The average strengths are shown in continuous lines. Confidence intervals, obtained according to the method of Freund; Simon (2002) for a 90% confidence, are shown in dashed lines. The highest mean strength (5.03 MPa) was obtained in flexural beam test EN 14488-3, followed by DPT in large and small cylinder (both with mean strength of 3.29 MPa), the lowest mean strength was obtained in DEWS test (1.86 MPa). It is noticed that the mean strength of the DEWS test is almost a third of that obtained in the flexural beam test. According to the *FIB* Model Code (2010) in a rigid plastic linear model, the uniaxial tensile strength could be considered as a third of the flexural strength.

Figure 4.8b, 4.8c and 4.8d show the comparison of individual results of residual strengths by fibre content at crack-openings of 0.5, 1.5 and 2.5 mm. The linear regressions are shown on continuous lines and the confidence intervals on dashed lines. All correlations are linear and pass through the origin. The highest correlation is obtained in the flexural beam test EN 14488-3 (R^2 between 0.98 and 0.99), followed by the DPT in large cylinder (R^2 between 0.93 and 0.96). The DPT in small cylinder and the DEWS test have the lowest correlation, R^2 between 0.89 and 0.95 the former and between 0.90 and 0.94 the latter. The highest strengths were obtained in the flexural beam test EN 14488-3, followed by the DPT in large and small cylinders, which practically maintain the same trend line. This shows that any of the specimen sizes subjected to the DPT here can be used in the evaluation of residual strength, as they provide similar results. The lowest strengths correspond to the DEWS test.

To test the equality of the residual strengths of the DPT in the large and small cylinder, a t-student statistical analysis was performed, comparing the means of the

two samples ($H_0: \mu_1 = \mu_2$), with a confidence of 95% ($t_{tabulated}$ 1.96). The $t_{calculated}$ values of the residual strengths for the crack-openings at 0.5, 1.5 and 2.5 mm were: 0.76, 0.75 and 0.67, respectively, being within the acceptance region ($t_{calculated} < t_{tabulated}$), thus proving the equality of the population averages.

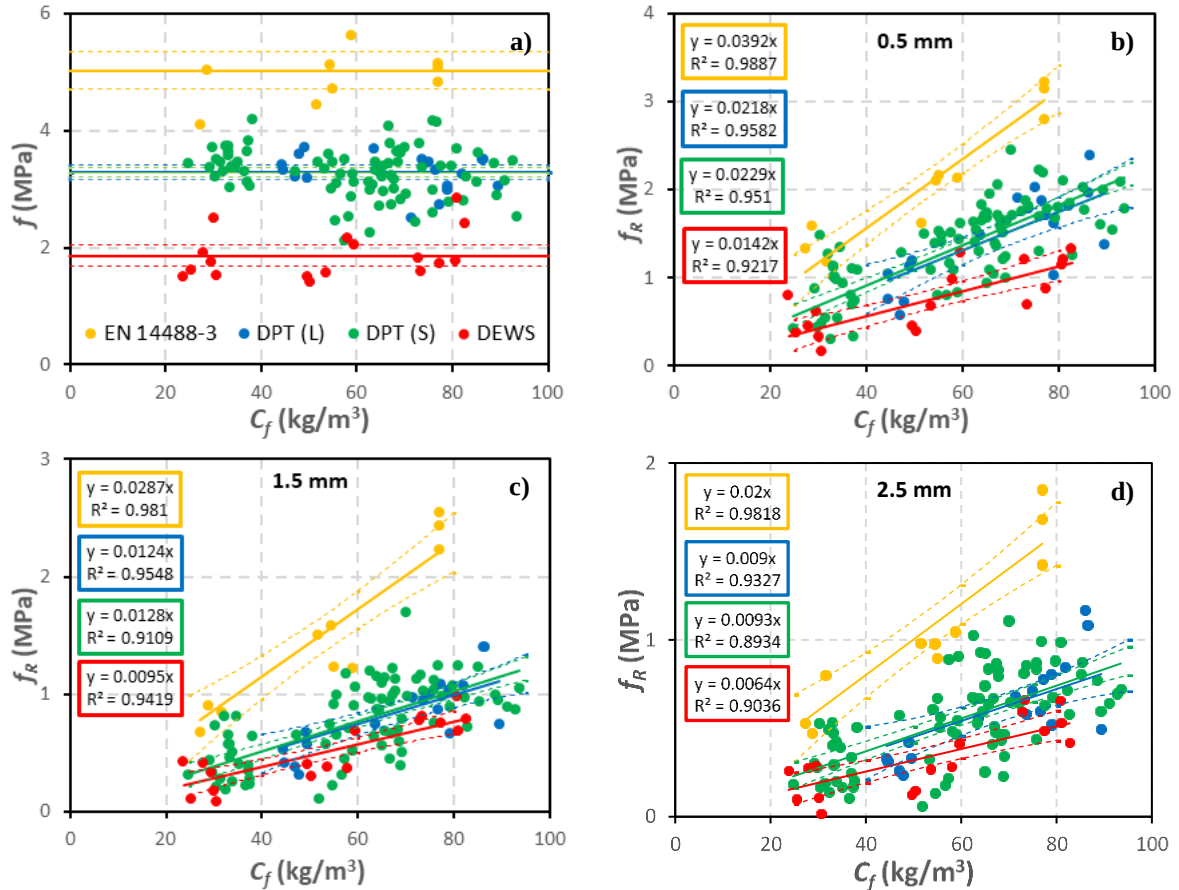


Figure 4.8 - Comparison of maximum strengths (a); and residual strength results at 0.5 mm (b), 1.5 mm (c) and 2.5 mm (d) crack-openings by fibre content between the flexural beam test EN 14488-3, DPT in large - DPT (L) and small - DPT (S) cylinder and DEWS test. Source: Cáceres *et al.* (2021a).

To correlate the tests, residual strengths were obtained from linear regression equation in Figure 4.8. Since the DPT on both cylinder sizes does not show significant differences, a single linear regression was adopted for each crack-opening considering both datasets. The linear regression equations were: at 0.5 mm ($y = 0.0227x$), at 1.5 mm ($y = 0.0127x$) and at 2.5 mm ($y = 0.0092x$). Table 4.5 shows the residual strengths found for each crack-opening. Figure 4.9 shows the correlations obtained between the residual strengths obtained with the flexural test and the alternative tests.

High correlations (R^2 above 0.98) were obtained between residual strength results of flexural beam test EN 14488-3 and alternative tests. The highest correlation was obtained with the DEWS test ($R^2 = 0.997$), a fact that can be justified because the

specimens of this test were extracted from the ends of the beams used in the flexural test. Furthermore, in these two tests, there is no influence of the internal friction of the matrix, which produces results with less influence of intervening variables. The DPT has a slightly lower correlation, R^2 of 0.985. The excellent correlations obtained between the proposed new tests and the flexural beam test EN 14488-3 indicate that these tests could be used in the evaluation of the residual strength of the FRSC, replacing the EN 14488-3 test. Nevertheless, the DEWS test is the most promising due to the advantage of being a test with a type I fracture, directly providing the results of tensile strength by crack-opening. The following section shows a more detailed assessment considering the post-cracking tensile results of the flexural beam test EN 14488-3, according to the parameters established in the *FIB* Model Code (2010).

Table 4.5 - Residual strengths for each crack-opening ($f_{0.5\text{ mm}}$, $f_{1.5\text{ mm}}$, $f_{2.5\text{ mm}}$) in MPa in fibre contents of 30, 60 and 80 kg/m³, according to the linear regression equations for EN 14488-3, DPT and DEWS tests. Source: Cáceres *et al.* (2021a).

Residual strengths (MPa) according to the linear regression equations									
C_f (kg/m ³)	$f_{0.5\text{ mm}}$			$f_{1.5\text{ mm}}$			$f_{2.5\text{ mm}}$		
	30	60	80	30	60	80	30	60	80
EN 14488-3	1.2	2.4	3.1	0.9	1.7	2.3	0.6	1.2	1.6
DPT	0.7	1.4	1.8	0.4	0.8	1.0	0.3	0.6	0.7
DEWS	0.4	0.9	1.1	0.3	0.6	0.8	0.2	0.4	0.5

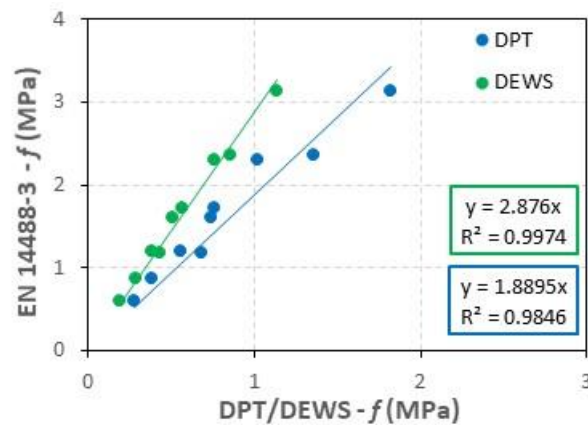


Figure 4.9 - Correlation of the residual strength results between the EN 14488-3 test with DPT and DEWS tests. Source: Cáceres *et al.* (2021a).

4.3.4 Comparison of constitutive models

Codes (RILEM, 2003, CNR, 2006; CPH 2008; *FIB Model Code*, 2010) and studies (LOK; XIAO, 1998; DUPONT, 2003; VANDEWALLE *et al.*, 2003; TLEMAT; PILAKOUTAS; NEOCLEOUS, 2006; di PRISCO; COLOMBO; DOZIO, 2013; THAI; NGUYEN; NGUYEN, 2020) establish constitutive models based on flexural beam tests for FRC. However, these references do not focus on FRSC. Since there is a current trend to transfer the approach of the *FIB Model Code* to FRSC technology (ITA, 2020; LARIVE *et al.*, 2020) to obtain constitutive models for flexural beam test, it was considered necessary to apply the results of the EN 14488-3 test to *FIB Model Code* parameters. The residual strengths of the EN 14488-3 test in Table 4.5 were converted into tensile strengths, using the constitutive equations of the *FIB Model Code* (Equations 4.11–4.12). These equations describe a linear post-cracking with strain-softening behaviour (see Figure 4.10a), where: f_{FTS} and $f_{FT2.5}$ are the tensile strengths at 0 and 2.5 mm of crack-opening, respectively; f_{R1} and f_{R3} are the residual strengths of the flexural beam test in 0.5 and 2.5 mm, respectively. The results obtained from the tensile strength of the EN 14488-3 test are shown in Table 4.6. The post-cracking lines derived from these results are shown in Figures 4.11.

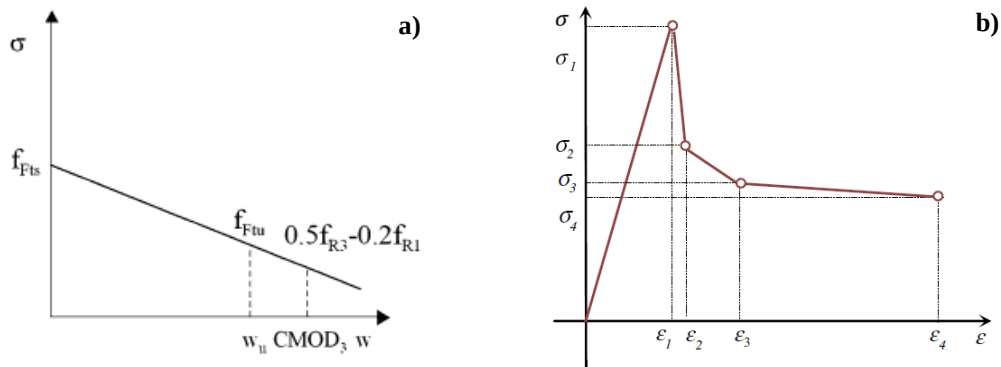


Figure 4.10 – Linear post-cracking model by the *FIB Model Code* (2010) utilized in the flexural beam test EN 14488-3 (a). Simplified diagram $\sigma - \varepsilon$ of the constitutive model for the DPT by Blanco *et al.* (2014) (b). Source: Cáceres *et al.* (2021a).

$$f_{FTS} = 0.45f_{R1} \quad (4.11)$$

$$f_{FT2.5} = 0.5f_{R3} - 0.2f_{R1} \quad (4.12)$$

Table 4.6 - Tensile strength results in MPa of flexural beam test EN 14488-3 according to *FIB Model Code* (2010). Source: Cáceres *et al.* (2021a).

EN 14488-3 - σ (MPa)			
C_f	30 kg/m ³	60 kg/m ³	80 kg/m ³
F_{FTs}	0.5	1.1	1.4
$F_{FT2.5}$	0.1	0.1	0.2

To convert the strength results of DPT into tensile strength, it was necessary to use the constitutive equations proposed by Blanco *et al.* (2014). These equations describe the post-cracking behaviour of tensile strength by strain $\sigma - \varepsilon$ at four levels of strain: $\varepsilon_1, \varepsilon_2, \varepsilon_3, \varepsilon_4$ (see Figure 4.10b). The increments of the strain $\Delta\varepsilon_i$ from the peak load are: $\Delta\varepsilon_1 = \varepsilon_2 - \varepsilon_1 = 0.1 \text{ ‰}$, $\Delta\varepsilon_2 = \varepsilon_3 - \varepsilon_1 = 3.9 \text{ ‰}$, $\Delta\varepsilon_3 = \varepsilon_4 - \varepsilon_1 = 19.9 \text{ ‰}$. The $\Delta\varepsilon_i$ were converted into vertical displacement increments $\Delta\delta_{Pi}$ using Equation 4.13, where: R is the radius of the cylinder; n is the number of radial cracks formed in the test; β is half the fracture angle of the conical wedge that appears under the load discs after performing the test, i.e. 25° . Thus, the vertical displacement increments for large cylinders ($\varnothing 150 \text{ mm} \times 150 \text{ mm}$) are: $\Delta\delta_{P1} = 0.02 \text{ mm}$, $\Delta\delta_{P2} = 0.75 \text{ mm}$ and $\Delta\delta_{P3} = 4.00 \text{ mm}$. According to the results obtained in the DPT on a larger cylinder, the $\Delta\delta_{Pi}$ correspond to $\Delta TCOD_{Pi}$ crack-opening increments of: $\Delta TCOD_{P1} = 0.03 \text{ mm}$, $\Delta TCOD_{P2} = 0.92 \text{ mm}$ and $\Delta TCOD_{P3} = 4.87 \text{ mm}$. In order to unify the results, since it was proved that there is no significant difference between the residual strengths of the DPT in large and small cylinders and that they almost maintain the same trend line in Figure 4.8, these increments were adopted for both cylinder sizes.

The tensile strength corresponding to peak load σ_1 and each crack-opening increment from the peak load $\sigma_{\Delta TCOD_{Pi}}$, were calculated according to Equations 4.14 and 4.15, which were adapted from Blanco *et al.* (2014). Where: F_{Pmax} is the peak load; $F_{\Delta TCOD_{Pi}}$ is the load corresponding to the crack-opening increments $\Delta TCOD_{Pi}$ from the peak load; β is 25° ; μ_K is the kinetic friction coefficient, a value of 0.7 was adopted; and A is the radial value of the cracked surface. For the calculation of A , Equation 4.16 was used, where: d and H are the diameter and height of the cylinder, respectively; a is the diameter of the load application disc, that is, 37.5 mm for the large cylinder and 25 mm for the small cylinder; and β is 25° .

Thus, the individual results of the tensile strength by fibre content of the DPT, which correspond to the peak load and the crack-opening increments $\Delta TCOD_{Pi}$, were calculated. With these results, linear regressions were performed passing through the

origin, except for the peak load results, since this property depends on the concrete matrix. For this particular case, the average value was adopted. The tensile strength values at each Δ_{TCODPi} were calculated through linear regression for the fibre contents of 30, 60 and 80 kg/m³. The results are shown in Table 4.7. From these results, the post-cracking linear behaviour of the DPT was plotted (see Figure 4.11).

$$\Delta\delta_{Pi} = \frac{\Delta\varepsilon_i \pi R}{n \cdot \tan \beta \cdot \sin \frac{\pi}{3}} \quad (4.13)$$

$$\sigma_1 = \frac{F_{Pmax}}{2 \cdot \pi \cdot A} \times \frac{\cos \beta - \mu_k \cdot \sin \beta}{\sin \beta + \mu_k \cdot \cos \beta} \quad (4.14)$$

$$\sigma_{\Delta TCODPi} = \frac{F_{\Delta TCODPi}}{2 \cdot \pi \cdot A} \times \frac{\cos \beta - \mu_k \cdot \sin \beta}{\sin \beta + \mu_k \cdot \cos \beta} \quad (4.15)$$

$$A = \frac{d \cdot H}{4} - \frac{a^2}{4 \cdot \tan \beta} \quad (4.16)$$

Table 4.7 - Tensile strength results in MPa of the DPT according to the constitutive equations of Blanco *et al.* (2014). Source: Cáceres *et al.* (2021a).

Δ_{TCODPi} (mm)	DPT - $\sigma_{\Delta TCODPi}$ (MPa)		
	30 kg/m ³	60 kg/m ³	80 kg/m ³
0.00	1.9	1.9	1.9
0.03	0.6	1.2	1.6
0.92	0.3	0.6	0.8
4.87	0.1	0.2	0.2

Besides the post-cracking linear behaviour of the DPT and EN 14488-3 test, Figure 4.11 also includes the lines that describe the post-cracking behaviour of the DEWS test in the contents of 30, 60 and 80 kg/m³, derived from strength results of Table 4.5. The stress-crack opening ($\sigma - w$) of all tests are similar. For crack-openings bigger than 1.5 mm and the same fibre content, DEWS and DPT show similar results that are consistently bigger than those observed in the EN 14488-3 tests. The biggest difference between the test is 0.3 MPa in 2.5 mm crack-opening for the content of 80 kg/m³. For small crack openings ($w < 1.5$ mm) the EN 14488-3 and DEWS show similar results, which differ slightly from the values obtained with the DPT. Interestingly, all test methods show nearly the same results for 0.5 mm crack opening in each of the 3 fibre contents assessed here.

The good approximations of the linear post-cracking behaviour of the tests, confirm that the new proposals of tests in smaller-scale can substitute the flexural

beam test EN 14488-3 according to the parameters of the *FIB* Model Code. The DEWS has the advantage of being able to directly represent the tensile strength response by crack-opening, as if it were a uniaxial direct tensile test, due to the fracture type I that occurs in the specimens. The DPT on both cylinder sizes is also promising, but it is necessary to develop an analytical process using constitutive equations, to obtain the post-cracking response of tensile strength by crack-opening.

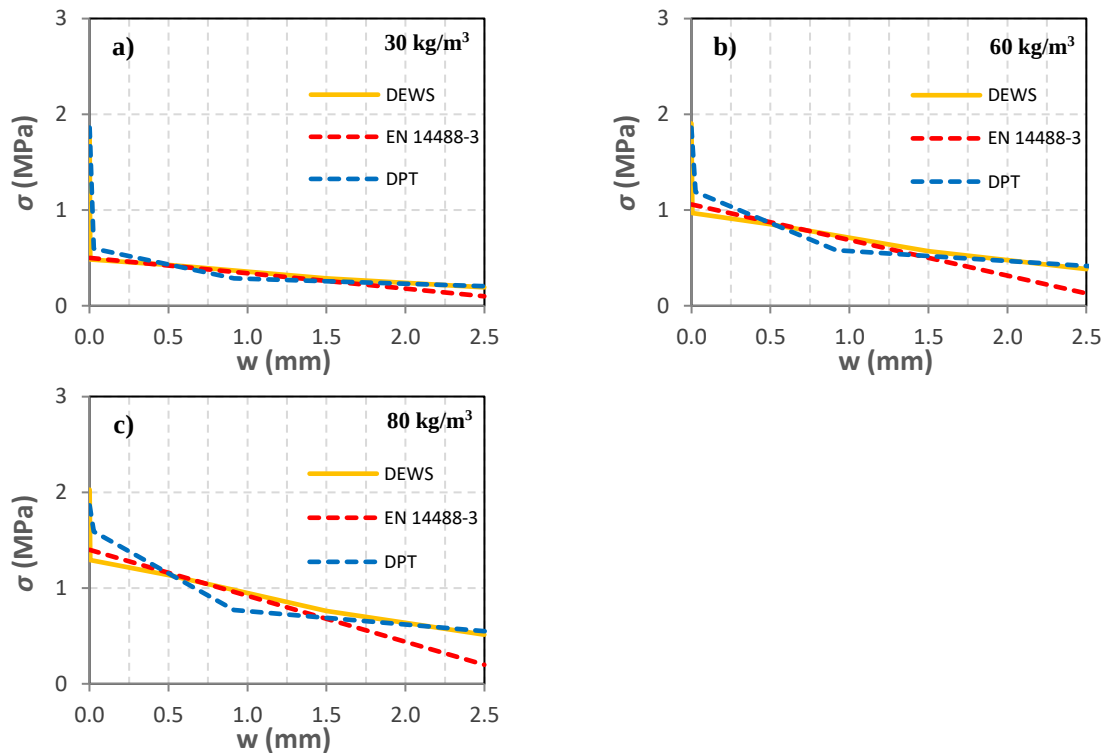


Figure 4.11 - Comparison between the tensile strength results by crack-opening ($\sigma - w$) of flexural beam test EN 14488-3 according to the *FIB* Model Code (2010), DPT according to the constitutive equations of Blanco *et al.* (2014) and DEWS test for fibre contents of 30 kg/m³ (a), 60 kg/m³ (b) and 80 kg/m³ (c). Source: Cáceres *et al.* (2021a).

4.4 Conclusions

- The highest CV in the residual strengths was observed in the DEWS test (mean CV = 40%) and DPT in small cylinder (mean CV = 35%). This can be attributed to the small fracture surface and by the type of fibre used with a low aspect-ratio ($\lambda = 25$). The DPT in large cylinder presented a mean CV of 24%, which remained almost constant for all mixtures. The flexural beam test EN 14488-3 showed the lowest mean CV of 13%. However, this test was the only one

performed in a closed-loop system machine, thus reducing the effect of post-peak instability.

- Although the high level of variation of results, high correlation factors were obtained with the flexural beam test EN 14488-3 and the alternative tests showing excellent parallelism. The DEWS test resulted in a R^2 correlation of 0.997 and is particularly compatible with the assessment of the constitutive curve used in the design. The DEWS presents fracture type I and the tensile strength results are obtained directly associate to crack-openings, similarly to an uniaxial direct tensile test. Therefore, the constitutive models could be obtained in a more simplistic way. However, the DEWS demands more time to the preparation of the specimens. Thus, this test becomes more suitable for studies prior to the execution of the work, in the assessment of the constitutive equations of the FRSC. Although the prisms of the DEWS test were obtained by cutting the ends of the tested beams, it is noteworthy that this test can also be carried out from cores extracted from panels or the structure.
- The approach proposed in the study also showed that it is possible to predict the flexural beam test EN 14488-3 based on the results of the DPT on both cylinder sizes, since a high correlation was obtained ($R^2 = 0.985$). The DPT on cylinders with a height and diameter of 100 and 150 mm practically show the same trend in terms of residual strength by fibre content in the evaluated crack-openings. It was statistically proven that the residual strengths of both cylinders do not differ significantly. The constitutive models obtained for FRSC from the DPT results were also close to that of the EN 14488-3 test, although demanding a more complex analysis. This, in addition to the fact that the specimens require very little preparation, opens the possibility of using the DPT as a complementary and practical method in the control of FRSC structures, both in the routine control of tunnel execution or even for existing structures evaluation.
- The tests commonly used to determine the residual strength of the FRSC by flexural beam test EN 14488-3 are complex, as the beams need to be cut from previously sprayed panels, which can weigh up to 110 kg, making handling difficult. This will be even more difficult if the EN 14651 is adopted because the specimens are larger.

- The proposed correlations represent a simple FRSC control tool based on smaller-scale tests. The focus is also in line with the philosophy of the *FIB* Model Code (2010) that prioritize the constitutive model use and can serve as an example for future correlations using other types of fibres. However, the correlations cannot be generalized. Further studies need to be done with different compressive strengths levels, other types of fibres and spraying at different angles.

5 INTEGRATE APPROACH FOR QUALITY CONTROL OF FIBRE-REINFORCED SPRAYED CONCRETE FOR TUNNEL LINING

5.1 Introduction

Fibre-reinforced sprayed concrete (FRSC) is widely used in tunnel lining applications; fibres provide ductility (AUSTIN; ROBINS, 1995) and facilitate load redistribution away from cracked regions toward more structurally competent regions (BERNARD; THOMAS, 2020). The square panel test (SPT) specified in EN 14488-5 and the round panel test (RPT) defined in ASTM C1550 (ASTM C1550, 2020) are widely used to assess the post-cracking mechanical response of FRSC. The RPT has great acceptance due to the lower scatter of results and greater within-batch repeatability if compared with other test methods (TRAN; BERNARD; BEASLEY, 2005; BERNARD; XU, 2008; BERNARD; XU; CARINO, 2010; di PRISCO; PLIZZARI; VANDEWALLE, 2009). During the test, the round panel experiences bi-axial flexure in response to a central point load that simulates one of the most common modes of failure found in FRSC tunnel linings (MORGAN *et al.*, 1989; BARRETT; MCCREATH, 1995; BERNARD, 2000).

Comparative studies (BERNARD, 2002; PAPWORTH, 2002; MYREN, BJØNTEGAARD, 2010) found a linear relationship between the energy absorption measured in the SPT and RPT. The test results from SPT and RPT are represented in terms of energy absorption that is used in empirical FRSC tunnel sizing methods, such as the Q-System (BERNARD; THOMAS, 2020). This contrasts with the modern tendency to seek a characterization of FRSC that provides constitutive models trying to approximate the *FIB* Model Code design philosophy of FRC and FRSC (ITA, 2020; THOMAS, 2020; LARIVE *et al.*, 2020). Recent guidelines, such as those of ITA Working Group No. 12 and ITAtech (ITA, 2020), propose the three-point flexural bending test in EN 14651 to obtain design parameters for FRSC structures according to the *FIB* Model Code.

Spraying of test panels does not guarantee the exact reproduction of the concrete conditions of the tunnel lining (MARTIN *et al.* 2011). Spraying process factors, such as the spraying surface, spray direction, impact velocity and rebound (AUSTIN;

ROBINS, 1995; FIGUEIREDO, 1997; ARMELIN, 1997; AUSTIN; PEASTON; ROBINS, 1997; JOLIN, 1999; KAUFMANN *et al.* 2013; GINOUSE; JOLIN; BISSONNETTE, 2014; GINOUSE; JOLIN, 2016), produce a significant variation in fibre content and orientation in the tunnel lining if compared with equivalent sprayed specimens. The spraying distance between what is measured on the panels and on the structure can differ significantly, hence affecting the FRSC mechanical properties. Since the extraction of round or square panels directly from the tunnel lining is neither practical nor feasible in most situations (CÁCERES; CAVALARO; FIGUEIREDO, 2021), which can compromise the representativeness of results from RPT, SPT and bending tests of sprayed samples. Bernard; Oliveira; Forrest (2022) proposed a point-loading in-situ test to evaluate the FRSC tunnel lining. This evaluation method can be considered a load test under real conditions to evaluate the actual structural response of the lining. Nonetheless, this is an expensive and destructive method that damages the lining, which might require significant posterior repair.

The RPT specified in ASTM C1550 weights around 91 kg (Ø800 mm × 75 mm) and is difficult to produce, handle and test (MINELLI; PLIZZARI, 2011). At least three people are necessary during testing to handle the specimen. This test requires the use of larger equipment, which implies a higher cost. Smaller versions of the round panel supported on three points (Ø600 mm × 60 mm) (MINELLI; PLIZZARI, 2011) or on continuous support (Ø600 mm × 100 mm) (BJØNTEGAARD, 2009) were proposed. Still the smaller round panels have a considerable weight of 40 and 65 kg, respectively, which maintain at least part of the production, handling and testing issues.

The double punch test (DPT) and the double-edge wedge splitting (DEWS) test of specimens weighting around 2 kg have been used to evaluate the post-cracking response of FRSC. Both the DPT and DEWS test allow characterizing cores extracted from the structure, which can map a larger area and entail significantly simpler post-repair procedures. Several studies from the literature have investigated the characterization of FRSC using the DPT (SILVA, 2017; SEGURA-CASTILLO *et al.*, 2018; CARMONA; MOLINS, 2019; GALO BARDES *et al.*, 2019; CARMONA; MOLINS; GARCÍA, 2020; MONTEIRO; SILVA, 2020; CÁCERES; CAVALARO; FIGUEIREDO, 2021; CÁCERES *et al.*, 2021a) to obtain the residual strength or energy absorption. Comparatively, fewer studies evaluated the FRSC by the DEWS test.

Previous experiences used the DPT test to assess the FRSC behaviour in real tunnel linings, such as the tunnel situated on the Tamoios highway in São Paulo, Brazil

(NOVA SERRA DA TAMOIROS, 2022), the metro of Lima in Peru and the Chuquicamata underground mine in Chile (CARMONA; MOLINS; GARCÍA, 2020). To the authors' best knowledge, no project has applied the DEWS test to evaluate real tunnel linings.

Cáceres *et al.* (2021a) demonstrated that results from the DPT and DEWS test can provide design parameters for FRSC structures according to the most recent design trends, being an alternative to traditional panel tests. Studies by Carmona; Molins; García (2020) and Cáceres; Cavalaro; Figueiredo (2021) found high correlation of absorbed energy results between the DPT and SPT according to EN 14488-5 (R^2 above 0.98). No studies were found on the simulation of RPT using constitutive models derived from DPT or DEWS test for FRSC or on the correlation between the energy absorption results from DPT and RPT in FRSC specimens.

This study combines experimental and numerical investigations to evaluate if constitutive models derived from small-scale tests, such as DPT and DEWS test, can be used to predict the behaviour of larger panels in the RPT ASTM C1550. The numerical model by Salehian; Barros; Taheri (2014) was adopted to simulate the RPT experimental curves using the small-scale tests constitutive models as input. The correlation between the results of energy absorption derived from the DPT and RPT was also verified, confirming the link between new and traditional approaches. Findings demonstrate that small-scale tests are a viable method to evaluate the mechanical behaviour of FRSC both in regular quality control programs and to verify an existing tunnel lining condition.

The study presentation starts with the methodology (experimental program; test setups and procedures; numerical model), followed by the results and analysis. Next, numerical simulations are used to simulate the RPT response to validate the constitutive models. Finally, the conclusions are presented.

5.2 Methodology

The experimental study sought to reproduce the quality control conditions found in a real work situation as the FRSC is highly sensitive to production conditions and scale. In this sense, all specimens were produced on-site during the construction of

the Vila Formosa metro station by the crew and the equipment regularly used in the execution of the shafts and tunnels from the São Paulo Metro Line 2 Consortium.

5.2.1 Materials and spraying process

A ready-mix plant supplied the concrete in mixer trucks for the wet-mix spraying process. The production and spraying took place in three working days, only varying the fibre content incorporated in the concrete (nominal contents of 15, 12 and 30 kg/m³ for the first, second and third day, respectively). These fibre contents were chosen to verify if the test methods used in the evaluation were sensitive enough to changes in the mechanical behaviour. Table 5.1 summarizes the concrete compositions used.

Table 5.1 – Concrete mix formulation. Source: Cáceres; Cavalaro; Figueiredo (2023).

Materials	Content (kg/m ³)
Cement (70% CEM I 52.5 and 30% blast-furnace slag)	426
Quartz sand (0 - 0.60 mm)	559
Artificial sand (0 - 4.75 mm)	372
Coarse aggregate (4.75 - 9.5 mm)	868
Water	182
Polyfunctional admixture*	1.10
Superplasticiser	0.44

* This admixture concurrently satisfies different requirements, such as high water reduction, slump retention and maintenance of workability for a long time (Aïtcin; Flatt, 2016).

The steel fibre used was Dramix 3D 65/35 BG, hooked-shape with 35-mm length and aspect-ratio λ of 65. The fibre was introduced directly into the concrete mixer truck and mixed for a minimum of 5 minutes (see Figure 5.1a). The mixer trucks were the same regularly used in the work and the volumes of concrete destined to the mixture of the fibre were residual and consequently estimated. Therefore, there was a difference between the initial proposal of fibre contents (10, 20 and 30 kg/m³) and the nominal contents in the first two days. Then the concrete was placed in an Aliva 263 spray pump, applying a spraying pressure of 7 bar. The concrete was sprayed by an experienced nozzle operator on wooden moulds positioned at 20° with the vertical axis (see Figure 5.1b). An alkali-free accelerator at 3.7% by cement weight was used to

ensure adequate concrete consolidation over the surface. The round specimens were screeded to achieve a uniform thickness.

Each workday entailed the production of 5 round panels (nominal dimensions: diameter of 780 mm and a thickness of 75 mm) and 4 square panels (nominal dimensions: base of 600 mm × 600 mm, top of 800 mm × 800 mm and thickness of 100 mm). The difference in diameter of the round panel used in the study and that specified by the ASTM C1500 standard is because the span of the testing machine available only allowed a maximum diameter of 780 mm. The average concrete compressive strength at 1 month was 36.4 ± 0.5 MPa, 39.6 ± 0.2 MPa and 31.3 ± 0.3 MPa for nominal fibre contents of 15, 12 and 30 kg/m³, respectively. The results meet the characteristic compressive strength ($f_{ck} = 30$ MPa).

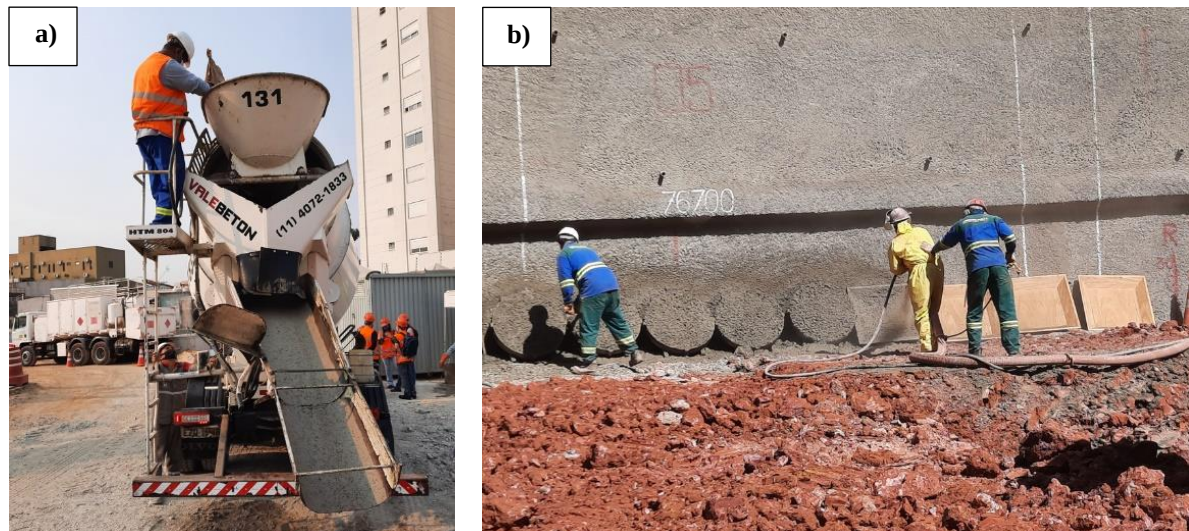


Figure 5.1 – Fibre incorporation to the mixer truck (a); spraying process (b). Source: Cáceres; Cavalaro: Figueiredo (2023).

5.2.2 Extraction and preparation of specimens

Forty-eight cylinders with nominal dimensions Ø100 mm × 100 mm for the DPT were extracted from half of the total square panels (see Figure 5.2a). The rough ends of the cylindrical cores were cut to ensure the specified specimen height. Twenty-one beams, with nominal dimensions of 600 mm in length, 125 mm in width and 75 mm in height for the flexural beam test EN 14488-3, were cut from the other half of the square

panels (see Figure 5.2b). The beams were taken from the bottom of the panels to ensure a less favourable condition in terms of fibre incorporation.

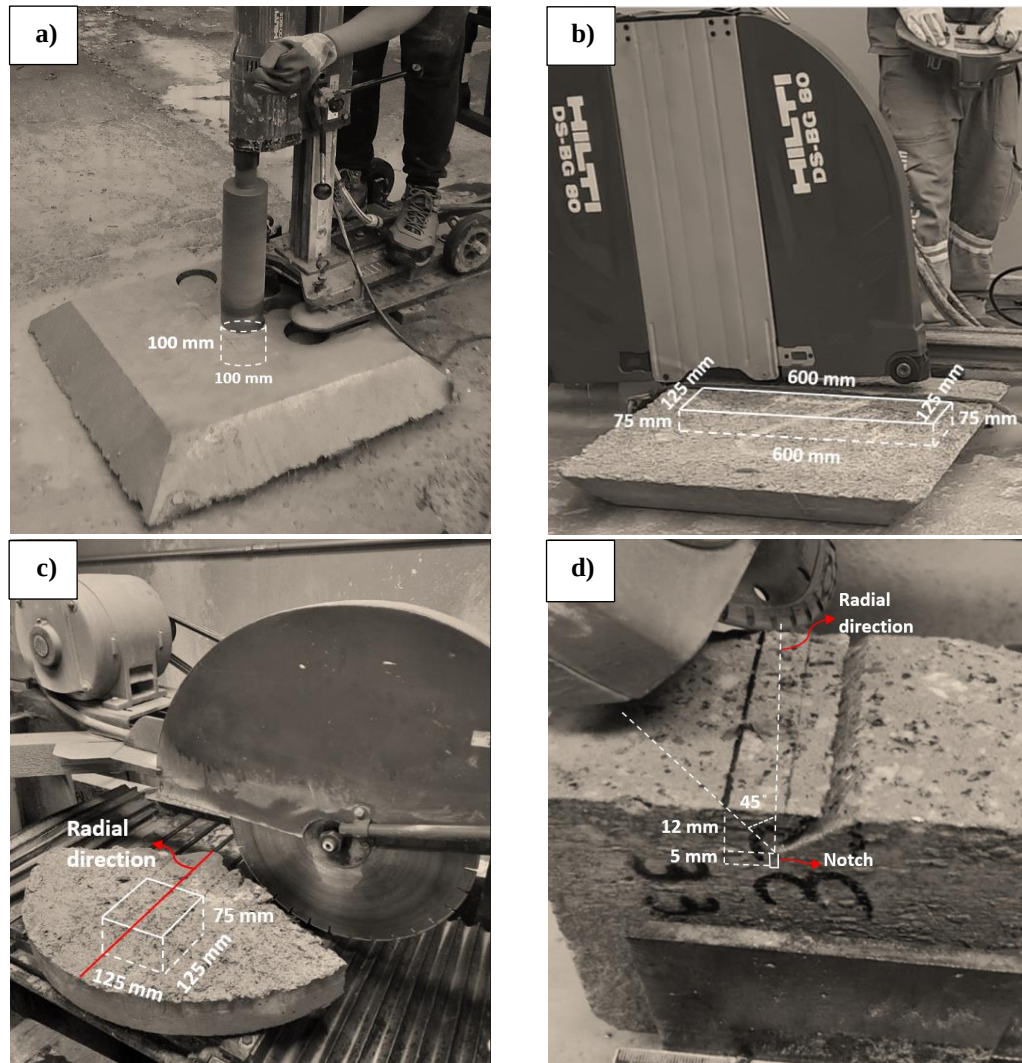


Figure 5.2 – Extraction of cylinders from square panels (a); cutting beams from square panels (b) cutting small prisms from circular segments for the DEWS test (c); making the wedge and notch in the prisms (d). Source: Cáceres; Cavalaro; Figueiredo (2023).

After testing the round panels according to ASTM C1550, the circular segments were cut in their radial direction and away from the cracks into smaller prisms (nominal dimensions of 125 mm in length, 125 mm in width and 75 mm in height as per Figure 5.2c) used for the DEWS test. The rough faces of the prisms were cut to ensure the desired width. To induce the crack formation in the radial direction of the prisms, a wedge was cut and then a notch was made in the middle of the top and bottom faces of the specimens (see Figure 5.2d). Steel plates were glued over the wedges to accommodate the metallic load application rollers.

The specimens were prepared and tested at an age greater than 3 months to minimize the impact of the evolution of concrete strength over time on the test results. The notations used to present the results are DPT, FBT, DEWS and RPT corresponding to the cylinders Ø100 mm × 100 mm of the DPT, beams of the EN 14488-3 test, prisms of the DEWS test, and round panels of the ASTM C1550 test, respectively. The numbers following the notation refer to the nominal fibre content. For example, DEWS_12 refer to the prisms of the DEWS test with nominal fibre content of 12 kg/m³.

5.2.3 Determination of fibre content

The fibre content in the cylinders of the DPT was determined by the inductive test (TORRENTS *et al.* 2012; CAVALARO *et al.* 2015; CAVALARO *et al.* 2016). A calibration process using the same steel fibre was performed on three styrofoam cylinders of Ø100 mm × 100 mm (785.40 cm³). The fibres were inserted manually and randomly distributed in the volume of the cylinders in three contents: 10, 20 and 30 kg/m³. The correlations between the fibre content placed in the styrofoam cylinders and the sum of the inductance variation ΔL_T , measured in three orthogonal axes L_i is shown in Figure 5.3. Equation 5.1 provides the steel fibre content in the cylinders (C_f), where β is the inductance coefficient of the fibre from Figure 5.3 (0.0053), ΔL_T is the total inductance variation, and V is the volume of the cylinder.

The orientation number (n_i) and the contribution of the fibres in each axis (C_i) are given by Equations 5.2 and 5.3 where γ is an inductance parameter that depends on the fibre aspect-ratio, $B_{V,i}$ is a constant that depends on the magnetic field over the volume of the cylinder, L_i is the inductance measurement on a specific axis and L_e is the sum of the ratio between each L_i measured in each of the orthogonal axis and the corresponding constant $B_{V,i}$. Parameters $B_{V,x} = B_{V,y}$ are equal to 536 and $B_{V,z}$ is equal to 538 for cylinders of Ø100 mm × 100 mm; γ is equal to 0.05 (CAVALARO *et al.*, 2016).

The average fibre contents obtained in the cylinders for the DPT test were considered the same for beams tested according to EN 14488-3 since they all come from square panels sprayed one after the other. The fibre content in the prisms used

in the DEWS test was obtained by crushing the specimens and gathering fibres with a magnet after the test. The fibre content of the round panels was determined considering the average value obtained from crushing the two prisms cut from the remaining circular segments.

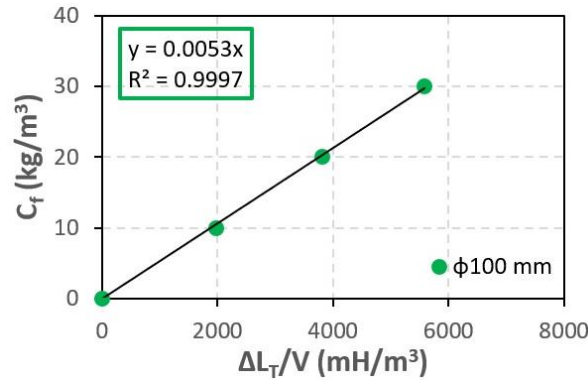


Figure 5.3 - Inductive method calibration in styrofoam cylinders of Ø100 mm × 100 mm. Source: Cáceres; Cavalaro; Figueiredo (2023).

$$C_f = \beta \times \frac{\Delta L_T}{V} \quad (5.1)$$

$$n_i = 1.03 \cdot \sqrt{\frac{L_i \cdot (1+2\gamma) - L_e \cdot B_{V,i} \cdot \gamma}{L_e \cdot B_{V,i} \cdot (1-\gamma)}} - 0.85 \quad (5.2)$$

$$C_i = \frac{n_i}{\sum_{i=x,y,z} n_i} \quad (5.3)$$

5.2.4 Mechanical test setup and testing procedure

Round panel test ASTM C1550

The RPT was carried out on 15 round panels Ø780 mm × 75 mm (5 panels for each nominal content), using a 200 tf Shimadzu universal testing machine (see Figure 5.4a). The detailed test setup can be found elsewhere (ASTM C1550, 2020). A mortar was placed in the central part of the panels to reduce the spraying surface irregularities and ensure regular uniform load application. The surface of the panel in contact with the mould was positioned on the support. Plastic films had to be placed on the transfer plates to reduce the frictional interaction between the panel and the support.

The panel was loaded by a hemispherical-ended piston with a constant displacement rate of 4 mm/min, up to a central displacement of 40 mm. LVDTs (linear variable displacement transducers) were positioned at a yoke fixed to the support to minimize external deformations (see Figure 5.4b). Plastic films were placed on top of the transducers to prevent the transducers from penetrating the cracks when they opened. The absorbed energy was determined by calculating the area under the load-displacement curve (P - δ) using Equation 5.4, where E is the absorbed energy, P_i is the load corresponding to a displacement δ_i , and δ_m is the maximum displacement.

The influence of the panels thickness and diameter on the RPT absorbed energy results was reported by Bernard; Pircher (2001) and Sandbakk (2011). The actual panel thickness was determined on fracture surfaces after completing testing (3 points along each radial crack). The actual diameter was obtained by two orthogonal measures around the panel before testing. A correction factor was used to compensate for the panels thickness and diameter influence on the RPT P - δ curves by Equation 5.5 from Bernard; Pircher (2001), where P_c is the corrected load, P_i is the measured load for a vertical displacement δ_i , t is the measured mean thickness, t_0 is the nominal thickness (75 mm), d is the measured mean diameter and d_0 is the nominal diameter (780 mm). The corrected energy (E_c) was obtained by the area under the P_c - δ curve using Equation 5.4.

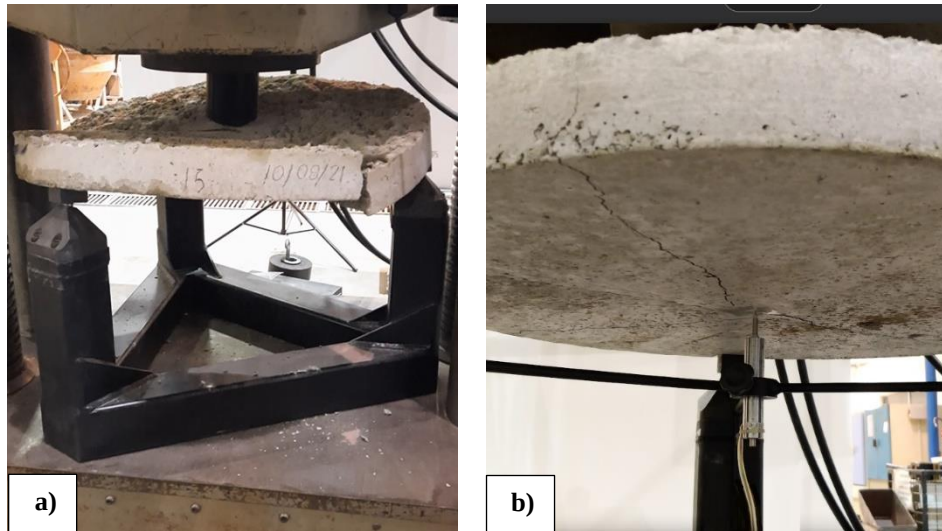


Figure 5.4 – Round panel test ASTM C1550 (a) and positioning of LVDT (b). Source: Cáceres; Cavalaro; Figueiredo (2023).

$$E = \sum_{i=0}^{i=\delta_m} \left[(\delta_{i+1} - \delta_i) \cdot \frac{P_i + P_{i+1}}{2} \right] \quad (5.4)$$

$$P_c = P_i \cdot \left(\frac{t_0}{t}\right)^\alpha \cdot \left(\frac{d_0}{d}\right) \quad (5.5)$$

With

$$\alpha = 2 - \delta/40$$

Flexural beam test EN 14488-3

This test was performed in 21 specimens (seven beams for each fibre content). For the nominal content of 12 kg/m³, one beam was lost due to a failure outside the central third. The test was carried out in an INTERMETRIC IM750SRV universal testing machine with a closed-loop system. Detailed information of the test configuration is given in EN 14488-3. The vertical displacement was measured by two LVDTs placed in the central part at the top of each side of the beam, to prevent extraneous deformations and minimize the variation in results (see Figure 5.5).

The flexural strength (f_{Rim}) is obtained by Equation 5.6 and the crack-opening displacement (COD) at the base of the beam was determined by Equation 5.7 from Carmona; Molins (2019), where P_δ is the load related to several vertical displacements δ , L is the test span (450 mm), b is the beam width, d is the height of the beam and e is the crack eccentricity of the tested beam with respect to the mid-span.



Figure 5.5 – Flexural beam test EN 14488-3. Source: Cáceres; Cavalaro; Figueiredo (2023).

$$f_{Rim} = \frac{P_\delta \cdot L}{b \cdot d^2} \quad (5.6)$$

$$COD = \frac{4 \cdot \delta \cdot d}{(L - 2 \cdot e)} \quad (5.7)$$

Double punch test (DPT)

The DPT was carried out on 48 cylinders $\varnothing 100 \text{ mm} \times 100 \text{ mm}$ (16 cylinders for each nominal content), using a 200 tf Shimadzu universal testing machine in open-loop system (see Figure 5.6). Test setup information is available in UNE 83515 (AENOR, 2010). The residual strength is calculated by Equation 5.8 from Saludes (2006), where $f_{R,\delta p}$ is the residual strength for a vertical displacement δ_p , $P_{\delta p}$ is the residual load for a vertical displacement δ_p , a is the diameter of the steel disc and H is the height of the cylinder specimen. The energy absorbed is the area under the load-displacement curve by Equation 5.4.

According to the DPT test configuration, the increase in the circumference of the cylinder must be measured by a circumference extensometer (TCOD – total circumferential opening displacement) at half the height of the cylinder. This extensometer poses a limitation, as it is an expensive equipment and is not very common in most technological control laboratories (MONTE; TOALDO; FIGUEIREDO, 2014). Pujadas *et al.* (2013) proposed a simplified methodology that converts the vertical displacement of the testing machine into TCOD.

The vertical displacement of the testing machine (δ_p) is converted into TCOD according to Equations 5.9 and 5.10 from Pujadas *et al.* (2013). Where: n is the number of radial cracks formed in the test; a is the diameter of the steel disc; l is the length of the wedge formed under the steel discs; P is the load at the calculated point; P_{cr} and $\delta_{p,cr}$ are the load and vertical displacement at the maximum load point, respectively; $P_{R,0}$ and $\delta_{P,R,0}$ are the load and the vertical displacement at the starting point of the residual strength, respectively.



Figure 5.6 – DPT on cylinders $\varnothing 100 \text{ mm} \times 100 \text{ mm}$. Source: Cáceres; Cavalaro; Figueiredo (2023).

$$f_{R,\delta p} = \frac{4.P\delta p}{9.\pi.a.H} \quad (5.8)$$

$$TCOD = n.\frac{a.\delta_{p,R,0}}{2.l}.\sin\frac{\pi}{n}.\left(1 - \frac{P}{P_{cr}}\right), \quad \delta_{p,cr} < \delta_p < \delta_{p,R,0} \quad (5.9)$$

$$TCOD = n.\frac{a}{2.l}.\sin\frac{\pi}{n}.\left[\delta_p - \delta_{p,cr} + \delta_{p,R,0}.\left(1 - \frac{P_{R,0}}{P_{cr}}\right)\right], \quad \delta_p > \delta_{p,R,0} \quad (5.10)$$

Double-edge wedge splitting (DEWS) test

The DEWS test was performed on 18 prisms (6 prisms for each nominal content). The test was carried out in a 100 kN EMIC DL 10000 universal testing machine in an open loop-system, following the recommendations of Borges *et al.* (2019). The crack-opening displacement of the fracture plane was measured by two LVDTs positioned on the middle height of each face of the prism (see Figure 5.7). The average of the two measurements was the crack-opening w .

The load provided by the machine was converted into effective load acting on the prism P_{ef} using Equation 5.11, where P is the load applied by the test machine, μ is the friction coefficient between the cylindrical rollers and the steel plates and θ is the angle formed between the wedge surface and the notch centre line (45°). The tensile strength σ is obtained according to di Prisco; Ferrara; Lamperti (2013) by Equation 5.12, where P_{ef} is the effective load, b is the width of the cross-section of the prism and h_{lig} is the ligament between the ends of the two notches.



Figure 5.7 – DEWS test carried out in prisms specimens extracted from the round panel' segments. Source: Cáceres; Cavalaro; Figueiredo (2023).

$$P_{ef} = P.\frac{(\cos\theta - \mu.\sin\theta)}{(\sin\theta + \mu.\cos\theta)} \quad (5.11)$$

$$\sigma = \frac{P_{ef}}{b \cdot h_{lig}} \quad (5.12)$$

5.2.5 Energy absorption comparative analysis

The Australian Shotcrete Society (CONCRETE INSTITUTE OF AUSTRALIA, 2010) define typical toughness levels based on RPT at 40 mm of displacement. The energy requirements are 280 J for non-structural or low deformations, 360 J for moderate ground support and 450 J for high-levels ground support. The EN 14487-1 standard define typical toughness levels of FRSC based on the square panel test (SPT) EN 14488-5 at 25 mm of displacement. The energy class requirements are: 500 J (E 500), 700 J (E 700) and 1000 J (E 1000), according to the ground support conditions. Papworth (2002) defined equivalent energy absorption levels based on the correlation between the RPT and SPT obtained by Bernard (2002) ($SPT_{25\text{ mm}} = 2.5 \cdot RPT_{40\text{ mm}}$, in J). The corresponding energy requirements in RPT are: 200 J, 280 J and 400 J for each energy class, respectively.

The same methodology as Cáceres; Cavalaro; Figueiredo (2021) was used for the comparative analysis. This is based on the correlations of energy absorption results by fibre content of samples tested using the DPT and RPT. From these correlations, it is possible to find which energy level corresponds to each test for a specific fibre content. The corresponding DPT energy levels for the Australian Shotcrete Society and EN 14487-1 energy requirements were obtained considering confidence intervals. To verify the correspondence between the tests, the energy absorption results were divided by the fracture area of the specimens.

5.2.6 Constitutive models

The constitutive models for the numerical simulations in item 5.4 were obtained using the same methodology as Cáceres *et al.* (2021a). To obtain constitutive models for flexural beam test EN 14488-3, the equations considered in the *FIB* Model Code

for FRC were used. The average residual strength result for each nominal content in 0.5 mm ($f_{0.5\text{ mm}} = f_{R1}$) and 2.5 mm ($f_{2.5\text{ mm}} = f_{R3}$) were converted into tensile strengths, using Equations 5.13-5.14, where f_{FTS} and $f_{FT2.5}$ are the tensile strengths at 0 mm and 2.5 mm of crack-opening, respectively.

In agreement with Cáceres *et al.* (2021a), the conversion of the strength results of DPT into tensile strength follows the approach proposed by Blanco *et al.* (2014). DPT results from a small Ø100 mm × 100 mm cylinder, presented vertical increments $\Delta\delta_{Pi}$ of $\Delta\delta_{P1} = 0.01$ mm, $\Delta\delta_{P2} = 0.51$ mm and $\Delta\delta_{P3} = 2.59$ mm that correspond to $\Delta TCOD_{Pi}$ crack-opening increments of $\Delta TCOD_{P1} = 0.01$ mm, $\Delta TCOD_{P2} = 0.62$ mm and $\Delta TCOD_{P3} = 3.17$ mm, respectively. The tensile strength corresponding to peak load σ_1 and each crack-opening increment from peak load σ_{TCODPi} were obtained with Equations 5.15-5.16, where F_{Pmax} is the peak load, $F_{\Delta TCODi}$ is the load corresponding to the crack-opening increments $\Delta TCOD_{Pi}$, β is 25° , μ_K is the kinetic friction coefficient and A is the radial value of the cracked area. Equation 5.17 was used to calculate A , where d and H are respectively the diameter and height of the cylinder specimen, and a is the diameter of the load application disc. The peak strength for each nominal content was obtained using the average value, since this property depends on the concrete matrix. The residual tensile strengths at each crack-opening for each nominal content were determined by linear regression equations passing through the origin.

For the constitutive model of the DEWS test, the peak strength for each nominal content was obtained by the average value of experimental data. The residual tensile strengths at 0.01 mm and 3 mm crack width for each nominal content were obtained by linear regression equations passing through the origin. The DEWS test directly provides the FRC constitutive model (di PRISCO; FERRARA; LAMPERTI, 2013; BORGES *et al.*, 2019).

$$f_{FTS} = 0.45f_{R1} \quad (5.13)$$

$$f_{FT2.5} = 0.5f_{R3} - 0.2f_{R1} \quad (5.14)$$

$$\sigma_1 = \frac{F_{Pmax}}{2.\pi.A} \times \frac{\cos \beta - \mu_K.\sin \beta}{\sin \beta + \mu_K.\cos \beta} \quad (5.15)$$

$$\sigma_{\Delta TCODPi} = \frac{F_{\Delta TCODPi}}{2.\pi.A} \times \frac{\cos \beta - \mu_K.\sin \beta}{\sin \beta + \mu_K.\cos \beta} \quad (5.16)$$

$$A = \frac{d.H}{4} - \frac{a^2}{4.\tan \beta} \quad (5.17)$$

5.2.7 Numerical model

The numerical model developed by Salehian; Barros; Taheri (2014) was adopted to simulate the experimental load-displacement curves of the RPT ASTM C1550 from small-scale tests (DEWS and DPT). A general overview of the model is presented below. First, the numerical model that describes the compression behaviour of FRC is detailed, then the numerical model that simulates the tensile behaviour of FRC and finally the cinematic assumption to simulate the RPT results.

Compressive behaviour

The pre-peak compressive behaviour of FRC is characterized by the stress-strain law ($\sigma_{cc}-\varepsilon_{cc}$) (see Figure 5.8a), obtained from Equation 5.18, which is based on Equations 5.19-5.21. In these equations, $\varepsilon_{cc,p}$ is the strain corresponding to the compressive strength (f_{cc}), p is a parameter ranging between 0 and 1, W_f is the fibre weight percentage, $\varepsilon_{cc,p}^{PC}$ is the strain at the compressive strength of the plain concrete of same strength, $E_{c,sec}$ and E_c are the secant and Young's modulus of elasticity of concrete, respectively.

$$\sigma_{cc}(\varepsilon_{cc}) = f_{cc} \frac{\frac{\varepsilon_{cc}}{\varepsilon_{cc,p}}}{(1-p-q) + q\left(\frac{\varepsilon_{cc}}{\varepsilon_{cc,p}}\right) + p\left(\frac{\varepsilon_{cc}}{\varepsilon_{cc,p}}\right)^{\frac{1-q}{p}}} \quad (5.18)$$

With

$$q = 1 - p - \frac{E_{c,sec}}{E_c}, p + q \in]0,1[, \frac{1-q}{p} > 0 \quad (5.19)$$

$$\varepsilon_{cc,p} = \varepsilon_{cc,p}^{PC} + 0.0002W_f \quad (5.20)$$

$$p = 1.0 - 0.919 \exp(-0.394W_f) \quad (5.21)$$

In the post-peak stage, the compressive behaviour is simulated by the stress-effective strain ($\varepsilon_{cc,ef} = \varepsilon'_{cc} + u/L_h$) diagram in Figure 5.8b, where u is the concrete wedge sliding displacement in the compression zone of a bending element and L_h is an equal spacing for the flexural cracks formed along the beam. The concrete

compressive stress for the sliding displacement u in the post-peak stage is obtained in Equation 5.22, where ϕ_c is the concrete frictional angle.

$$\sigma_{cc}(u) = \frac{2}{\sin(2\phi_c)} \left(\frac{-30.142 \left(\frac{u}{\cos(\phi_c)} \right) \left(\frac{f_{cc}}{30} \right)^{0.91} + 0.497 f_{cc}}{1 - 51.623 \left(\frac{\sin(\phi_c)}{f_{cc}} \right) \left(\frac{u}{\cos^2(\phi_c)} \right) \left(\frac{f_{cc}}{30} \right)^{0.91}} \right) \quad (5.22)$$

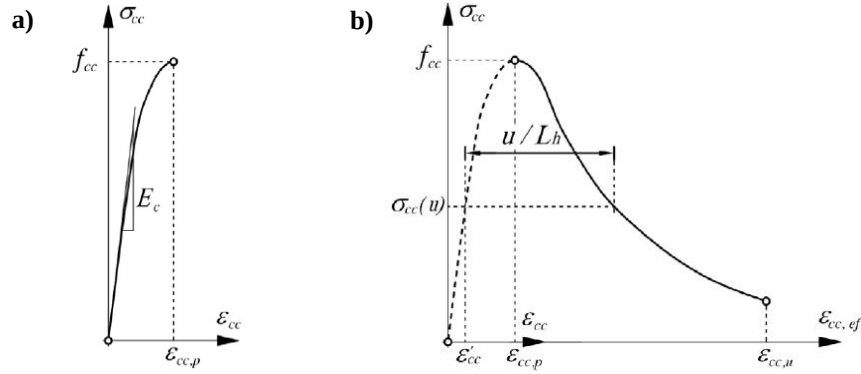


Figure 5.8 – Pre-peak stress-strain (a) and post-peak stress-deformation response compressive behaviour of FRC (b). Source: Salehian; Barros; Taheri. (2014).

Tensile behaviour

The pre-peak behaviour of FRC is simulated by a linear stress-strain response (σ_{ct} - ϵ_{ct}) (see Figure 5.9a) using Equation 5.23, where ϵ_{cr} is the strain at the crack initiation and f_{ct} is the tensile strength given by Equation 5.24 from the *FIB* Model Code. The post-cracking response is described by a σ - w diagram formed by multi-linear segments (see Figure 5.9b) determined in Equation 5.25, where $\alpha_m = \sigma_m/\sigma_0$ is the normalized stress parameter according to the constitutive model adopted corresponding to crack width w_m and w_u is the ultimate crack width.

$$\sigma_{ct}(\epsilon_{ct}) = E_c \epsilon_{ct} \quad (0 \leq \epsilon_{ct} \leq \epsilon_{cr}) \quad (5.23)$$

$$f_{ct} = 0.30 \cdot f_{ck}^{2/3} \quad (5.24)$$

$$\sigma_{ct}(w) = [\alpha_m + (\alpha_{m+1} - \alpha_m) \cdot \frac{w - w_m}{w_{m+1} - w_m}] \cdot f_{ct} \quad (5.25)$$

With

$$(w_m < w \leq w_{m+1})$$

$$[m = 0 \text{ to } 6, \alpha_0 = 1, w_0 = 0, \alpha_6 = 0, w_6 = w_u]$$

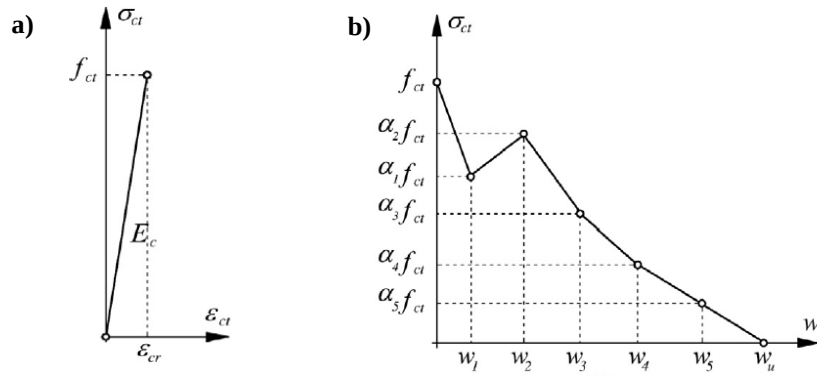


Figure 5.9 – Stress-strain pre-peak (a) and post-peak stress-crack width response tensile behaviour for FRC (b). Source: Salehian; Barros; Taheri (2014).

Cinematic assumption

In RPT, three radial cracks often propagate between the supports, dividing the panel into three segments. The imposed load causes a vertical deformation at the centre of the panels and a rotation of the intact segments around their connected dominant crack. The cross section of the panel is discretized in n layers (see Figure 5.10). For each rotation θ_i^k resulting from the imposed central displacement δ_i^k , the axial displacement of layer D_j is obtained by considering its position d_j and the depth of the neutral axis d_{NA} .

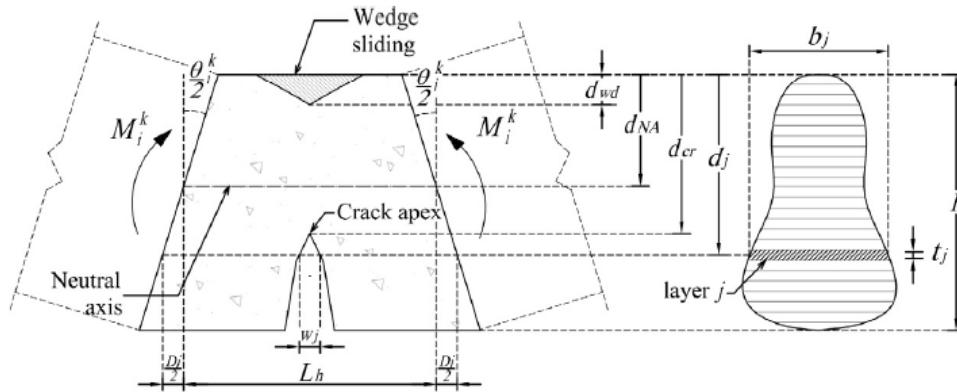


Figure 5.10 – Cracked FRC segment submitted to pure bending and layer approach to discretize the cross section. Source: Salehian; Barros; Taheri. (2014).

With those results, the effective strain in compression and the crack width in tension are determined. Then the compressive and tensile forces of the layer cross section are calculated using the numerical models described above for the compressive (Equations 5.18-5.22) and tensile (Equations 5.23-5.25) behaviour of the FRC. d_{NA} is obtained by satisfying the equilibrium of internal forces of the layer of the cross section (tensile stresses are balanced by compressive stresses). After the

equilibrium has been achieved, the bending moment M_i^k of the unit width of the panel corresponding to θ_i^k is determined. By applying the principle of the virtual work, the load P_c^k corresponding to the central point displacement δ_i^k of the panel is derived. Consult Salehian; Barros; Taheri (2014) for a more detailed description of the cinematic equations and the algorithm used to model the RPT.

5.3 Results and analysis

5.3.1 Effective fibre content

Table 5.2 summarizes the effective fibre content in specimens used for specific tests. The results include the mean values, standard deviation (SD), coefficient of variation (CV) and number of specimens per sample (N). Results indicate a variation between the nominal contents (15, 12 and 30 kg/m³) and the real fibre contents incorporated in the specimens after the spraying process. The CV in the cylinders was higher than those obtained in prisms. This variation could be explained by the larger number of samples and by the small size of the cylinders (approximately 70% of the volume of the prisms).

Table 5.2 - Fibre content (C_f) in kg/m³ by the inductive test and crushing method. Source: Cáceres; Cavalaro; Figueiredo (2023).

	C_f by the inductive test			C_f by crushing					
	DPT Ø100 × 100 mm			RPT ASTM C1550*			DEWS prisms		
	DPT_15	DPT_12	DPT_30	RPT_15	RPT_12	RPT_30	DEWS_15	DEWS_12	DEWS_30
Mean	15.9	12.4	27.5	14.4	12.0	26.8	14.8	11.9	26.4
SD	1.6	1.6	2.8	0.7	1.2	1.6	1.2	0.7	1.8
CV (%)	10.0	13.2	10.1	4.8	10.3	6.1	8.0	5.7	6.8
N	16	16	16	5	5	5	6	6	6

* The fibre content of the RPT was determined by crushing prisms cut from the remained circular segments.

Table 5.3 shows the fibre incorporation on each axis of the cylinders. The mean value of fibre contribution on axes C_x and C_y is 0.38 and 0.37, respectively. This reflects the tendency of fibres to align with the substrate plane during the spraying, which includes 75% of the fibre contribution ($C_x + C_y = 0.75$) as opposed to the 25%

contribution in the direction normal to that plane ($C_z = 0.25$). This finding is in line with those by Segura-Castillo *et al.* (2018), Galobardes *et al.* (2019) and Cáceres *et al.* (2021a) who found values of fibre contribution parallel to the substrate plane equal to 0.85, 0.80 and 0.76, respectively.

Table 5.3 - Fibre incorporation on each axis (C_x , C_y , C_z) by the inductive test. Source: Cáceres; Cavalaro; Figueiredo (2023).

DPT Ø100 mm × 100 mm									
	DPT_15			DPT_12			DPT_30		
	C_x	C_y	C_z	C_x	C_y	C_z	C_x	C_y	C_z
Mean	0.37	0.35	0.28	0.39	0.39	0.22	0.39	0.38	0.23
SD	0.02	0.02	0.01	0.02	0.02	0.02	0.04	0.04	0.02
CV (%)	4.8	5.0	4.2	5.3	5.6	7.6	10.2	9.2	8.8
N	16	16	16	16	16	16	16	16	16

5.3.2 Energy absorption results

Figures 5.11a and 5.11b show the load-displacement (P - δ) curves of the DPT and RPT, respectively. Figures 5.11c and 5.11d show the energy absorption-displacement (E - δ) curves of DPT and RPT, respectively. Table 5.4 summarizes the energy absorption of the RPT for a displacement of 40 mm E_{40} , according to ASTM C1550. Detailed panels thicknesses and diameter measurements, and the corrected energy value (E_c) at 40 mm are also reported in Table 5.4. Table 5.5 shows the energy absorption of the DPT for a displacement of 5 mm E_5 , following similar criteria to previous studies on FRSC by Silva (2017), Galobardes *et al.* (2019) and Cáceres; Cavalaro; Figueiredo (2021). The mean values, standard deviation (SD), coefficient of variation (CV) and number of specimens (N) are also provided in both tables.

The general cracking pattern on RPT had three radial cracks between pivot supports, as expected for this type of test (BERNARD; PIRCHER, 2001; SALEHIAN; BARROS; TAHERI, 2014). The typical number of cracks that appears on the DPT was three, which is in agreement with Pujadas (2013).

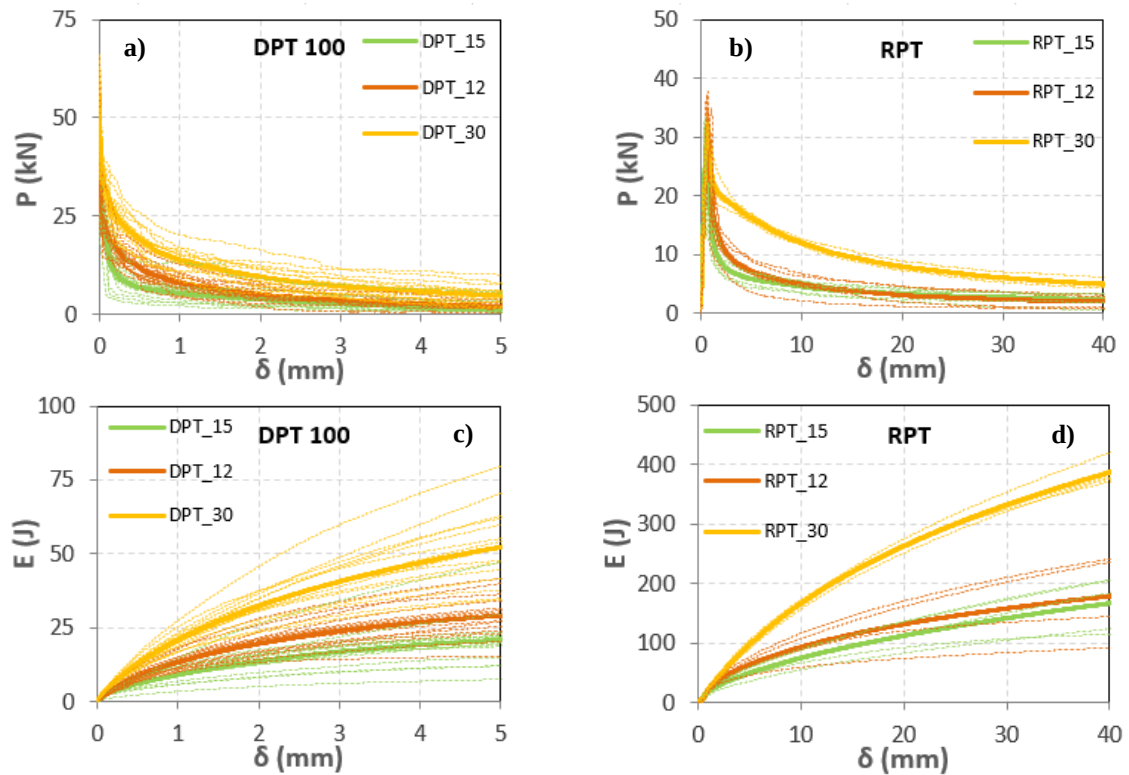


Figure 5.11 – Load-displacement (P - δ) curves by DPT Ø100 mm × 100 mm (a) and RPT ASTM C1550 (b). Energy absorption-displacement (E - δ) curves by the DPT Ø100 mm × 100 mm (c); and RPT ASTM C1550 (d). The average curves are shown in continuous lines. Source: Cáceres; Cavalaro; Figueiredo (2023).

Table 5.4 – Absorbed energy in 40 mm (E_{40}) in J for round panels according to ASTM C1550, panel thickness (t) and diameter (d) in mm, corrected absorbed energy (E_c) in J. Source: Cáceres; Cavalaro; Figueiredo (2023).

	RPT_15				RPT_12				RPT_30			
	E_{40}	t	d	E_c	E_{40}	t	d	E_c	E_{40}	t	d	E_c
Mean	166.5	83.8	778.2	139.3	178.6	85.7	780.2	141.9	386.3	82.0	779.2	334.5
SD	44.3	2.6	1.3	37.9	62.9	1.5	0.8	47.5	19.2	1.2	1.3	20.6
CV (%)	26.6	3.1	0.2	27.2	35.2	1.7	0.1	33.5	5.0	1.5	0.2	6.2
N	5	5	5	5	5	5	5	5	5	5	5	5

Table 5.5 – Absorbed energy in 5 mm (E_5) in J for cylinders of Ø100 × 100 mm based on DPT. Source: Cáceres; Cavalaro; Figueiredo (2023).

DPT Ø100 mm × 100 mm			
	DPT_15	DPT_12	DPT_30
Mean	20.8	29.1	52.3
SD	8.8	6.9	12.7
CV (%)	42.2	23.7	24.2
N	16	16	16

In both tests, the specimens with nominal content of 12 kg/m^3 showed higher energy absorption results than those of 15 kg/m^3 . This may be explained by the more favourable fibre orientation in relation to the cracked plane that occurred in specimens with nominal contents of 12 kg/m^3 . A larger number of fibres perpendicular to the fractured surface enhance the post-cracking strength of FRC (BENTUR; MINDESS, 2007). Notice that specimens with nominal content of 12 kg/m^3 have a higher number of fibres oriented in the plane parallel to the spraying surface (0.78) than those of 15 kg/m^3 (0.72) (see Table 5.3).

The results from the RPT show smaller coefficient of variation (mean $CV = 22\%$) than the equivalent results from the DPT (mean $CV = 30\%$) for the same nominal contents. This could be associated to the small size and total cracked surface of the DPT cylindrical specimens. Note that the CV should decrease with the increase in the fracture surface (MINELLI; PLIZZARI, 2011; CAVALARO; AGUADO, 2015; CARMONA; MOLINS; AGUADO, 2018). The fracture surface of specimen of the RPT is six times greater than the cylinder used in the DPT, which gives it certain consistency and stability in results. A larger fracture surface would be equivalent to an increase in the sample size of smaller specimens, which would bring the results closer to an ideal mean and reduced dispersion (CAVALARO; AGUADO, 2015). Both DPT and RPT show higher CV on specimens with lower nominal contents due to the high post-peak instability and the proportionally higher influence of variations in the mechanical response if compared with mixes containing larger fibre contents. In RPT, this may be exacerbated by the variation in panels thicknesses.

Comparative analysis between the tests

The comparison of energy absorption results between the tests followed the description in item 5.2.5. Figure 5.12a shows the relationship between energy absorption and fibre content of samples tested by DPT and RPT. The correlation coefficients were higher for the RPT ($R^2 = 0.97$) than for the DPT ($R^2 = 0.92$), which may be attributed to the smaller fracture surface of the specimens in the DPT. Figure 5.12b shows the relationship between the energy normalized by the total theoretical cracking area (W/W_c) and the fibre content for DPT and RPT. The 2 tests present similar correlations when the normalized energy is considered. This indicates that both approaches show similar sensitivity to variations in fibre content. It also opens the

possibility to use either test for assessing the energy absorption used in the traditional tunnel design approaches.

Table 5.6 summarizes the RPT energy absorption levels in EN 14487-1 and Australian Shotcrete Society (AuSS), the average fibre content to achieve these energy levels and the corresponding energy level for the DPT calculated using linear regressions in Figure 5.12a (numbers between brackets represent the results calculated for a 90% confidence level indicated graphically by the dashed lines). Additional studies should be performed with different type and content of fibres to obtain correlations of energy absorption due to the significant impact of these parameters on the flexural performance of FRSC (AUSTIN; ROBINS, 1995; PAPWORTH, 2002; NGUYEN, 2003).

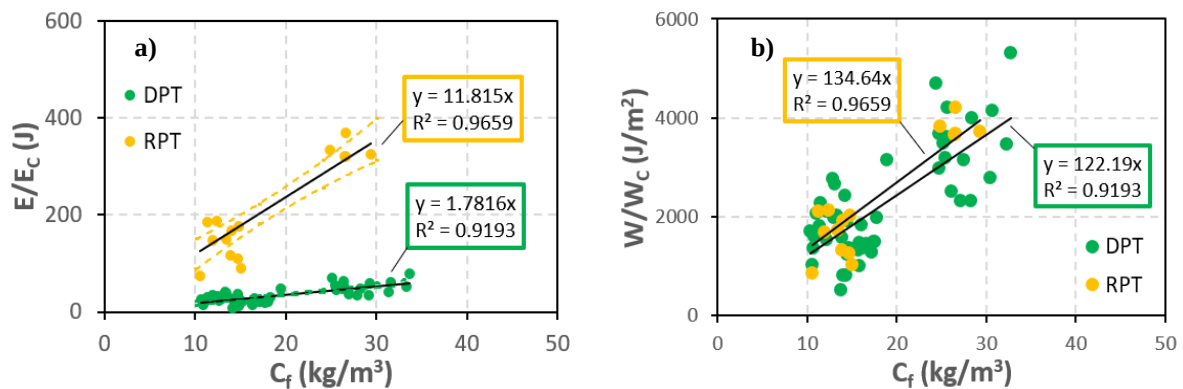


Figure 5.12 – Correlation between energy absorption results from the RPT ASTM C1550 and DPT Ø100 mm × 100 mm with fibre content (C_f), in J-kg/m³ (a); and J/m² – kg/m³ (b). Source: Cáceres; Cavalaro; Figueiredo (2023).

Table 5.6 – Corresponding energy absorptions of DPT and RPT ($E_{DPT,5\text{ mm}}$ and $E_{RPT,40\text{ mm}}$, in J) according to the energy levels of EN 14487-1 ($E_{SPT,25\text{ mm}}$ in J) and AuSS ($E_{RPT,40\text{ mm}}$ in J), and mean fibre content (C_f in kg/m³) to obtain these energy levels. Source: Cáceres; Cavalaro; Figueiredo (2023).

EN 14487-1				AuSS			
EN 14488-5	RPT	DPT	Fibre Content	AuSS	RPT	DPT	Fibre Content
E_{25}	E_{40}	E_5	C_f	Class	E_{40}	E_5	C_f
E 500	200 [± 21]	30 [± 3]	17	E 280	280 [± 28]	42 [± 3]	24
E 700	280 [± 28]	42 [± 3]	24	E 360	360 [± 45]	54 [± 4]	30
E 1000	400 [± 55]	60 [± 7]	34	E 450	450 [± 67]	68 [± 8]	38

5.3.3 Strength results

The load-displacement (P - δ) curves of the EN 14488-3 test and DPT in cylinders $\varnothing 100 \text{ mm} \times 100 \text{ mm}$, and the load-crack opening (P - w) curves of the DEWS test are shown in Figure 5.13. These curves were converted into stress-crack opening curves (f - COD , f - $TCOD$, σ - w) using Equations 5.6-5.12. The mean stress-crack opening curves are depicted in Figure 5.14. The mean values, standard deviation (SD), coefficient of variation (CV) and number of specimens per sample (N) are summarized in Table 5.7.

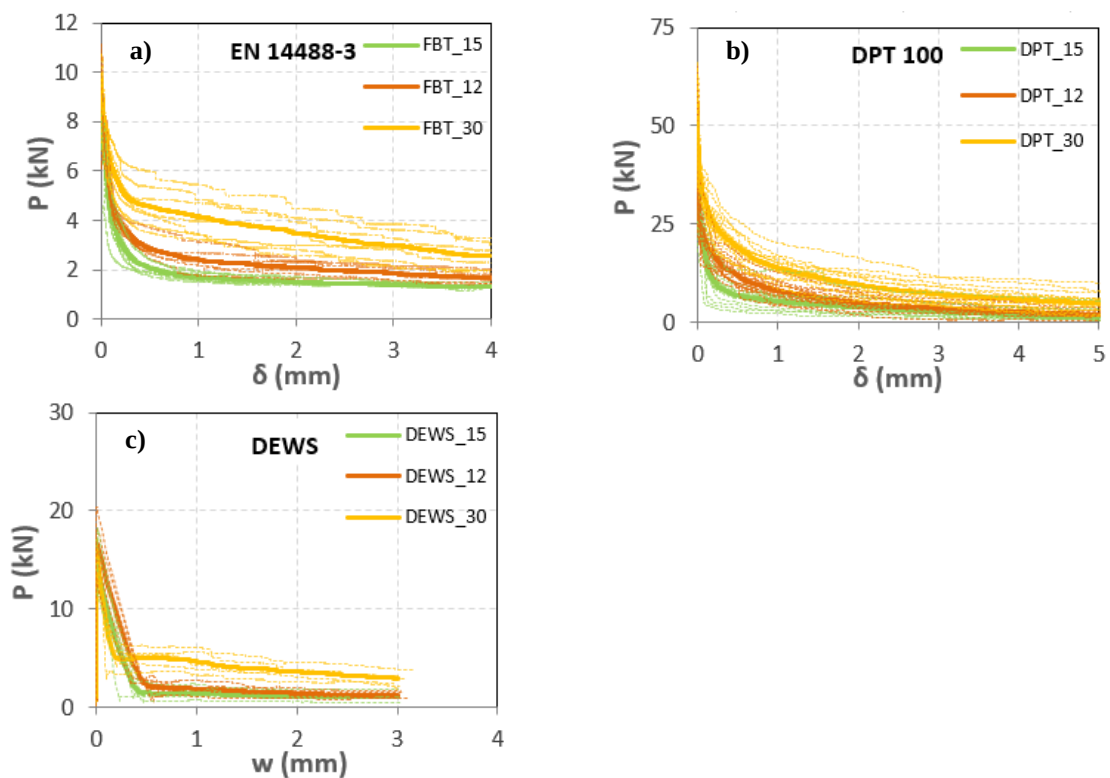


Figure 5.13 – P - δ curves by the flexural beam test EN 14488-3 (a); by the DPT $\varnothing 100 \text{ mm} \times 100 \text{ mm}$ (b); and load-crack opening (P - w) curves by the DEWS test (c). The mean curves are shown in continuous lines. Source: Cáceres; Cavalaro; Figueiredo (2023).

All curves show strain-softening behaviour (see Figures 5.13 and 5.14). This behaviour is expected for FRC in hyperstatic structures (MINELLI; PLIZZARI, 2011), such as tunnel linings (FIGUEIREDO, 2011; BERNARD; THOMAS, 2020; THOMAS; BERNARD, 2021). Considering the maximum strength results, the three tests present almost the same CVs with mean values of 9%, 11% and 14% for the EN 14488-3 test, DEWS test and DPT, respectively. Specimens with nominal content of 12 kg/m^3 show higher post-cracking strength results than those of 15 kg/m^3 . This could be due to the more favourable fibre orientation on the plane parallel to the sprayed surface in the former, as highlighted in item 5.3.2. The higher CVs are presented in the DPT (mean CV = 35%) and DEWS test (mean CV = 25%) due to the small fracture surface and due to the random orientation of fibres on this surface. This may be also associated with a higher intensity of post-peak instability in DPT (SIMÃO *et al.*, 2019) and DEWS test (BORGES *et al.*, 2019). This is a typical behaviour when there is a higher difference between maximum and residual strength. Besides the smaller fracture area, the EN 14488-3 test shows the lower CV (mean CV = 16%). This may be because the EN 14488-3 test was carried out in a closed-loop system machine, which led to a better control at the onset of cracking.

5.3.4 Constitutive model - new approach

The constitutive models for the EN 14488-3, DEWS and DPT tests were obtained as described in item 5.2.6. The tensile strength results at each crack-opening are shown in Table 5.8 and the derived post-cracking constitutive curves are shown in Figure 5.15. As in the study of Cáceres *et al.* (2021a), similar constitutive curves are obtained using the results of the 3 tests. The constitutive curves from the DPT remains generally between those obtained from the DEWS and the EN 14488-3 tests. In general, the constitutive curves from the EN 14488-3 tests present the highest residual strength. The results are consistent with the findings of Martinelli *et al.* (2021), who observed higher tensile strength values for FRC three-point bending beam test EN 14651 compared with DPT and DEWS test also using a higher aspect-ratio fibre ($\lambda = 60$).

Table 5.8 – Tensile strength results in MPa for flexural beam test EN 14488-3, DEWS test and DPT.
Source: Cáceres; Cavalaro; Figueiredo (2023).

EN 14488-3 - σ_{COD} (MPa)				
COD (mm)	σ	12 kg/m ³	15 kg/m ³	30 kg/m ³
0.00	F_{FTs}	0.5	0.7	1.3
2.50	$F_{\text{FT2.5}}$	0.2	0.2	0.4
DEWS – σ_{COD} (MPa)				
COD (mm)	σ_m	12 kg/m ³	15 kg/m ³	30 kg/m ³
0.00	σ_0	1.8	1.9	1.8
0.01	σ_1	0.3	0.3	0.7
3.00	σ_3	0.1	0.2	0.4
DPT - $\sigma_{\Delta\text{TCODPi}}$ (MPa)				
ΔTCODPi (mm)	σ_m	12 kg/m ³	15 kg/m ³	30 kg/m ³
0.00	σ_0	1.6	1.6	1.8
0.01	σ_1	0.6	0.8	1.6
0.62	σ_2	0.3	0.3	0.6
3.17	σ_3	0.1	0.1	0.3

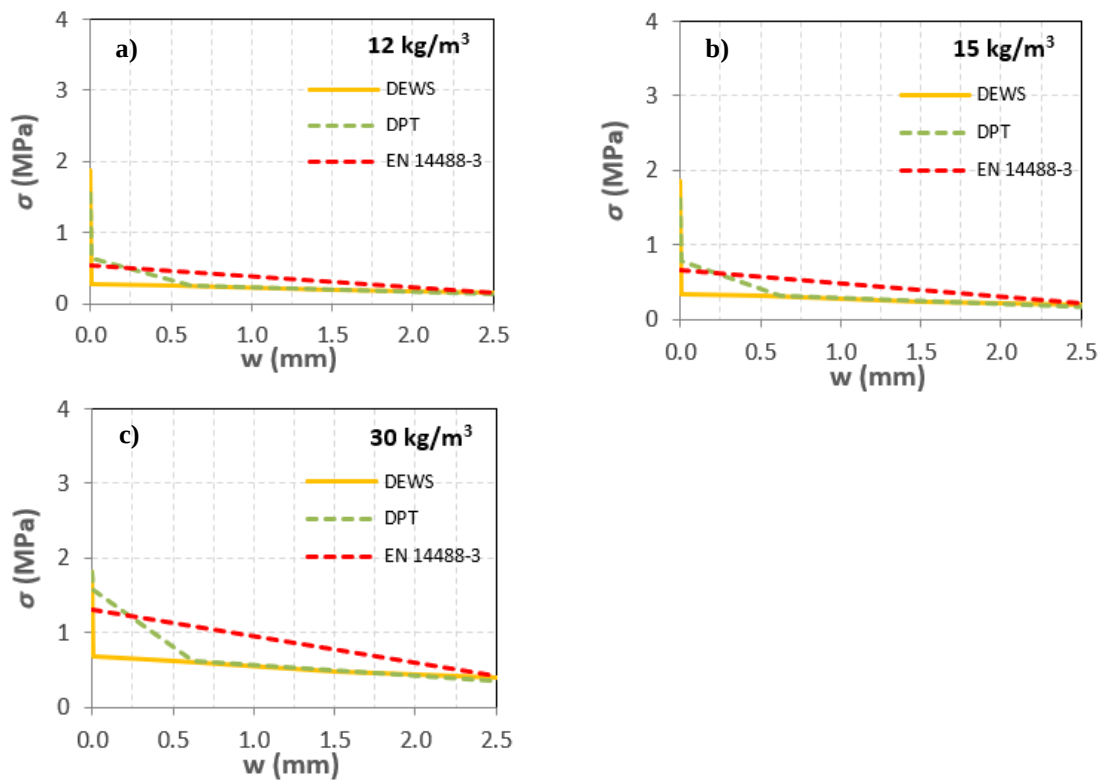


Figure 5.15 – Tensile strength results by crack opening (σ - w) determined by DEWS test, DPT Ø100 mm $\times$ 100 mm and flexural beam test EN 14488-3 for fibre contents of 12 kg/m³ (a), 15 kg/m³ (b) and 30 kg/m³ (c). Source: Cáceres; Cavalaro; Figueiredo (2023).

5.4 RPT numerical simulation

5.4.1 Numerical simulation

The RPT P - δ analytical curves were obtained using the numerical model proposed by Salehian; Barros; Taheri (2014) as explained in item 5.2.7. Tables 5.9 and 5.10 summarize the parameters obtained experimentally for the compressive and tensile behaviours of the FRSC, respectively.

Table 5.9 – Materials properties of FRSC used to simulate the compressive behaviour. Source: Cáceres; Cavalaro; Figueiredo (2023).

Materials properties of FRSC			
C_f (kg/m ³)	12	15	30
f_{cc} (MPa)	39.6	36.4	31.3
E_c (GPa)	28.6	27.8	26.7

* E_c was obtained using the semi-analytical formulation for sprayed concrete proposed by Galobardes *et al.* (2014).

Table 5.10 – Parameters defining the σ - w diagram obtained from constitutive models of DPT and DEWS test. Source: Cáceres; Cavalaro; Figueiredo (2023).

DPT (12 kg/m ³)				DEWS (12 kg/m ³)			
w (mm)	σ (MPa)	$\alpha_m = \sigma_m/\sigma_0$	$\sigma_{converted}$ (MPa)	w (mm)	σ (MPa)	$\alpha_m = \sigma_m/\sigma_0$	$\sigma_{converted}$ (MPa)
$w_0 = 0.00$	$\sigma_0 = 1.6$	$\alpha_0 = 1.0$	$\alpha_0.f_{ct} = 2.9$	$w_0 = 0.00$	$\sigma_0 = 1.9$	$\alpha_0 = 1.0$	$\alpha_0.f_{ct} = 2.9$
$w_1 = 0.01$	$\sigma_1 = 0.6$	$\alpha_1 = 0.4$	$\alpha_1.f_{ct} = 1.2$	$w_1 = 0.01$	$\sigma_1 = 0.3$	$\alpha_1 = 0.1$	$\alpha_1.f_{ct} = 0.4$
$w_2 = 0.62$	$\sigma_2 = 0.3$	$\alpha_2 = 0.2$	$\alpha_2.f_{ct} = 0.5$	$w_2 = 3.00$	$\sigma_2 = 0.1$	$\alpha_2 = 0.1$	$\alpha_2.f_{ct} = 0.2$
$w_3 = 3.17$	$\sigma_3 = 0.1$	$\alpha_3 = 0.1$	$\alpha_3.f_{ct} = 0.2$				
DPT (15 kg/m ³)				DEWS (15 kg/m ³)			
w (mm)	σ (MPa)	$\alpha_m = \sigma_m/\sigma_0$	$\sigma_{converted}$ (MPa)	w (mm)	σ (MPa)	$\alpha_m = \sigma_m/\sigma_0$	$\sigma_{converted}$ (MPa)
$w_0 = 0.00$	$\sigma_0 = 1.6$	$\alpha_0 = 1.0$	$\alpha_0.f_{ct} = 2.9$	$w_0 = 0.00$	$\sigma_0 = 1.9$	$\alpha_0 = 1.0$	$\alpha_0.f_{ct} = 2.9$
$w_1 = 0.01$	$\sigma_1 = 0.8$	$\alpha_1 = 0.5$	$\alpha_1.f_{ct} = 1.4$	$w_1 = 0.01$	$\sigma_1 = 0.3$	$\alpha_1 = 0.2$	$\alpha_1.f_{ct} = 0.5$
$w_2 = 0.62$	$\sigma_2 = 0.3$	$\alpha_2 = 0.2$	$\alpha_2.f_{ct} = 0.6$	$w_2 = 3.00$	$\sigma_2 = 0.2$	$\alpha_2 = 0.1$	$\alpha_2.f_{ct} = 0.3$
$w_3 = 3.17$	$\sigma_3 = 0.1$	$\alpha_3 = 0.1$	$\alpha_3.f_{ct} = 0.2$				
DPT (30 kg/m ³)				DEWS (30 kg/m ³)			
w (mm)	σ (MPa)	$\alpha_m = \sigma_m/\sigma_0$	$\sigma_{converted}$ (MPa)	w (mm)	σ (MPa)	$\alpha_m = \sigma_m/\sigma_0$	$\sigma_{converted}$ (MPa)
$w_0 = 0.00$	$\sigma_0 = 1.8$	$\alpha_0 = 1.0$	$\alpha_0.f_{ct} = 2.9$	$w_0 = 0.00$	$\sigma_0 = 1.8$	$\alpha_0 = 1.0$	$\alpha_0.f_{ct} = 2.9$
$w_1 = 0.01$	$\sigma_1 = 1.6$	$\alpha_1 = 0.9$	$\alpha_1.f_{ct} = 2.5$	$w_1 = 0.01$	$\sigma_1 = 0.7$	$\alpha_1 = 0.4$	$\alpha_1.f_{ct} = 1.1$
$w_2 = 0.62$	$\sigma_2 = 0.6$	$\alpha_2 = 0.3$	$\alpha_2.f_{ct} = 1.0$	$w_2 = 3.00$	$\sigma_2 = 0.4$	$\alpha_2 = 0.2$	$\alpha_2.f_{ct} = 0.6$
$w_3 = 3.17$	$\sigma_3 = 0.3$	$\alpha_3 = 0.1$	$\alpha_3.f_{ct} = 0.4$				

The RPT analytical P - δ curves for each nominal fibre content using the constitutive models of DPT and DEWS test are shown in dashed lines in Figure 5.16 and are compared with RPT experimental P_c - δ curves in continuous lines. A good approximation is observed between these curves.

The RPT_DPT analytical P - δ curves tend to be higher than the RPT_DEWS analytical P - δ curves for displacements up to 10 mm, while the experimental P_c - δ curves normally remain between them. A good agreement between the analytical P - δ and the experimental P_c - δ curves is observed for displacements between 10 and 20 mm. Both analytical P - δ curves tend to slightly underestimate the experimental P_c - δ curves for displacements above 20 mm. A similar behaviour was observed in the RPT FRC simulations by Salehian; Barros; Taheri (2014).

Figure 5.17 shows the comparison of the RPT analytical E - δ and experimental E_c - δ curves for each nominal fibre content. The RPT_DPT analytical E - δ curves are slightly above the RPT_DEWS analytical E - δ curves. For displacements up to 40 mm (region of interest for specification of the energy absorption in the RPT), both analytical E - δ curves are close to the mean experimental E_c - δ curve. A significant difference between experimental E_c - δ and analytical E - δ curves is observed for displacements greater than 25 mm in the mix with the highest fibre content. In this case, the numerical predictions would be on the safe side as the energy estimated would be smaller than the one measured with the RPT.

The significant difference in energy absorption between the experimental and analytical curves in 30 kg/m³ for displacements greater than 25 mm could be because the constitutive models of the small-scale tests only cover a maximum crack-opening of 2.5 mm, which makes it difficult to accurately simulate the energy in large displacements (e.g. 40 mm). For lower fibre contents (12 and 15 kg/m³), the reduced post-cracking strength capacity tends to approximate the behaviours at reduced levels of absorbed energy. For the content of 30 kg/m³, the higher level of absorbed energy amplifies the absolute differences observed between the experimental and analytical curves. Furthermore, small differences between the experimental and analytical P - δ curves have a cumulative effect that tends to increase the distance between the results from the simulations and the experimental curves.

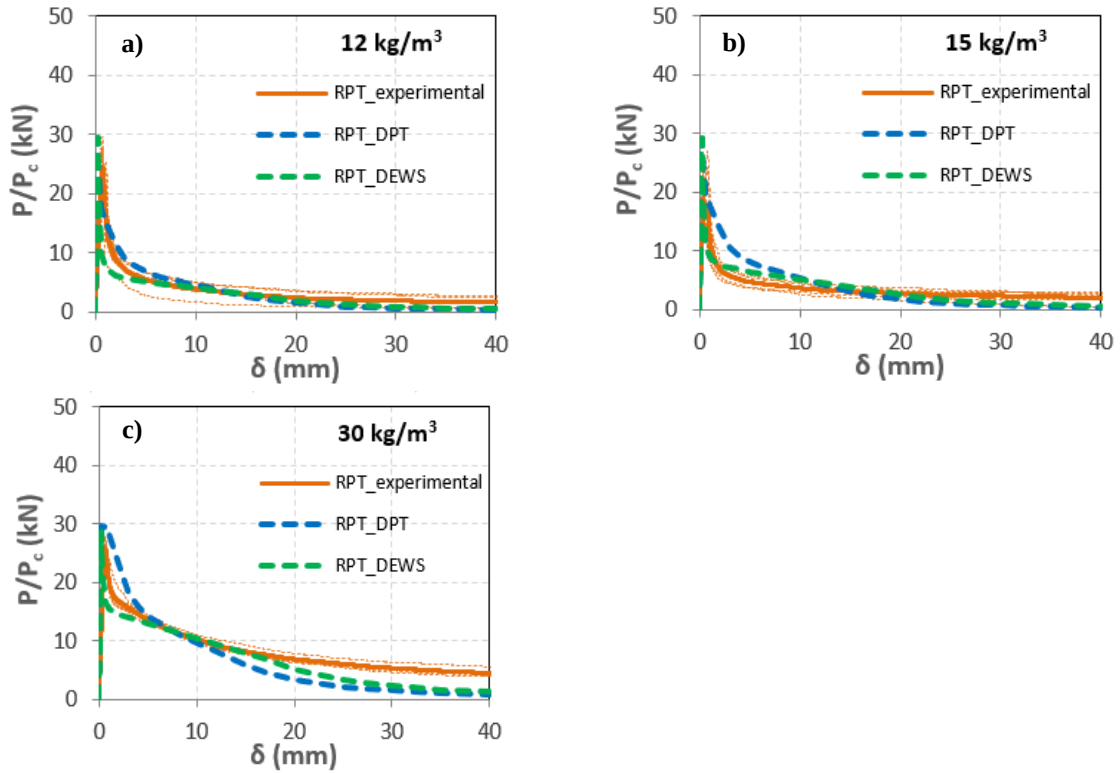


Figure 5.16 – Comparison between RPT experimental P_c - δ and analytical P - δ (assuming the constitutive models of the DPT and DEWS test) curves for nominal fibre contents of 12 kg/m³ (a), 15 kg/m³ (b) and 30 kg/m³ (c). Source: Cáceres; Cavalaro; Figueiredo (2023).

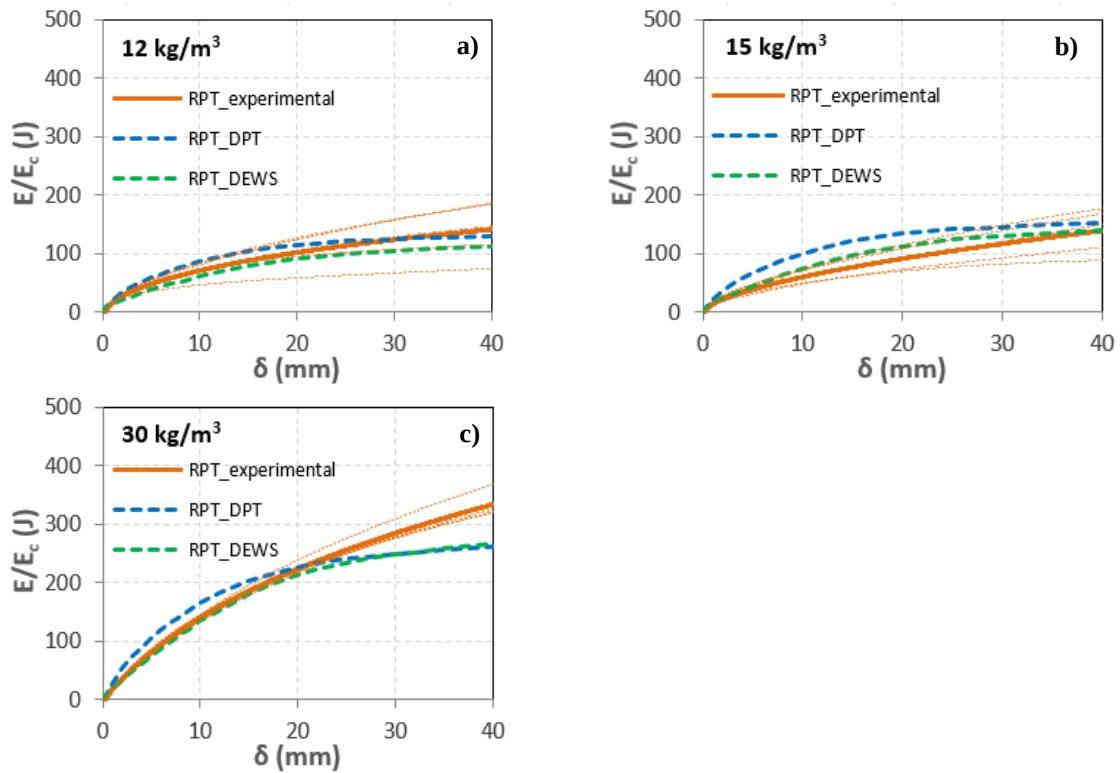


Figure 5.17 – Comparison between RPT experimental E_c - δ and analytical E - δ (assuming the constitutive models of the DPT and DEWS test) curves for nominal fibre contents of 12 kg/m³ (a), 15 kg/m³ (b) and 30 kg/m³ (c). Source: Cáceres; Cavalaro; Figueiredo (2023).

5.4.2 Validation of the constitutive models used for the numerical simulation

The constitutive models of the RPT experimental P_c - δ curves were contrasted with those adopted from the small-scale tests used for the numerical simulation. The constitutive models of the RPT were obtained by the inverse analysis procedure proposed by Nour *et al.* (2015) and by the equations to determine a simplified σ - w diagram proposed by Minelli; Plizzari (2015). The average results of the RPT experimental P_c - δ curves (see Figure 5.16) were used as input data. Figure 5.18 shows the comparison between the constitutive curves based on the inverse analysis of the RPT results and those derived from using the DEWS, DPT and EN 14488-3 tests.

The constitutive curves from the DPT and DEWS test results are close to those obtained from the inverse analysis of RPT results using the approaches described by Nour *et al.* (2015) and by Minelli; Plizzari (2015). These constitutive curves also match the post-cracking behaviour derived from the flexural bending beam test EN 14488-3 (shown in dashed red lines) according to the *FIB* Model Code.

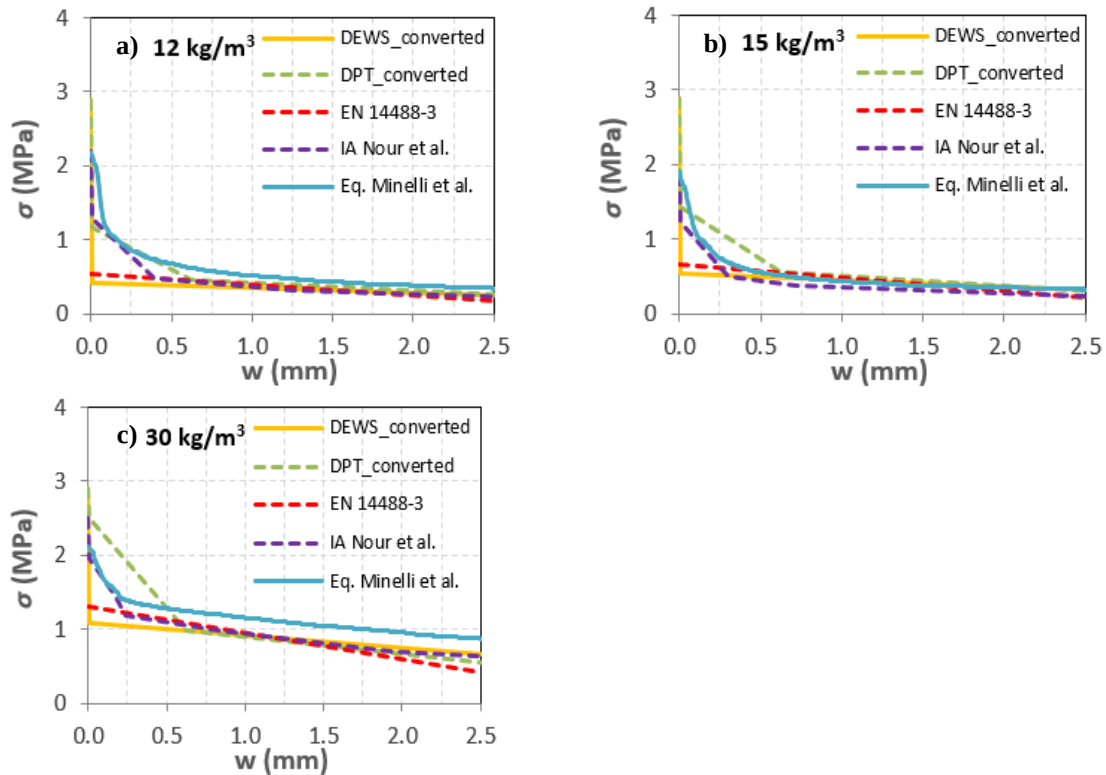


Figure 5.18 – Tensile strength results by crack opening (σ - w) of DEWS test and DPT constitutive models, of flexural beam test EN 14488-3 according to the *FIB* Model Code (2010), of round panel test ASTM C1550 by inverse analysis of Nour *et al.* (2015) and by the simplified stress-crack width law for FRC of Minelli; Plizzari (2015), for fibre contents of 12 kg/m³ (a), 15 kg/m³ (b) and 30 kg/m³ (c). Source: Cáceres; Cavalaro; Figueiredo (2023).

5.5 Conclusions and final remarks

This study demonstrated that the traditional control approaches of FRSC, using energy absorption, and the recent approach, based on the determination of constitutive models, are fully connectable. This allows for an enhancement to future FRSC specifications and quality control programs for tunnel lining. In addition, it was possible to reach the following specific conclusions:

- The study shows that two FRSC assessment approaches can be integrated by using small-scale tests. This facilitates the transition from the traditional approach, by means of tests of energy absorption in panels, to the new approach, based on obtaining constitutive models to have design parameters in accordance with current international tendencies and recommended practical prescriptions.
- RPT and DPT show good correlation of results when energy absorption values are divided by the fractured area of each test specimens. Higher CV of energy absorption values is presented in both tests for lower fibre contents due to the high post-peak instability. The largest CV of both tests for lower fibre contents is disadvantageous for obtaining representative results. However, what really needs to be known is the effective structural parameters of the FRSC in the tunnel structure, including their level of dispersion. It is thus important to have instruments (such as tests on extracted cores) to guarantee the final quality of the structure.
- Numerical and experimental investigations confirm that small-scale tests (DPT and DEWS) can guarantee good predictability of results of the structural behaviour of RPT by means of constitutive models. One of the main innovations is to make it possible to control the real FRSC incorporated into the tunnel lining from extracted cores in regular quality control programs and for verifying existing structures.
- The numerical model adopted from Salehian; Barros; Taheri (2014) satisfactorily reproduces the complete structural performance of RPT

(experimental curves), based on small-scale tests (DPT and DEWS) constitutive models. The input constitutive models were corroborated using the approaches proposed by Nour *et al.* (2015) and Minelli; Plizzari (2015), and by the post-cracking behaviour derived from the flexural bending beam test EN 14488-3 according to the *FIB* Model Code.

The study was parameterized using small fibre contents, which is one of the most critical conditions in the FRC technology (BENTUR; MINDESS, 2007). Consequently, any other fibre with a higher content will be in better conditions for FRSC evaluation. This demonstrates that the methodology is robust enough to evaluate a large spectrum of fibres.

Although the *FIB* Model Code does not contemplate the EN 14488-3 test, this test method already presented good proximity to this structural code to derive design parameters (CÁCERES; SANTOS; FIGUEIREDO, 2017). The EN 14651 test is more direct to approximate the sprayed concrete to the *FIB* Model Code in terms of specification, but it is much more laborious during the preparation of specimens and in test execution.

Despite the good results from this study, further analysis is necessary to establish the minimum ductility requirements for FRSC tunnel linings based on constitutive models obtained from small-scale tests. This will allow advancing towards a new condition for FRSC structural behaviour classification in line with current FRC parametrization trends for structural applications.

The experimental campaign comprised a study in a specific condition with limited, albeit significant, number of tests. It is necessary to develop follow-up studies of real tunnels construction, obtaining a large number of samples, to improve the confidence in the representativeness of the determinations and tolerances that should be established for quality control purposes.

6 CONCLUSIONS

6.1 General conclusion

This study demonstrates the viability of the alternative approach for the quality control and determination of design parameters of FRSC using small-scale tests (DPT, DEWS), without the need for traditional empirical design methods based on panel tests. The correlation between the small-scale tests and panel tests was also demonstrated, enabling the transition from the traditional to the new approach. Small-scale tests may be used in regular quality control programs or to verify tunnel lining structural conditions. Due to the small dimensions of the specimens and the simple nature of the characterization process, these tests can also be used to assess a significantly bigger number of points in the tunnel, enabling the control of the material effectively incorporated in the structures.

6.2 Specific conclusions

- The traditional tests used to determine the post-cracking behaviour of FRSC based on panels are complex. The square panel EN 14488-5 can weigh up to 110 kg and the round panel ASTM C1550 up to 91 kg, making production, handle, transport, and testing difficult. These tests require larger test machines, which are not common in most laboratories used for regular FRSC quality control. Flexural beam for the test EN 14488-3 needs to be cut from sprayed panels, involving a laborious and difficult cutting process. Beam tests also need high-spec testing machines provided with closed-loop system to reduce the scatter of results, which are also unavailable in most quality control laboratories.
- The small-scale tests (DPT, DEWS) specimens proposed in the study weigh up to 2 kg, are easy to handle, and require less complex equipment for testing, which enables better conditions for operators in the laboratory.

- The energy absorption level of traditional panel tests (EN 14488-5 and ASTM C1500) and DPT directly relate to the actual fibre content incorporated in the SFRSC. This can be used to evaluate the corresponding absorbed energy level according to empirical tunnel sizing methods based on the square panel test EN 14488-5 or round panel test ASTM C1550 from DPT energy absorption results. If the energy absorption of the traditional panel tests and DPT is divided by the corresponding fracture area, these tests show high correspondence of results.
- Panel tests (EN 14488-5, ASTM C1550) have small CV, which is associated with the larger fracture area in these specimens. Nevertheless, the square panel test EN 14488-5 shows increase of CV at higher fibre contents, due to the increment in number of cracks and degree of redundancy. Instead, the round panel test ASTM C1500 shows high CV at lower fibre contents due to the high post-peak instability. In these cases, it is necessary to assess a large number of panels to obtain representative results.
- Due to the smaller fracture area the small-scale tests (DPT, DEWS) show high CV, this is disadvantageous for obtaining representative results. Nonetheless, it is more important to assess the level of dispersion of the actual material incorporated in the structure. The lower CV of panel tests could inhibit mapping the structure, which is fundamental in control programs. In this respect, the extraction of cores from tunnel lining for DPT or DEWS test could guarantee the quality control of the actual structure.
- The residual strength results of the EN 14488-3 test show a good correlation with those of small-scale tests. It is possible to obtain constitutive models from both small-scale tests (DPT, DEWS) in conformity with new trends to obtain design parameters for FRSC according to *FIB* Model Code, as per the ITA guidelines (ITA, 2020).
- This approach aligns with the design philosophy of the *FIB* Model Code, which prioritizes constitutive models that can be used for numerical simulations, providing an orientation for structural uses. The numerical model adopted by Salehian; Barros; Taheri (2014) reproduce with high accuracy the post-cracking experimental curves of the round panel test ASTM C1550, based on small-scale tests (DPT, DEWS) constitutive models. Despite the higher CV, the small-scale

test results satisfactorily reproduced the round panel test ASTM C1550 post-cracking behaviour.

- The study presented a unique method that allows the integration of two FRSC assessment approaches using small-scale tests (DPT, DEWS). This includes the traditional approach by means of energy absorption round panel test ASTM C1550 used for empirical specifications of FRSC; and the new approach that comprehends obtaining design parameters for tunnel lining structures through constitutive models, according to current trends to transfer the *FIB* Model Code design philosophy from FRC to FRSC. Small-scale tests bring the possibility of integrating numerical models for predicting the tunnel lining structural behaviour (new approach) with the execution and material quality control process of FRSC (traditional approach) more easily.
- The study was parameterized using two types of steel fibre, smaller ($\lambda = 25$) and higher ($\lambda = 65$) aspect-ratios, showing that the methodology is robust enough to practically evaluate a large spectrum of fibres. The methodology adopted can be used in the future for other types of fibres for structural purposes, such as the polymeric macrofibres. However, the results obtained in the study cannot be extrapolated directly or used as starting parameters for other projects.
- The performance of different types of fibres varies enormously in FRSC (AUSTIN; ROBINS, 1995; PAPWORTH, 2002; NGUYEN, 2003). In this sense, it is possible to move towards new conditions for classifying the structural behaviour of FRSC, as with the conventional FRC. For example, the criteria for minimum ductility of the *FIB* Model Code can be adopted. According to the results, the constitutive models of the small-scale tests to meet these minimum ductility criteria ($f_{R1k}/f_{Lk} > 0.4$ and $f_{R3k}/f_{R1k} > 0.5$; where f_{Lk} is the peak strength, f_{R1k} and f_{R3k} are the residual strengths at crack-openings of 0.5 and 2.5 mm, respectively) are different for both steel fibres. The fibre with smaller aspect-ratio ($\lambda = 25$) demands fibre contents greater than 58 kg/m³ to achieve a residual strength greater than 0.76 MPa in 0.5 mm (f_{R1k}) and 0.38 MPa in 2.5 mm (f_{R3k}), considering a f_{Lk} equal to 2 MPa. For the fibre with a higher aspect-ratio ($\lambda = 65$), a fibre content greater than 33 kg/m³ is needed to reach a residual strength greater than 0.72 MPa in 0.5 mm (f_{R1k}) and 0.36 MPa in 2.5 mm (f_{R3k}).

6.3 Suggestions for future research

Despite the advances described, there are still topics for further research on the subject. Some of the primary ones are listed below.

- Develop a more exhaustive characterization of FRSC for tunnel linings through small-scale tests, with different concrete strength levels, greater variety and amount of fibres, spraying directions and techniques to extend the experimental data. Special attention should be given to polymeric macrofibres as they can present greater variation in results at lower contents when tested in machines with lower frame stiffness (MONTEIRO; SILVA, 2020). Small-scale tests can help in the development and validation of new design models in the future, underpinned by new techniques such as big data and artificial intelligence.
- Develop a case study, simulating a real tunnel lining structure. The experimental data could be obtained by mapping larger areas of the lining through small-scale tests. Analytical models can be obtained from observations of FRSC performance under service conditions.
- Use numerical modelling such as finite element methods to check the minimum ductility limits in FRSC tunnel lining structures, focusing on small-scale tests constitutive models and not on empirical methods of energy absorption tests. The minimum post-cracking behaviour level should be verified.
- The extraction of cores from an existing tunnel lining structure can also be used to study the durability of FRSC under different geological and environmental conditions, such as temperature, humidity, ground water chemistry, and freezing and thawing cycles. The long-term residual strength capacity of FRSC can be assessed using the DPT or DEWS test.
- This new approach based on small-scale tests can also be used to evaluate the performance of the lining after extreme events, such as a fire, significant dynamic loads, abrasion, or cavitation.

7 REFERENCES

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