Journal of Mechanical Research and Application JMRA
ISSN: 2251-7383, eISSN: 2251-7391
Vol. 4, No. 2, 2012, 49-56

Determination of Tensile Strength and Crack Growth of a Typical Polymer Concrete Using Circular Disc Samples

M. R. M. Aliha[1*], M. Heidari-Rarani[2], M. M. Shokrieh[3], M. R. Ayatollahi[4]

Received: 2 Aug. 2012; Accepted: 30 Nov. 2012

Abstract: Cracked and un-cracked Brazilian disc specimens subjected to diametral compression were used for conducting fracture toughness and tensile strength experiments on a polymer concrete (PC) material. The value of mode I fracture toughness (K_{Ic}) was determined from the center- cracked Brazilian disc and the indirect tensile strength (σ_t) was obtained from the un-cracked Brazilian disc specimen. The experiments showed the practical applicability of both cracked and un-cracked specimens for using as suitable techniques for measuring K_{Ic} and σ_t in PC materials. The average values of K_{Ic} and σ_t of tested PC were about 1.5 MPa√m and 8 MPa, respectively which are significantly greater than the corresponding values of K_{Ic} and σ_t obtained for conventional cement concrete tested with the same Brazilian disc specimens. Hence, for those structural applications that the risk of tensile rupture and crack growth is high, polymer concretes are more suitable candidates in comparison with the conventional cement concretes.

Keywords: Polymer Concrete, Brazilian Disc Test Specimen, Mode I Fracture Toughness, Indirect Tensile Strength

1. Introduction

A polymer concrete (PC) is a mixture of resin and mineral aggregates (silica). The resin, (e.g. epoxy or polyester) plays the role of a binder instead of cement binders in plain concretes and the silica usually includes sand and aggregate [1]. Due to this special combination, the PC is called a concrete-like composite. High mechanical strengths, good adhesion to most surfaces, good chemical resistance, fast curing at ambient temperatures, low permeability to water and good long-term durability with respect to freeze and thaw cycles of PC makes it a suitable material for construction and rehabilitation of civil infrastructure and a replacement for asphalt pavement. Some important applications of PC materials are the repair and anti-corrosion protection of old concrete structures (such as industrial floors) as well as the pre-cast elements (such as sewer pipes, drainage channels), and chemically resistant vessels (e.g. electrolytic cells for base metal recovery) [2]. Because of suitable mechanical properties of epoxy resin and especially its high binding resistance, this type of resin is widely used for manufacturing of polymer concretes in comparison with other resins.

The unsaturated isophtalic and orthophtalic polyesters due to much less cost than epoxy resins can also be used as a binder in PC at special conditions such as harsh environments like acid or alkaline media or water [3]. Czarnecki [4] claims that in the next 25 years it will be necessary to build the same number of constructions as the existing today in order to meet demands for new housings. The need to double the number of buildings on the Earth's surface drives specialists to analyze the past per-

1*. Corresponding Author: Assistant Professor, Welding and Joining Research Center, School of Industrial Engineering, Iran University of Science and Technology, 16846-13114, Tehran, Iran (Email address: mrm_aliha@iust.ac.ir)
2. Ph. D. Student, Composites Research Laboratory, Center of Excellence in Experimental Solid Mechanics and Dynamics, School of Mechanical Engineering, Iran University of Science and Technology, 16846-13114, Tehran, Iran (heidarirarani@iust.ac.ir)
3. Professor, Composites Research Laboratory, Center of Excellence in Experimental Solid Mechanics and Dynamics, School of Mechanical Engineering, Iran University of Science and Technology, 16846-13114, Tehran, Iran (shokrieh@iust.ac.ir)
4. Professor, Fatigue and Fracture Laboratory, Center of Excellence in Experimental Solid Mechanics and Dynamics, School of Mechanical Engineering, Iran University of Science and Technology, 16846-13114, Tehran, Iran (m.ayat@iust.ac.ir)

formance of the civil construction sector and reflect on possible actions to deal with the issues that have to be addressed. However, since these materials are among the newly developed construction materials, the study of their mechanical properties is necessary before being used in practical and industrial applications.

Cracking and brittle fracture are among the main causes of the overall failure in PC materials. Therefore, it is important to evaluate the tensile strength (σ_t) and the fracture toughness (K_{Ic}) of these materials using appropriate experimental methods. A suitable test specimen should have simple geometry and loading setup. Accordingly, a few test specimens have been used in the past by researchers to obtain the value of K_{Ic} for PC materials. Most of these specimens are rectangular beams subjected to bend loading [5-11]. For example, Reis and coworkers [6-9] have employed the edge notched rectangular beam specimens under symmetric three-point bending to investigate mode-I fracture behavior of different PC materials. They mainly focused on the critical stress intensity factor (K_{Ic}) and the crack tip opening displacement (CTOD). They also studied the effects of various parameters such as size and amount of the chopped glass fibers, the type of chopped fiber (i.e. glass, carbon or natural fibers) and the notch depth on mechanical and fracture properties of PC such as modulus of elasticity, K_{Ic}, flexural strength, and compressive strength.

Other researchers used the beam shape specimens made of PC for mixed mode fracture studies as well [11]. Prata et al. [12] investigated the influence of the aggregate's aspect ratio on the fracture behavior of a low cement aluminum silicate refractory at two different temperatures (110 °C and 1000 °C) by beam shape specimens. However, preparation of test specimen from PC material in the shape of rectangular beam configuration usually needs large size of samples and consequently a big amount of material should be used for each specimen which increases the cost of experiments. Moreover, the heavy weight of such relatively big samples may induce some unfavorable effects which decrease the reliability of the test results or increase the risk of concrete fracture due to its heavy weight. Thus, in this research a more suitable test configuration, i.e., Brazilian disc specimen is used for tensile strength and fracture toughness evaluation of PC materials. Then, the practical applicability of the employed specimen is investigated experimentally.

2. Brazilian disc specimen

Fig. 1 shows schematically the Brazilian disc (BD) specimen used in this research. The BD specimen is circular disc of radius R and thickness t and is subjected to diametral compressive load P, which can be used for conducting both the tensile strength and the fracture toughness tests. The cracked BD specimen with a center crack of length $2a$ can be used for obtaining K_{Ic}. When the crack line is along the direction of applied load P, the BD specimen is subjected to pure mode I deformation because of its symmetry with respect to the crack plane. The tensile strength can be also evaluated from the un-cracked BD specimen (Fig. 1b). Although the load applied during the test is compressive, the generated stress at the center of specimen becomes tensile. Hence, at a critical level of applied load, the specimen is split into two halves due to these tensile stresses. Consequently, the tensile strength of tested material can be determined from the maximum critical tensile stress. The mentioned method is called the indirect tensile strength testing technique and is often used for brittle and quasi brittle materials which are weak against the direct tensile loads.

Although the BD specimen has been used in the past especially for conducting tensile and fracture experiments on rock materials [13-16],

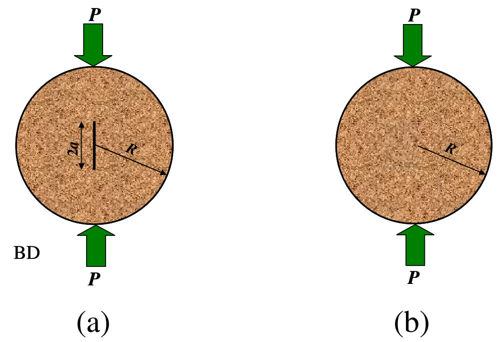

Fig. 1. (a) Center cracked and (b) un-cracked BD specimen subjected to diametral compression.

practical applicability of such samples has not been investigated for the polymer concrete materials. This configuration has some primary advantages that make it a good candidate specimen for testing PC materials. For example, because of its simple geometry preparation of the Brazilian disc test specimen from PC mixtures is easy. Testing of such specimens can also be easily done by the conventional testing machines using compression fixtures. Furthermore, cylindrical shapes can be easily obtained by using common and standard field coring equipment. This is considered as a major advantage because the Brazilian disc specimen can be prepared conveniently from the cores extracted directly from the field and site projects. Moreover, in comparison with the rectangular beam specimens, the BD samples need less PC materials for specimen casting and consequently decrease the cost of experiments.

Thus, the main aim of this research is to study the practical applicability of the center cracked and uncracked BD specimens for measuring the fracture toughness and tensile strength of the PC materials. It is shown that the BD specimens are suitable test specimens for determination of K_{Ic} and σ_t in PC materials. It is also shown that the obtained test data are significantly greater than those K_{Ic} and σ_t values obtained for the common cement concretes tested with the same SCB specimens, indicating the improved properties of the PC materials against tensile rupture in comparison with the conventional concretes.

3. PC manufacturing and testing

A typical PC material is composed of three main ingredients: thermoset resin, mineral aggregate and chopped strand glass fiber. In order to obtain good physical and mechanical properties of the PC, it is necessary to use appropriate percentages of the ingredients with suitable types and sizes in the PC composition. Using the Taguchi approach [17], Shokrieh and his coworkers [18] have recently studied the optimum percentages of the PC ingredients to obtain best strength properties. According to Ref. [18], the optimized composition of PC was found as: 48.3 Wt. % of coarse mineral aggregate (with 4-6 mm in size), 32.2 Wt. % of foundry sand filler (with 0.5-1.5 mm in size), 19 Wt. % of epoxy resin, and 0.5 Wt. % of chopped glass fiber.

The same composition was used in this research for investigating the tensile strength and the fracture toughness of the PC materials using the BD specimens. The epoxy resin and the polyester resin are two common types of resins which are frequently used for fabricating the PC materials. However, due to better bonding performance of the epoxy resin in comparison with the polyester resin, the ML506 resin based on bisphenol F with a polyamine hardener HA-11 (produced by Mokarrar Industrial Group in Iran) was used to fabricate PC in this research. Table 1 shows the physical and mechanical properties of ML506 resin used for manufacturing the PC samples. Furthermore, E-glass chopped fibers of length 6 mm were also prepared by cutting the continuous fibers, in order to use in the PC composition. The chopped glass fibers, sand fillers and epoxy resin with the above-mentioned weight fraction were mixed together inside a container to obtain a uniform mixture.

In order to manufacture the circular shape specimens, the polymer composite mixture was cast into the steel rings with 130 mm inner diameter and 40 mm height. Before casting, the inner surfaces of the rings were coated with release film to provide de-molding of the PC specimens. The prepared PC samples were cured at room temperature for 7 days and post-cured for 2 hours at 80°C.

Table 1. Mechanical and physical properties of ML506 epoxy resin used for manufacturing PC material.

Mechanical properties		**Physical properties** (for volume 50 cm^3)	
Tensile strength, MPa	76.1	Density, g/cm^3	1.11
Tensile modulus, GPa	2.79	Viscosity at 25°C, cP	1450
Compressive strength, MPa	97.4	Curing time, min	25
Compressive modulus, GPa	2.6	Gel time, min	24
Flexural strength, MPa	96	Time to Max. strength, days	7
Bending modulus, GPa	3.64	Max. curing temperature, (post-curing)	80°C

For preparation of a center crack in the cracked BD specimens, a thin plate of 40 mm in length and 0.5 mm in thickness and coated with release film was inserted in the center of disc. The plate was later removed after curing to create an initial crack of length $2a$ = 40 mm. Thus, the crack length to radius ratio (a/R) was 0.3 in the cracked BD specimen.

Using the procedure described above, several cracked and un-cracked BD specimens were fabricated from the PC material. Meanwhile, in order to compare the strength and fracture resistance properties of the PC material with plain cement concretes, some test specimens were also manufactured from a common concrete mixture containing ingredients of cement, water, and aggregates. The proportions of granular materials in the manufactured concrete mixture were as follows: 0.5:1:3.6:5, i.e. the mixture contained 0.5 part of water, 1 part of cement, 3.6 part of fine aggregate, and 5 part of coarse aggregate. The maximum size of the coarse aggregate was less than 10 mm. The 28-days compressive strength of the fabricated cement concrete was obtained experimentally as 31.26 MPa from the cylindrical specimens with diameter and height of 150 mm and 300 mm, respectively. For the sake of comparison and to avoid undesirable size effects on the test results, the corresponding dimensions of the cracked and un-cracked specimens were selected to be the same and for each case between 3 and 5 specimens were manufactured.

The test samples were then tested using a servo hydraulic tension/compression test machine (Zwiek/Roell). The tests were carried out at room temperature and under displacement control conditions with a constant cross head speed of 0.5 mm/min. Fig. 2 shows the test setup and the fixtures used for the experiments. For conducting the tests, the BD specimens were placed carefully between two flat plates and then were loaded until the final fracture.

The complete load-displacement data were recorded during the tests using a computerized data logger. Fig. 3 shows typical load-displacement curves obtained for the tested PC materials. The load-displacement curves for all the cracked and un-cracked samples and for both PC and cement concrete were nearly linear, showing the brittle failure behavior of the tested materials. Therefore, the tensile strength and fracture resistance of these materials were determined from the maximum load recorded for each test. In the next section, the obtained results are presented.

(a) cracked BD

(b) un-cracked BD

Fig. 2. Experimental set-up used for the testing BD specimens made of a typical PC material.

4. Results and discussion

The tensile strength of tested materials can be determined using un-cracked BD specimens from Eq. (1) [16]:

$$\sigma_t(\mathrm{BD}) = \frac{P_{\mathrm{split}}}{\pi t R}\left[0.156\left(\frac{t}{R}\right) + 0.964\right] \quad (1)$$

Mode-I fracture toughness (K_{Ic}) of the cracked BD specimen was also determined from Eq. (2) [19]:

$$K_{\mathrm{Ic}}(\mathrm{BD}) = Y_{BD}\,\frac{P_{\mathrm{f}}}{R t}\sqrt{\frac{a}{\pi}} \quad (2)$$

where Y_{BD} is the geometry factors for the cracked B D specimen. By using the peak tensile splitting load (P_{split}) for each un-cracked BD specimen and the fracture load at the onset of crack growth (P_{f}), the corresponding values of σ_{t} and K_{Ic} were calculated from Eqs. (1) and (2) for both polymer and plain concrete materials.Y_{BD} is function of the crack length ratio (a/R). Some analytical and numerical solutions are available for obtaining Y_{BD} [19, 20]. For example, for the tested mode-I samples (with a/R = 0.3), the corresponding geometry factor has been determined by Ayatollahi and Aliha [19] using the finite element method as: Y_{BD} = 1.135. The obtained σ_{t} and K_{Ic} data together with their mean values are presented in Table 2 where BD-F*i* and BD-T*i* stand for the cracked (fracture) and un-cracked (tensile) BD specimens and *i* is the specimen number.

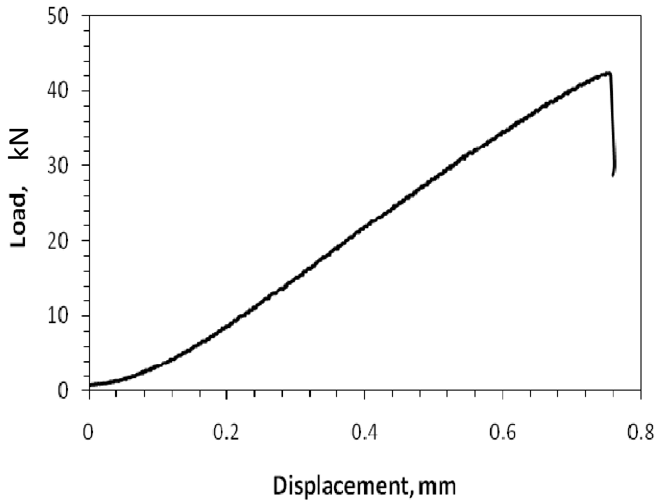

Fig. 3. Load-displacement curve of PC material.

Table 2. Summary of the results obtained for the critical loads, tensile strength and fracture toughness of BD specimens made of PC and Plain concrete.

Materials	Specimens	P_f, kN	σ_t, MPa	K_{Ic} (MPa√m)
Polymer Concrete	BD-T1	50	8.73	-
	BD-T2	45	7.85	
	BD-T3	56.5	7.34	
	Average	**50.5**	**7.97**	
	BD-F1	36.5	-	1.27
	BD-F2	36.67		1.28
	BD-F3	42.5		1.48
	BD-F4	47.1		1.64
	BD-F5	48.8		1.7
	Average	**42.31**		**1.474**
Conventional Cement Concrete	BD-T1	21	2.095	-
	BD-T2	22.17	2.21	
	BD-T3	11.52	1.15	
	Average	**18.23**	**1.81**	
	BD-F1	14.9	-	0.48
	BD-F2	13.8		0.44
	BD-F3	14.6		0.47
	BD-F4	13.1		0.42
	Average	**14.1**		**0.453**

According to the obtained test results, the average values of σ_t are about 8 and 1.8 MPa for the PC and the conventional cement concrete, respectively. The average values for K_{Ic} obtained from the BD specimens made of PC and conventional cement concrete was found about 1.5 and 0.45MPa√m, respectively.

Since the maximum tensile stresses for both cracked and un-cracked BD samples take place along the direction of applied load, it is expected that the cracking of both specimens would grow in this direction. This phenomenon is in very good agreement with the observed cracking and fracturing path for the tested cracked and un-cracked specimens (see Fig. 4 for typical fracture paths observed in the tested specimens). It was observed from the broken samples that the fracture of cracked specimens started from the crack tip and then extended along the direction of initial crack and finally terminated at the location of applied load. Similarly, for the un-cracked samples, a tensile crack is initiated from the center of samples and then extended towards the applied load location. The fracture paths for all the tested samples were straight (even passing through the silica aggregates) and stable without any significant curving to split the samples into two halves.

As mentioned earlier, evaluation of the tensile strength and crack growth resistance for newly-developed engineering materials such as polymer concretes is important issue to use them in practical applications. In this research, the application of two simple test methods for determination of σ_t and K_{Ic} in PC materials was investigated. It was shown that the employed disc shape specimens (i.e., cracked and un-cracked BD specimens) can be successfully used for the determination of tensile and fracture strength of PC and plain concrete materials. Hence, due to some advantages such as simple geometry of test specimens, convenience of specimen casting or coring, easy test set up, ability of testing with ordinary test machines and fixtures, much less material required for manufacturing the test samples, practical applicability of the BD specimens and the reasonably good agreement that exist between the test results, it is recommended to use the mentioned cracked and un-cracked BD specimens for evaluating repeatable and reasonable values for σ_t and K_{Ic} of polymer and plain concrete materials.

Moreover, a comparison of test data obtained for polymer and plain concretes (presented in Table 2) reveals that the average tensile strength and fracture toughness of tested PC is about 4.5 and 3.5 times the corresponding values of σ_t and K_{Ic} of the plain concrete, respectively. The unidirectional compressive strength of the tested PC was also obtained about 55-65 MPa which is about 2 times greater than the corresponding value of 30-35 MPa obtained for the plain concrete.

(a) PC cracked BD

(b) PC un-crack BD

Fig. 4. Typical fracture paths observed for the cracked and un-cracked disc shape specimens made of PC material.

This shows significantly improved strength properties of the newly- developed polymer concretes in comparison with the conventional plain concretes. However, the currently used PC materials are still significantly weaker than some other engineering and construction materials. Therefore, a more comprehensive research studies are required to obtain stronger and cheaper polymer concrete materials.

5. Conclusions

- The practical applicability of Brazilian disc test specimen was investigated experimentally for obtaining the tensile strength (σ_t) and mode I fracture toughness (K_{Ic}) of a typical chopped strand glass fiber reinforced polymer concrete material.
- It was shown that both cracked and un-cracked BD specimens could be used as suitable test specimens for determining σ_t and K_{Ic} in the PC materials.
- The experimentally obtained values of σ_t and K_{Ic} were noticeably higher than the tensile strength and fracture toughness of the conventional and ordinary cement concretes. Hence, for those structural applications that the risk of tensile rupture and crack growth is high, polymer concretes are more suitable candidates in comparison with the ordinary cement concretes.

Nomenclature

σ_t	Tensile strength (MPa)
K_{Ic}	Mode I fracture toughness (MPa$\sqrt{m}$)
a	Half of the crack length (m)
R	Radius (m)
t	Thickness (m)
P	Load (N)
Y_{BD}	Geometry factor

Subscripts

f	fracture
BD	Brazilian disc

References

[1] Czarnecki, L., "The status of polymer concrete", Con crete International Design Construction, 1985, 7, 47–53.

[2] Czarnecki, L., Garbacz, A., Kurach, J., "On the characterization of polymer concrete fracture surface", Cement and Concrete Composites, 2001, 23, 399-409.

[3] Gorninski, J.P., Dal Molin, D.C., Kazmierczak, C.S., "Comparative assessment of isophtalic and orthophtalic polyester polymer concrete: Different costs, similar mechanical properties and durability", Construction and building materials, 2007, 21, 546-555.

[4] Czarnecki, L., "Polymers in concrete on the edge of the millennium". In: Tenth International Congress on Polymers in Concrete and Icpic/Icri International Concrete Repair Workshop, Honolulu, Hawaii: Proceedings, International Center Aggregate Research (ICAR), Universality of Texas at Austin, 2001.

[5] Krause, R.F., Fuller, E.R., "Fracture Toughness of Polymer Concrete Materials Using Various Chevron-Notched Configurations", ASTM STP 855, 1984, 309-323.

[6] Reis, J.M.L., Ferreira, A.J.M., "Fracture behavior of glass fiber reinforced polymer concrete", Polymer testing, 2003, 22, 149-153.

[7] Reis, J.M.L., de Oliveira, R., Ferreira, A.J.M., Marques, A.T., "A NDT assessment of fracture mechanics properties of fiber reinforced polymer concrete", Polymer testing, 2003, 22, 395-401.

[8] Reis, J.M.L., Ferreira, A.J.M., "A contribution to the study of the fracture energy of polymer concrete and fiber reinforced polymer concrete", Polymer testing, 2004, 23, 437-440.

[9] Reis, J.M.L., Ferreira, A.J.M., "Assessment of fracture properties of epoxy polymer concrete reinforced with short carbon and glass fibers", Construction and Building Materials, 2004, 18, 523-528.

[10] Reis, J.M.L., Fracture and flexural characterization of natural fiber-reinforced polymer concrete, Construction and Building Materials, 2006, 20, 673-678.

[11] Avci, A., Akdemir, A., Arika H., "Mixed-mode fracture behavior of glass fiber reinforced polymer concrete", Cement and Concrete Research, 2005, 35, 243-247.

[12] Prata, L.B., Libardi W., Baldo, J.B.,"The effect of aggregate aspect ratio and temperature on the frac-

ture toughness of a low cement refractory concrete", Materials Research, 2003, 6, 545-550.

[13] Aliha, M.R.M., Ashtari, R., Ayatollahi, M.R.,"Mode I and mode II fracture toughness testing for marble". Journal ofAppliedMechanics Materials, 2006, 5-6, 181-188.

[14] Khan K., Al-Shayea N.A.,"Effect of specimen geometry and testing method on mixed I-II fracture toughness of a limestone rock from Saudi Arabia", Rock Mechanics and Rock Engineering, 2000, 33, 179-206.

[15] Chang S.H., Lee C.I., Jeon S.,"Measurement of rock fracture toughness under modes I and II and mixed-mode conditions by using disc- type specimen", Engineering Geology, 2002, 66, 79–97.

[16] Aliha, M.R.M., "Indirect tensile test assessments for rock materials using 3-D disc-type specimens", Arabian Journal of Geo Sciences, under review.

[17] Ranjit K. Roy, "Design of experiments using the Taguchi approach: 16 steps to product and process improvement", Wiley-IEEE, 2001.

[18] Shokrieh M.M., Heidari-Rarani M., Shakouri M., Kashizadeh E., "Effects of thermal cycles on mechanical properties of an optimized polymer concrete", Construction and Building Materials, 2011, 25, 3540-3549.

[19] Ayatollahi M.R., Aliha M.R.M., "Wide range data for crack tip parameters in two disc-type specimens under mixed mode loading", Computational Materials Science, 2006, 38, 660-670.

[20] Atkinson C., Smelser R.E., Sanchez J. "Combined mode fracture via the cracked Brazilian disk test", International Journal of Fracture, 1982, 18, 279–291.