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PUNCH TEST FOR THE ASSESSMENT OF FRACTURE ENERGY ON CONCRETE MIXED TO NATURAL PLANT FIBERS

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Ductility of a material that collapses because of the propagation of cracks depends on elastic properties of the material, on the fracture energy as well as on the structural dimensions. In this paper, we discuss the use of the punch tests for the assessment of both the tensile strength and the fracture energy of cylindrical concrete specimens with different volume content of natural fibers derived from a very common plant of Sicily (agave). For the validation of the experimental results a numerical simulation of the test was also carried out a FEA using models in which tensile strength and fracture energy value, obtained by punch test, are an input of the material so that the failure load P can be obtained. A good accordance between numerical and experimental data permits us to support the use of the Punch Test (PT) as a more attractive testing method for the evaluation of the mechanical proprieties of the materials. PT, in fact, is much simpler to perform than the split cylinder test method. Besides, the study shows the improvement of the post cracking behavior of concrete element reinforced by the use of natural and renewable fiber.

Keywords: Testing method, FEA, Post-cracking characterization, Double punch test, Natural fiber, Environmental.

1 INTRODUCTION

Tensile strength of concrete specimen can be obtained from direct such as direct pull on briquettes but indirect test such as the Brazilian test on cylinder or flexural test on beams are often preferred due to reduced scattering of the results, often above 20%, and for their simplicity in performing. The double punch tests (DPT) with the relationship proposed by Chen (1970) seems to be an alternative solution capable of giving back representative values (Chen 1980) of the residual tensile strength as well as of the post cracking mechanical properties such as the toughness and the fracture energy. Further analytical study better defined the relationship between the peak load applied and the tensile strength of the material tested, accounting of a nonlinear fracture mechanism approach (Mazars 1986, Bortolotti 1988). Literature shows some results about the use of punch test also for the mechanical characterization of Fiber Reinforced Concrete with a very small averaged coefficient of variation (Molins *et al.* 2009). Portland cement concrete is a brittle material with a very poor tensile resistance. So, in order to realize very ductile structures, an increasing of the fracture energy is required. This goal can be achieved with the addition of fibers in the concrete. In literature, several different types of fibers have been used to reinforce cement-based materials since the 20th century (Aitcin 2000, Anania *et al*. 2013). In this paper punch test is applied to concrete mixture obtained by the use of natural fibers derived from Agave plant capable of replacing mineral or synthetic fibers (i.e., glass, steel fibers) and also cheaper than those. The Agave fiber is obtained by processing the leaves of Sisal Plant, a plant of the Agavaceae family, native from Mexico, but also grown in all areas with dry climates, including the Mediterranean coast. The fracture energy is evaluated from uniaxial tensile tests or bending tests using displacement control. The uniaxial tensile test is the most appropriate, but the test stability requires a very stiff closed-loop servo-controlled testing system (Bazˇant 2002). Direct tensile tests are difficult to carry out, because of the fragile nature of the concrete, but if performed correctly, it can provide very important information. Up now there are no standard methods for direct tensile tests, so, different modes are proposed in literature (Pujadas *et al.* 2014).

2 PUNCH TEST DESCRIPTION

The tensile strength and toughness of fiber reinforced concrete can be determined by indirect tensile tests and bending tests. Unfortunately, these tests lack in simplicity, reliability, or reproducibility. Thus, we need an alternative test method capable of overcoming these lacks. This need can be satisfied by DPT. It was introduced by Chen (1970), then modified by Chen and Yuan (1980). It permits us to assess the tensile strength of plain concrete as an alternative solution to the Brazilian test, which was so far, the most common indirect tension test. The DPT layout consists in a concrete cylinder vertically placed and subjected to axial compression by means of two steel circular punches located concentrically on the bottom and top surfaces of the cylinder. From the combined approach between the theory of linear elasticity and of plasticity for concrete, a close-form formula to calculate the tensile strength was obtained. The theory, developed by Chen, is based on two assumptions. The first hypothesis is based on the idea that good local deformability of the concrete in both tension and compression, is such that the generalized theorems of limit analysis can be applied to concrete idealized as a linear elastic-perfectly plastic material. The second assumption is that the Mohr-Coulomb failure surface is modified in compression, and that a small shear stress is hypothesized as a yield surface for the concrete. The expression proposed by Chen and Yaun (1980) to calculate tensile strength is shown in Eq. (1).

$$f'_{t-Chen} = \frac{P}{\pi\,(1.20\;bH-a^2)} \tag{1}$$

In Eq. (1), P =Load Applied; f't = tensile strength; H = height of the specimen; b = radius of the specimen; a = radius of the punch; α = angle of the conical surface of rupture; φ = angle of internal friction. However, there are several other analytical approaches of the tensile strength in DPT given by different authors as Mortolotti, Molins Marti [5-7].

3 EXPERIMENTAL CAMPAIGN

3.1 The Samples

For the experimental purposes, no. 18 standard cylindrical samples specimens, with height (H) equal to the diameter (D), were performed. In the specific case, three different volume content of agave fibers, with tensile strength of 352.6 MPa and elastic modulus of 5.5 GPa, were considered: 6 specimens with 0%; 6 specimens with 4% and 6 specimens with 8% of agave fibers volume content. The volume considered was that of the concrete volume. Three specimens, of each mixture batch, were subjected to compression tests and the remaining three were used for testing of small punch. Each specimen was of cylinder shape 10 cm tall with a diameter of 10 cm. The punch diameter was equal to 2 cm. The adopted diameter of the punch (a) is a quarter of the diameter of the specimen (a/D = 1/4). The cement used is a Portland cement with limestone type II high initial resistance; a superplasticizer was added in order to avoid the risk of segregation of the mixture, which for the presence of the fibers are more likely to occur than to a simple concrete. The sands and gravels used in the various samples were extracted from the same quarry, and were maintained at the same conditions of temperature and humidity, so as to be able to present the same characteristics for all mixtures. Fibers had no data supplied by the manufacturer, therefore, a preliminary analysis, of their manual measurements have been carried out; the fiber length obtained varies from 35 mm to 40 mm. All cast specimens were stored at room temperature before de-molding, then they were cured in a water bath for 26 days.

3.2 Compressive Test

For each series of samples the uniaxial compressive strength was determined by compressive tests in the universal machine, according to the Italian standards. The average compressive strength is reported in Table 2. The data recorded demonstrates that the presence of the fibers determines also a slight increase of the ultimate load. These values were useful to define the maximum load to be applied on the sample during punch test.

Table 1. The concrete mixtures.

Component\Mix	Quantity	Unit
“cement”	2,1 10^{-3}	m^3
“water”	1.9	l
“sand”	10.3	kg
“Aggregate tot.”	8.8	kg
“sfluid”	3.7	cc
“fibers 0%”	0	gr
“fibers 4%”	46	gr
“fibers 8%”	92	gr

Table 2. Compressive load and strength.

Fiber content %	Averaged Compressive load [kN]	Cylindrical compressive strength [MPa]
0% fiber	141.7	14.4
4% Fiber	175.1	17.84
8% fiber	223.9	22.8

Figure 1. Averaged length of agave natural fibers.

Figure 2. Weight of agave fiber for samples 4% and 8%, in volume content, respectively.

3.3 Punch Tests

Once the compressive strength (f_{cm}) is determined, a prediction of the maximum punch load (P) can be numerically evaluated by referring both to the formula reported in the Italian rules and the Eq. (1). In fact, according to the Italian standard, once the cylindrical compressive strength is determined the tensile strength (f_t') can be assessed and, thus the maximum load. Each type of mixture 0%, 4%, 8%, was subjected to DTP. The test consists of loading the sample through two punches of 2 cm in diameter positioned axially. A loading system, is realized by two iron plates welded to the two punches, one upper and one lower. Two lodgings in plywood consisting of two concentric circles, one having the radius of the specimen and the other the radius of the punch both of them performed in order to have a perfect positioning of the punch in respect to the surface of the specimen (Figure 3). The specimen surface was troweled smooth so that roughness might not affect the experimental results. Each test, was carried out at displacement control, with the interface on the monitor of the terminal connected to the test machine. The displacement transducers were employed for the measurement of the displacement (Figure 4).

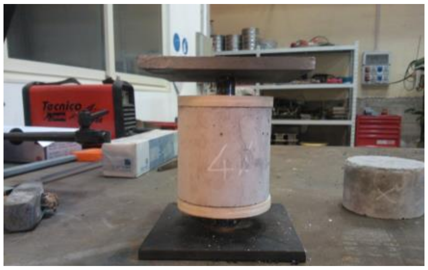

Figure 3. Punch loading system.

Figure 4. Punch test equipment.

Failure pattern is characterized by two or three radial main fractural planes (Figure 5) forming an angle of 120° approximately, although during the test we observed, a number of fracture planes ranges equal to two in the specific case of plain concrete. The compressive load transferred from the punches to the specimens gives back an almost uniform average tensile strength over all the diametric planes to be evaluated by Chen's formula reported in Eq. (1). The ideal failure mode for the DPT according to the Chen theory is a multi-radial crack, to ensure an accurate value of the averaged strength. Eq. (1) contains a coefficient k = 1.20, valid for all those cases where the circumferential opening angle (φ), varies between 0-30°.

So, the values of φ corresponding to the average of the load Pm and the f't found for each type of mixture, can be checked. To this aim, the equation 2 can be written by referring to the principle of virtual work, i.e., equaling the external work caused by the external force acting on the punch and the inner work that leads to the displacement of the failure surfaces.

Figure 5. Failure pattern of specimens depending on the fiber volume content 0%, 4%, and 8%.

Thus, the inverse of the previous equation is reported in equation 3 using data available: specimen size (a, H, b), the angle of the punch ($\alpha = 11.3°$), the failure load Pm (average value) and the resistance tensile f't. Finally, by applying the trigonometric formula of addition, the φ angle is obtained by Eq. (4); Table 3 summarized the data obtained. The ϕ angles are inside the gap 0-30° proposed by Chen's formula.

$$\frac{Q_m}{\pi a^2} = f_t^{'}\left[\frac{bH}{a^2}\tan(2\alpha+\varphi)-1\right] \qquad (2)$$

$$\tan(2\alpha+\varphi) = \frac{a^2}{bH} \qquad (3)$$

$$\varphi = \tan^{-1}\left[\frac{\frac{a^2}{bH}+\frac{Q_m}{\pi bHf_t'}-\tan 22.6}{1+\frac{a^2}{bH}\tan 22.6+\frac{Q_m}{\pi bHf_t'}\tan 22.6}\right] \qquad (4)$$

Table 3. The concrete mixtures.

Fiber volume content %	**Failure load P_m [N]**	**$f'_{t\text{-}Chen}$ [Mpa]**	**Φ [grad]**
0% fiber	19.45	*1.05*	27.7
4% fiber	29.13	*1.57*	28.7
8% fiber	33.2	*1.80*	27.4

From Figure 6, a decrease of the force after peak load can be observed with the increment of fiber content. In specimens reinforced with a larger fibers dosage, a hardening and more dissipative behavior can be noted because of a wider area under the curve. It was also observed that up to the peak values, both the matrix and the fibers contribute proportionally to the strength according to their volumetric percentages and their elastic modulus; after having reached the maximum value of stress, a post peak softening branch is shown which corresponds to that of the cementitious matrix. The strains are slightly lower than those that lead to the detachment of the matrix when this is without fibers, it intervenes with a dissipative mechanism of energy, that is the slipping of the progressive fibers. At this point we can say that the ductile behavior is achieved with a high value of fracture energy (Γf), severe enough to be appropriate for the size of the structure (Figure 7). The energy required to open a unit area of crack surface is defined as *fracture energy*. In Figure 7, the energy is plotted versus the maximum vertical displacement. We can say that, by adding fibers inside concrete, an increase in toughness, as well as of the specific fracture energy, can be recorded (Table 4).

Table 4. Specific fracture energy.

Fiber volume content %	**Failure Area A_c [mm^2]**	***Fracture Energy* Γ [J]**	**Specific Fract. En. [mJ/mm^2]**
0% fiber	10,000	1.3	0.13
4% fiber	13,500	2.2	0.146
8% fiber	13,500	2.5	0.166

In fact, in the case of cylindrical specimens the area of the failure surface and the specific fracture energy are given, respectively, by Eq. (5) and Eq. (6).

$$A_C = 3(HR-a^2/\tan(\alpha)) \qquad (5)$$

$$\beta = \Gamma/A_c \qquad (6)$$

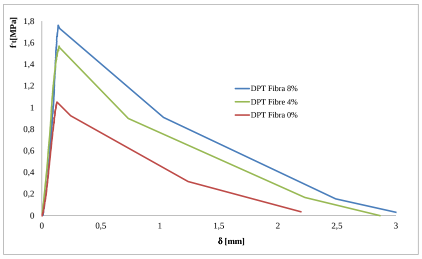

Figure 6. Chen Tensile strength vs displacement.

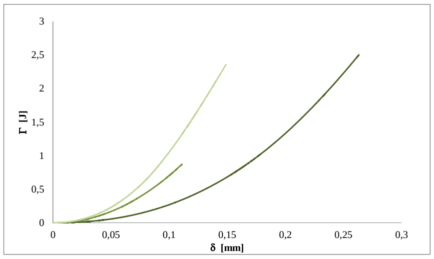

Figure 7. Fracture energy vs displacement.

4 CONCLUSIONS

Punch tests were aimed not only to the determination of the indirect tensile strength of the reinforced concrete but, also, to the evaluation of the gain in terms of fracture energy of the fiber reinforced concrete in respect to the plain one. The DPT, in fact, provides sufficient data to evaluate the performance of FRC thanks to its simplicity, reliability, and reproducibility. The simplicity of this test is primarily in the samples. Being cylindrical specimens, the test allows its application even on the cores extracted from existing structures. This can be useful in forensic investigations involving the mechanical characteristic of the fiber-reinforced concrete. An improvement of the mechanical post cracking characteristics of the material can be also observed due to plant fiber. A real increase of the ductility of the material and consequently of the tensile strength was, in fact, found. In conclusion, we can say that the present investigation represents a meaningful contribution for the assessment of the efficiency of natural fiber in the post-peak behavior of fiber reinforced concrete. The gain in fracture energy and toughness is useful not only in all cases in which a greater tensile strength is required, but also for further employment of this kind of concrete in practical field such as industrial concrete floor or spritz beton for the stabilization of the tunnels.

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