

Evaluation of fibre-reinforced concrete fracture energy through tests on notched round determinate panels with different diameters



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HIGHLIGHTS

- Fibre reinforced concrete was used instead of fibre reinforced shotcrete.
- Round determinate panels were pre-notched along three equally spaced radial directions.
- Besides central load and deflection, also the crack mouth opening displacement was measured.
- Experimental tests on panels of different diameters but same thickness gave size-independent results.
- Agreement between experimental and analytical results validated method to obtain material properties.

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ABSTRACT

The Round Determinate Panel (RDP) test has proven to be a reliable method for designing the fibre dosage of shotcrete used in rockbolting operations of underground mining sites. It remains, however, a method that measures the structural performance of the panel but that does not give any intrinsic property of the material itself. Furthermore, this experimental procedure requires the use of large, heavy panels that could generate safety risks. The feasibility of smaller panel sizes is investigated in this study, as well as the potential for deriving a procedure that would estimate the specific fracture energy of the material. It is based on simple kinematic assumptions and its reliability has been verified by using more complex numerical tools. This research could lead to the revision of the methods currently used to design sprayed fibre-reinforced concrete for tunnel linings.

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1. Introduction

The use of fibre reinforced concrete (FRC) in ground support engineering operations has become more and more common in recent years. In particular, the use of fibre reinforced shotcrete (FRS) [1–3], that is fibre reinforced concrete sprayed rather than poured, has shown its advantages in terms of safety and time efficiency management in the lining of new segments of tunnels in underground mining sites.

A standard procedure to calculate the appropriate fibre dosage is the use of the Barton's chart [4–7]. This is an empirical method that correlates the required toughness J of the fibre reinforced shotcrete with the spacing between anchoring bolts, the quality of rocks, and other geological parameters. The toughness of FRS gives a measurement of the ductility properties of the composite material induced by the presence of the fibres: in other words, it estimates the capacity to maintain the integrity of the ground

support in case large deformations due to cracks occur by absorbing the energy produced in the process [8]. Two main experimental procedures exist that allow the toughness J of FRS to be calculated. The first is the EFNARC panel test [9]: it consists of a square panel continuously supported along its edges and loaded at the centre (as shown in Fig. 1a). The second method is the Round Determinate Panel (RDP) test [10], consisting of a round specimen supported on 3 points and subject to a point load applied at the centre, as shown in Fig. 1b. The RDP test presents one major advantage when compared to the EFNARC test that is the configuration of the failure mechanism. In fact, the square panel is a statically indeterminate structure, and as such the crack pattern at failure (one example is shown in Fig. 1c) might substantially differ from test to test. On the other hand, the round panel is a statically determinate structure, whose failure mechanism is always characterised by the formation of three and only three cracked lines, as shown in Fig. 1d. This, together with the large dimension of the cracked area (3 cracks 400 mm long and 75 mm deep) provides a certain consistency and stability of the obtained experimental results (when compared, for instance, with the ASTM [11] or the EN-14651

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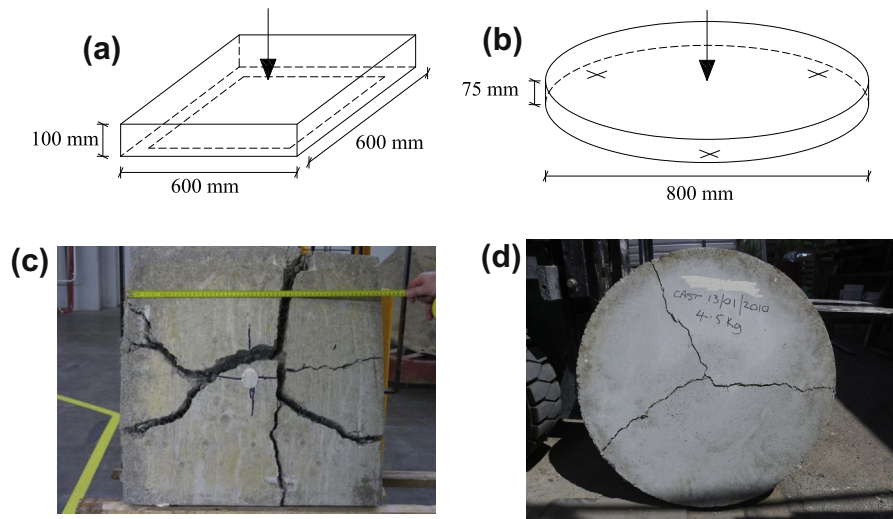


Fig. 1. In (a) scheme of the EFNARC [9] panel test and (c) possible crack pattern; in (b) scheme of the RDP test [10] and (d) typical crack pattern.

notched beam tests [12]), whose coefficient of variation is in general of the order of 10–12% [13,14]. Furthermore, the order of magnitude of the dispersion of the residual strength is similar to the one observed in actual structural elements while the dispersion observed on beam tests is in many cases fictitiously large, because of the small size of the fracture process zone, especially as far as steel fibres are concerned [15,16].

The large dimensions of the RDP, however, represent a strong limitation. Because of its weight, in fact, two people are always needed to move the panel and carry out the test. Furthermore, very stiff equipment is needed to perform the test. This type of rig cannot be transported to mining sites, so panels are usually sprayed and cured in the field and later transported to a laboratory (often many kilometres away from the mining site), where the testing equipment is located. During the journey, the samples are at risk of damage and hence altered results might be obtained. For these reasons other researchers have proposed to use panels with a smaller diameter [17].

One very interesting aspect of both the EFNARC and the RDP tests consists of the nature of the measured toughness J . As explained in more details in the following Sections, J is calculated as the area under the central load–central deflection curve. This is therefore a structural parameter rather than a material characteristic, and as such is dependent on the dimensions of the sample. The Barton's chart [7,18] and the modified Barton's chart [6] are strictly related respectively to ASTM beam test [11] and the RDP test [10]. Hence, any change of the testing procedure to obtain the toughness of the sample would require a proper recalibration of the chart. Furthermore, as previously mentioned, the Barton's chart is based on empirical observations and as such it does not have any sound and rigorously scientific foundation. More rigorous design methods are also used for the analysis of ground supporting structures (like for instance the Finite Element Analysis) that usually require the knowledge of material (and not structural) parameters.

This paper investigates the feasibility of a Notched RDP (NRDP) test to obtain material rather than structural properties. To this purpose, an experimental program conducted on panels of different diameters but equal thickness is presented in Section 2 while the mechanical approach used to interpret the experimental data is discussed in Section 3. The obtained results, shown in Section 4, suggest that there is no size effect when they are presented in terms of distributed moment vs. crack rotation angle. An analytical model is then described and used in Section 5 to identify the mechanical parameters that characterise the material fracture energy of the FRS. Finally, some conclusions are presented in Section 6.

2. Experimental program

The experimental program developed in this work aims to verify the possibility of measuring mechanical rather than structural parameters of fibre reinforced concrete (FRC) making use of simple lab tests. Although the goal of this research is oriented towards shotcrete applications, poured rather than sprayed fibre reinforced concrete was used in this work for logistic reasons of the laboratory where the experiments were carried out. Though it is quite understood that some differences exist between cast and shot concrete [19,20], since the purpose of the paper is to validate the experimental procedure and not to estimate the material properties as absolute entities, it is reasonable to state that the findings of this paper can be extended to shot fibre reinforced concrete.

The group of all tested samples consists of 9 round panels whose dimensions are reported in Table 1. In more details, three series of specimens were considered with diameters of 800, 600 and 500 mm and indicated here after as series S-800, S-600 and S-500, respectively. Each series comprises three samples. All samples have the standard panel thickness t of 75 mm. This is the nominal thickness as recommended by the ASTM C-1550 [11]. A further four cylindrical samples of 100 mm diameter and 200 mm height were cast to evaluate the compressive strength of the material.

The composition of the fibre reinforced concrete mix is presented in Table 2. A picture of the corrugated steel fibre used in present experiments is shown in Fig. 2a. The concrete showed a 28-days mean compressive strength $f_{cm} = 29.7$ MPa. All panels were cast from the same concrete batch and at the same time. Initially, all samples were left to cure in the formwork. Adequate curing was ensured by covering the specimens with heavy black plastic sheeting. After five days the mould was removed and the samples transferred to a controlled curing room at 21 °C and 98% relative humidity. The samples were left to cure until they reached their full 28-day strength prior to testing.

The theoretical models used to analyse the results obtained from the RDP test assume that the cracks occur exactly halfway between each support i.e. forming three equal circular sectors. However, this is not always the case. A cause of variance in the RDP test is the location of the cracks. To reduce this inconvenience but also for other reasons that will become clearer later, in the present investigation, all specimens were pre-notched as shown in Fig. 2b: three 15 mm deep steel channels with triangular cross-section were placed at 120° within the formwork so that all samples were cast with 3 existing radial indentations. In this way, the effective thickness h of the panels along the notch is equal to 60 mm only.

It is well known that in pre-mould notched samples, the distribution of the fibres in FRC might be altered due to the presence of the notch itself and hence the mechanical properties of the composite material might change [21,22]. For this reason, it is recommended to post-notch the cured sample using a saw. In the present work, however, this does not represent an issue because the strict characterization of the performances of the adopted fibres is beyond the purposes of the investigation; furthermore, since all samples were pre-notched using the same consistent procedure, it is reasonable to assume that a potential alteration of the material properties would have been uniform in all specimens and would have not affected the findings based on relative comparison. The adoption of post-notched samples is reasonably common amongst the current testing guidelines [12,23] and the use of a post-notched RDP should not represent an issue.

From each RDP test the following measurements were obtained:

- The centrally applied load P
- The central displacement δ

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