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# Application of BCN test for controlling fiber reinforced shotcrete in tunnelling works in Chile

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**Abstract.** In many tunnelling projects currently under construction in Chile, the quality of fiber reinforced shotcretes (FRS) is controlled by means of its energy absorption capacity determined by testing squared panel following the EFNARC recommendation. Nevertheless, this test requires large and heavy specimens, which have to be filled when concrete is sprayed into the tunnel and does not allow testing the concrete actually placed onto the support. Due to these difficulties, the quality of fiber reinforced shotcretes used in some projects has been controlled by means of the Barcelona (BCN) test, which is an indirect tension test, using cores drilled from the hardened tunnel support. To apply the BCN test, the dissipated energy measured by means of this test has been correlated with the energy absorption capacity of the fiber reinforced shotcretes using experimental data obtained from works. The aim of this paper is presenting this correlation and its application.

## 1. Introduction

In different tunnel construction projects in Chile, fiber reinforced shotcretes (FRS) used in the supports are controlled by their energy absorption capacity determined by means of the square panel tests according to EFNARC of 1996 [1]. However, this test requires large size and weight test specimens, which must be filled during the projection of the concrete into the tunnel. This often causes the panel to present defects or damages that disturb the results, increasing their scatter, with coefficients of variation (CoV) between specimens of the same sample greater than 20%.

In view of these difficulties, the use of the Barcelona (BCN) test [2],[3], has been proposed as an alternative for controlling fiber reinforced shotcrete, because this test is characterized for requiring a small specimen, with a large specific surface of cracking, which reduces the scatter of the results, and the specimens can be obtained by drilling cores from the hardened tunnel supports.

In order to use the Barcelona test in the control of the fiber reinforced shotcretes in the tunnel construction works of different projects, a correlation between the energy absorption capacity determined by EFNARC panels and energy dissipated in the BCN tests was developed. For that, at points where 14 samples of panels were filled point where panels were filled, were drilled 28 cores which were tested by BCN tests.

The aim of this paper is to present the results of this correlation and also its application to the quality control of the fiber reinforced shotcrete in the construction of tunnels in Chile.



## 2. Absorption energy capacity of fiber reinforced shotcrete

According to the project specifications, the energy absorption capacity of fiber reinforced shotcrete was determined by the square panel test, according to the EFNARC recommendation, establishing a minimum value of 1000 J.

In this test, a square panel of  $600 \times 600$  mm and 100 mm thick, supported on its four edges, is loaded at the center by a contact surface of  $100 \times 100$  mm, as can be seen in Figure 1. Following the EFNARC recommendations, the rough face of the specimen shall be on the bottom during the test and test is conducted under deformation control at a rate of midspan deflection of 1.5 mm/min.

The load – deformation curve shall be continuously recorded until a deflection of 25 mm is achieved at the center point of the panel. Using this response, the energy absorption capacity,  $E_{25}$ , can be calculated as:

$$E_{25}(\delta = 25) = \int_0^{25} P(\delta) d(\delta) \quad (1)$$

where  $P(\delta)$  is the load at deflection  $\delta = 25$  mm.

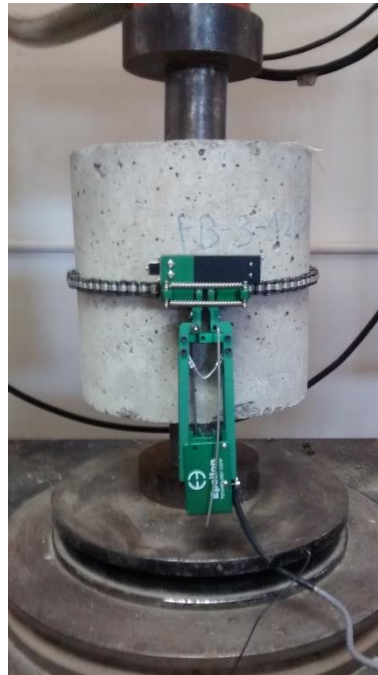


**Figure 1.** View of EFNARC panel test.

## 3. Energy dissipated in BCN test

The BCN test is an indirect tension test in which a cylindrical specimen of FRC is subjected to a double punching compression load by means of two cylindrical steel punches placed at the center of the upper and the lower faces, respectively, as shown in Figure 2. The cylinder has a diameter ( $d$ ) equal to its height ( $h$ ), and punches have a diameter ( $2a$ ) equal to 0.25 of the specimen diameter. During the test, the applied load,  $P$ , and the specimen Total Crack Opening Displacement ( $TCOD$ ), measured at half of its height; have to be recorded continuously, in order to obtain the  $P - TCOD$  curve.

During the test, the applied load produces a conical volume under triaxial compression stress beneath the punches, increasing the cylinder diameter and producing tensile stresses perpendicular to the radial lines of specimen. Due to this tensile stress with cylindrical symmetry, when the stress exceeds the tensile strength of concrete, cracks perpendicular to the field propagate through the specimen. This allows that the compression cone penetrates into the cylinder, as can be seen in Figure 3, increasing the specimen radius and producing two or more cracks. Then, the final state of the specimen present two aligned cracks or three cracks arranged approximately at  $120^\circ$  or, sometimes, four perpendicular cracks [4].



**Figure 2.** BCN test setup.

When the specimen cracks, the circumferential dilatation corresponds to the total cracks opening displacement (TCOD) and the energy dissipated can be calculated as:

$$E_{BCN,x} = \int_0^{Rx} P(Rx) d(Rx) \quad (2)$$

where  $E_{BCN,x}$  is the energy dissipated at a certain total circumferential deformation  $R_x$  value. According to the standard UNE 83515 [2], the energy has to be determined at 2.0 mm, 2.5 mm, 4.0 mm and 6.0 mm.

#### 4. Equivalence between $E_{BCN,6}$ and $E_{25}$

From an experimental research, in which three types of fiber reinforced concretes were tested, Carmona and Molins [5] proposed a correlation between dissipated energy at a circumferential deformation of 6.0 mm,  $E_{BCN,6}$ , and the energy absorbed by the panel at a center point deflection of 25 mm,  $E_{25}$ . These values were used taking into account that the panel test measures the energy absorption capacity at deflection of 25 mm, when cracks are widely open and the specimens exhibit a high degree of damage, allowing fibers to develop their full reinforcement capacity, these absorption energy will be compared with the energy dissipated in the BCN until a *TCOD* of 6 mm, which is the maximum deformation established in the standard.

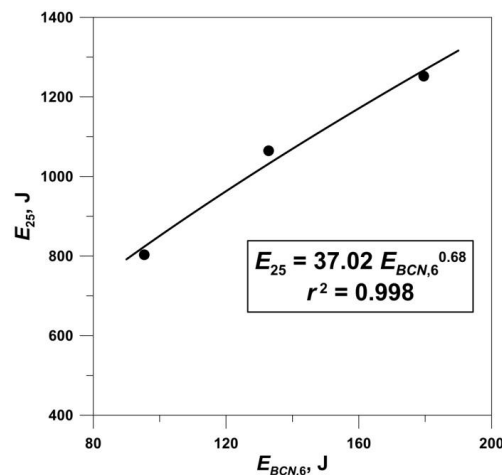
Using a nonlinear regression analysis, these author obtained an equation of the following form:

$$E_{25} = a \times (E_{BCN,6})^b \quad (3)$$

where  $a$ , and  $b$ , are experimental parameters which depend on the type and content of fibers in the concrete. In the research conducted by Carmona and Molins [5], detailed in Table 1, the value of the experimental parameters obtained were  $a = 37.02$  and  $b = 0.68$ , with a coefficient of determination  $r^2 = 0.998$ , and this fit is plotted in Figure 3.

**Table 1.** Summary of Carmona and Molins [5] research.

Material (kg/ m <sup>3</sup> )	Concrete		
	FRS – 4	FRS – 8	FRS – 12
Cement type IP	420		
Sand 0/10	1655		
Super plasticizer admixture	2.10		
Active admixtures	2.94		
Water	215		
Synthetic fiber content	4	8	12
Concrete Properties			
Compressive strength (MPa)	45	47	36
Volumetric substitution (%)	0.44	0.88	1.32
$E_{BCN,6}$ (J)	95.4 (9.4)	132.8 (11.8)	179.6 (12.1)
$E_{25}$ (J)	803.6 (11.7)	1064.9 (9.9)	1252.4 (10.7)

**Figure 3.** Correlation between energy dissipated and energy absorption capacity obtained by Carmona and Molins [5].

### 5. Development of an equivalence between both tests for FRS control at works

To replace the EFNARC panels by the BCN test in FRS control in the construction of mining tunnels in Chile, the following procedure was proposed to establish equivalence with the results of tests performed during the control at works:

- Identify 15 points where panels were sampled and whose intra-sample absorbed energy values have a CoV lower than 10%.
- Drill at least 2 cores of 150 mm diameter from the shotcrete of the tunnel support at each of the selected points.
- Obtain the dissipated energy at  $TCOD = 6.0$  mm of each core by mean of BCN test.
- Perform the statistical analysis and establish the correlation between the energy absorption capacity of the EFNARC square panel and the energy dissipated by the FRS in the BCN tests.

In this project, the concrete was reinforced with  $6 \text{ kg/m}^3$  of synthetic fibers. The fibers incorporated in the concrete were Barchip 54, with a length of 54 mm, a tensile strength of 640 MPa, a specific weight of  $9.1 \text{ kN/m}^3$  and a Young Modulus of 10 GPa.

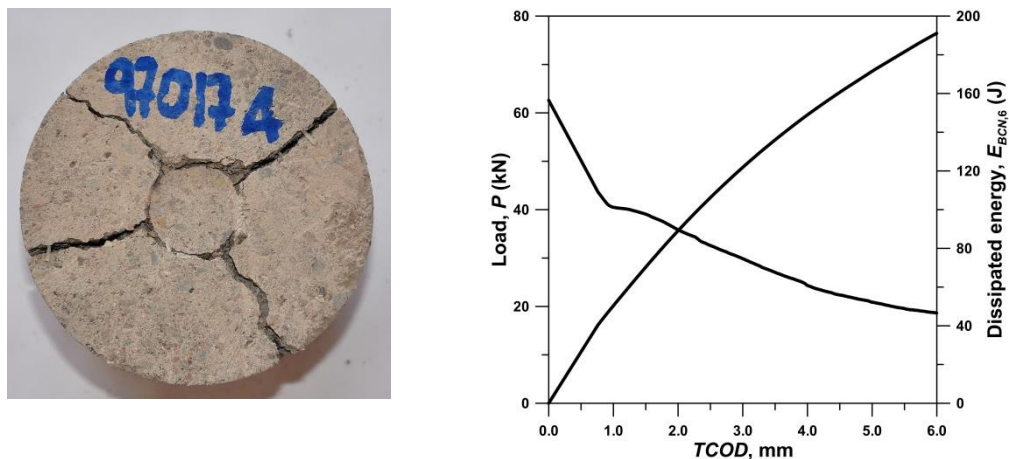
Following the proposed procedure, the 15 EFNARC panel sampling points given in Table 2 were selected, along with the values of the energy absorption capacity obtained during the control.

**Table 2.** Values of absorbed energy used in this research.

Sample	Panel 1	Panel 2	E (J)	CoV (%)
1	1005	967	986	2,7
2	1036	1025	1031	0,8
3	986	979	983	0,5
4	1009	998	1004	0,8
5	996	977	987	1,4
6	990	986	988	0,3
7	1023	910	967	8,3
8	1000	1001	1001	0,1
9	940	1004	972	4,7
10	1020	1004	1012	1,1
11	1025	1014	1020	0,8
12	948	931	940	1,3
13	978	1028	1003	3,5
14	970	953	962	1,3
15	986	1022	1004	2,5

At the same sampling points showed in Table 2, two cores of diameter  $d = 150 \text{ mm}$  and length  $h = 150 \text{ mm}$  were drilled for the BCN test. The tests were performed in a hydraulic system of 300 kN of capacity under displacement control, following the specifications and configuration given in standard UNE 83 515 (Figure 2). The circumferential deformation was measured at half of the height of the specimen with a circumferential extensometer with a total range of 12 mm. Data were recorded by Hewlett Packard model 7500 - XVI system.

The final state of the specimen can be seen in Figure 4, along with the typical experimental  $P - TCOD$  and  $TCOD - E_{BCN,6}$  curves. The results for each sample are given in Table 3.



**Figure 4.** State of specimens after BCN tests; (b) Typical curves obtained with BCN tests.

**Table 3.** Dissipated energy,  $E_{BCN,6}$ , obtained with BCN tests.

Sample	BCN-1 (J)	BCN-2 (J)	$E_{BCN,6}$ (J)	CoV (%)
1	218	237	228	5,9
<b>2</b>	<b>231</b>	<b>349</b>	<b>290</b>	<b>28,8</b>
3	292	258	275	8,7
4	305	305	305	0,0
<b>5</b>	<b>244</b>	<b>208</b>	<b>226</b>	<b>11,3</b>
<b>6</b>	<b>172</b>	<b>300</b>	<b>236</b>	<b>38,4</b>
<b>7</b>	<b>236</b>	<b>200</b>	<b>218</b>	<b>11,7</b>
8	230	220	225	3,1
9	191	219	205	9,7
10	287	295	291	1,9
<b>11</b>	<b>254</b>	<b>177</b>	<b>216</b>	<b>25,3</b>
12	322	311	317	2,5
13	276	292	284	4,0

As can be seen in Table 3, two samples (number X and Y) were discarded because they failed suddenly when cracking load was reach, due to low fiber content. On the other hand, the CoV of four samples, displayed in bold, are higher than 10% and, then, these results were also discarded.

With the aim of removing outliers from the data, both  $E_{BCN,6}$ , and  $E_{25}$  values were analysed using Grubbs and Dixon criteria using a statistical software. The results are shown in Table 4., It can be seen that sample from point 12, displayed in bold, ha to be discarded because the value of  $E_{25}$  was an outlier. Finally, only 8 values were used to obtain the correlation between  $E_{BCN,6}$ , and  $E_{25}$ .

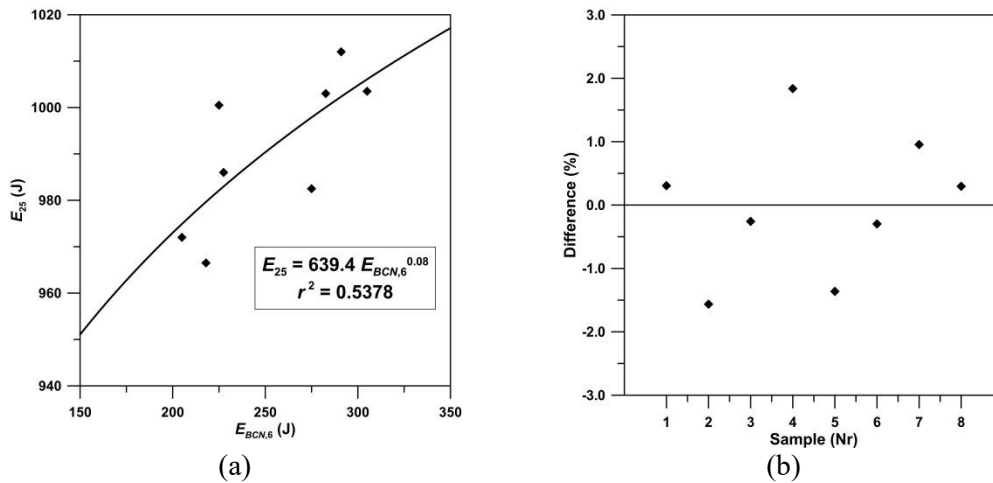
**Table 4.** Results of outliers analysis.

Sample Point N°	$E_{25}$ (J)	Criteria		$E_{BCN,6}$ (J)	Criteria	
		Grubbs	Dixon		Grubbs	Dixon
1	986	0,039	0,03889216	228	-0,7921524	-0,7921524
3	983	-0,114	-0,11424572	275	0,34170413	0,34170413
4	1004	0,805	0,80458155	305	1,05782404	1,05782404
8	1001	0,673	0,67332051	225	-0,85182906	-0,85182906
9	972	-0,574	-0,57365935	205	-1,32924233	-1,32924233
10	1012	1,176	1,17648783	291	0,72363475	0,72363475
<b>12</b>	<b>940</b>	<b>-1,974</b>	<b>-1,9737771</b>	317	1,34427201	1,34427201
13	1003	0,783	0,78270471	284	0,52471255	0,52471255

By means of statistical software, a nonlinear regression analysis was developed obtaining the following equation:

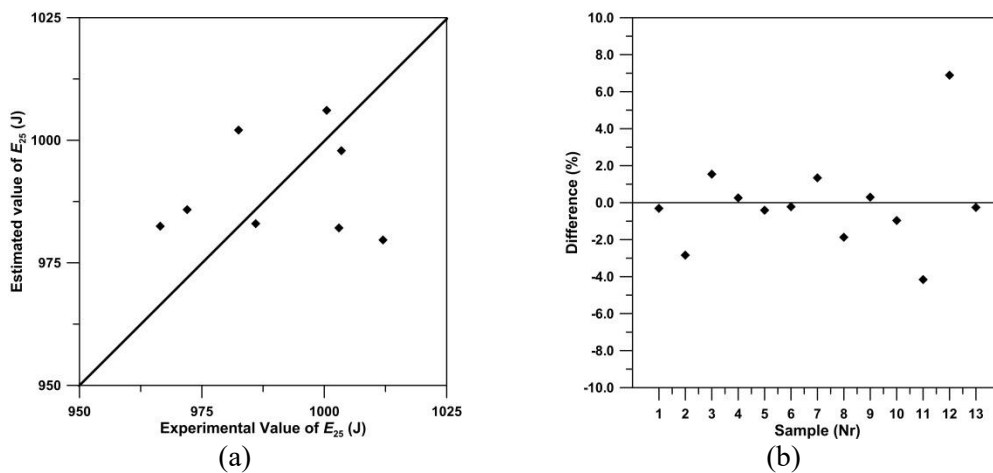
$$E_{25} = 639.4 \times (E_{BCN,6})^{0.08} \quad (4)$$

This correlation has a coefficient of determination  $r^2 = 0.5378$ . The experimental data and the equation (4) are plotted in Figure 5a, and the percent difference between experimental data and the estimated values are shown in Figure 5b, in which can be seen that the equation (4) has a good fit.



**Figure 5.** (a) Experimental values and equation (4); (b) Percent difference between experimental values of  $E_{25}$  and equation (4).

In order to prove the goodness of equation (4), the values of  $E_{25}$  were estimated using all the experimental data available in Table 3, achieving the result showed in Figure 6, where differences are lower than 5% for the most of the experimental data.



**Figure 6.** (a) Comparison between experimental values and equation (4) using all then available data; (b) Percent difference between experimental values of  $E_{25}$  and equation (4).



## 6. Conclusions

Taking in account that at laboratory level the BCN test has proved to be an adequate experimental procedure for systematic quality control of FRS at works due to its simplicity and low scatter, the results of this research allowed to to replace the EFNARC panel test in a mining tunnel work.

To apply the BCN test instead of EFNARC panel, a correlation based on the dissipated energy has been establish by using the values of energy absorption capacity determined during the ordinary control and the results of BCN tests conducted on cores drilled from the existing support in the tunnel.

The correlation proposed has differences lower than 5% for the most of experimental data available for this research and is now in use at work.

Additional refinements of this procedure will take into account the actual strength of concrete at the age of testing. Panel tests were developed at 28 days while the BCN test on the drilled cores were developed at 1000 days in average.

## Acknowledgements

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