DOI: http://dx.doi.org/10.12989/sem.2012.43.6.823

Experimental determination of tensile strength and K_{Ic} of polymer concretes using semi-circular bend (SCB) specimens

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(Received January 5, 2012, Revised May 12, 2012, Accepted August 9, 2012)

Abstract. An experimental method was suggested for obtaining fracture toughness (K_{Ic}) and the tensile strength (σ_t) of chopped strand glass fiber reinforced polymer concretes (PC). Semi-circular bend (SCB) specimens subjected to three-point bending were used for conducting the experiments on the PC material. While the edge cracked SCB specimen could be used to evaluate fracture toughness, the tensile strength was obtained from the un-cracked SCB specimen. The experiments showed the practical applicability of both cracked and un-cracked SCB specimens for using as suitable techniques for measuring K_{Ic} and σ_t in polymer concretes. In comparison with the conventional rectangular bend beam specimen, the suggested SCB samples need significantly less material due to its smaller size. Furthermore, the average values of σ_t and K_{Ic} of tested PC were approximately 3.5 to 4.5 times the corresponding values obtained for conventional concrete showing the improved strength properties of PC relative to the conventional concretes.

Keywords: polymer concrete; SCB specimen; tensile strength; fracture toughness; experiment

1. Introduction

A polymer concrete (PC) is a mixture of resin and mineral aggregates (silica or sand). The resin, (e.g., epoxy or polyester) plays the role of binder instead of cement binder in conventional concretes (Czarnecki 1985). The aggregate must be of good quality, free of dust and other debris and dry. Failure of these criteria can reduce the bond strength between the polymer binder and the aggregate. 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

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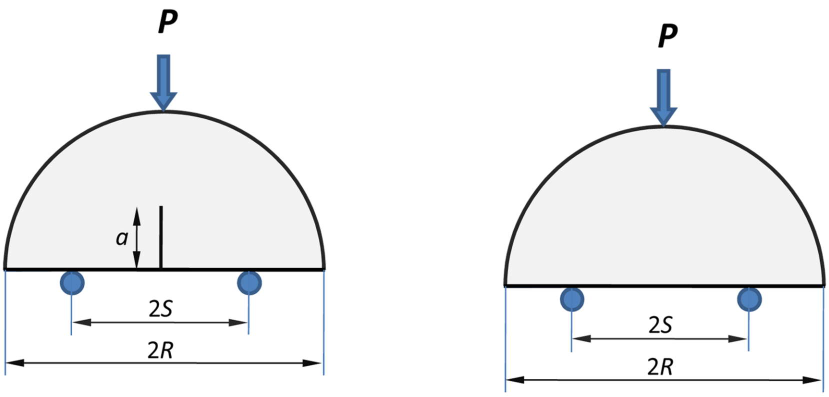
thaw cycles of PC makes it a suitable material for construction and rehabilitation of civil infrastructure and a replacement for asphalt pavement. Some important applications of PC materials are the repair and anti-corrosion protection of old concrete structures (such as industrial floors) as well as the pre-cast elements (such as sewer pipes, drainage channels), and chemically resistant vessels (e.g., electrolytic cells for base metal recovery) (Czarnecki *et al.* 2001). Because of suitable mechanical properties of epoxy resin and especially its good adhesion to most surfaces, this type of resin is widely used for manufacturing the polymer concretes in comparison with other resins. The unsaturated isophthalic and orthophthalic polyesters which are less expensive than the epoxy resins can also be used as a binder in PC at harsh environments like acid or alkaline media or water (Gorninski *et al.* 2007).

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. For example, Shokrieh *et al.* (2011) designed and manufactured a new PC material and investigated experimentally its mechanical properties such as compressive strength, flexural bending strength and interfacial shear strength. They also investigated the effect of freeze-thaw thermal cycles on the mechanical properties of the proposed PC material (Shokrieh *et al.* 2011). 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} or other strength properties for PC materials. Most of these specimens are rectangular beams subjected to bend loading (Krause and Fuller 1984, Reis and Ferreira 2003, 2004, Reis 2006, Avci *et al.* 2005, Kim *et al.* 2011). For example, Reis and coworkers (2003, 2004, 2006) 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 measuring the critical stress intensity factor (K_{Ic}) and the crack tip opening displacement (CTOD). They studied the effects of various parameters such as size and amount of chopped glass fiber, type of chopped fiber (e.g., glass, carbon or natural fibers) and depth of notch on properties such as modulus of elasticity, K_{Ic}, flexural strength, and compressive strength. Prata *et al.* (2003) investigated the influence of the aggregate's aspect ratio on fracture behavior of a low cement aluminum silicate refractory at two different temperatures (110°C and 1000°C) using notched beam specimens. Mixed mode fracture behavior of PC materials has also been studies using beam shape specimens by some researchers, e.g., Avci *et al.* (2005).

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. Thus, in this research a more suitable test configuration is suggested for strength and fracture resistance evaluation of PC materials. Then the practical applicability of the proposed specimens is investigated experimentally. It is shown that the suggested specimens can be used successfully for obtaining the fracture resistance and the tensile strength of the PC materials.

2. Semi-circular shape specimens for PC testing

Fig. 1 shows schematically the semi-circular bend specimens proposed in this research. The



(a) Cracked SCB (b) Un-cracked SCB

Fig. 1 Schematic representation of SCB test specimens (P is the applied load, 2R is the diameter of semi disc, a is the crack length and 2S is the loading span)

specimens have semi-circular shapes of radius R and thickness t which can be used for conducting both the tensile strength and the fracture toughness tests. The experiments are performed under symmetric three-point bending with a loading span of 2S. The cracked specimen with a crack of length a (Fig. 1(a)) can be used for obtaining K_{Ic} and the tensile strength can be evaluated from the un-cracked SCB specimen (Fig. 1(b)).

The cracked SCB specimen shown in Fig. 1 is subjected to pure mode I deformation because of its symmetry with respect to the crack plane. Although for the un-cracked SCB specimen, the load applied during the test is compressive, the generated stresses at certain location of the test specimen (i.e., middle of the bottom flat edge of the SCB specimen) become 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 SCB specimen has been used in the past especially for conducting tensile and fracture experiments on rock materials (Chong and Kuruppu 1987, Lim *et al.* 1994, Khan and Al-Shayea 2000, Chang *et al.* 2002, Ayatollahi and Aliha 2007, Aliha *et al.* 2007, 2010), practical applicability of such samples has not been investigated for the PC 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 SCB test specimen from PC mixtures is easy. Testing of such specimens can also be easily done by the conventional testing machines using three-point bend loading fixtures. Furthermore, cylindrical shapes can be easily obtained by using common and standard field coring equipments. This is considered as a major advantage because the SCB 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 SCB 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 proposed semi-circular specimens for measuring the tensile strength and fracture toughness of the PC materials. It is shown that both the cracked and un-cracked SCB 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 σ_t and K_{Ic} 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. Experimental procedure

3.1 Materials

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 (Ranjit 2001), Shokrieh and his coworkers (2011) have recently studied the optimum percentages of the PC ingredients to obtain the maximum bending and compressive strengths, and also the interfacial shear strength between the PC and inner surface of a steel ring. According to Shokrieh *et al*. (2011), 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. Other researchers (e.g., Mantrala and Vipulanandan 1995, Ferreira *et al.* 2000, Ribeiro *et al.* 2003, Soraru and Tassone 2004) have also proposed that the similar composition can provide approximately the best mechanical properties for PC materials. Thus, the same composition was used in this research for investigating the tensile strength and the crack growth resistance properties of the PC materials using the SCB specimens. As mentioned above, 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.

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^{o}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^{o}C

3.2 Test specimen preparation

In order to manufacture the circular shape specimens, the polymer composite mixture described in the previous section 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^{o}C. For creating the semi-circular discs, a very thin plate with thickness of 1 mm was placed along the diameter of the steel ring prior to casting. Thus, in each casting process, two semi-circular disc specimens of diameter 130 mm were produced. Similarly, for preparation of an edge crack in the cracked SCB specimens, a thin plate of 20 mm in length and 0.5 mm in thickness and coated with release film was inserted perpendicular to the flat edge in the middle of the semi-disc. The plate was later removed after curing to create an initial edge crack of length $a = 20$ mm. Thus, the crack length to radius ratio (a/R) was 0.3 in the cracked SCB specimens.

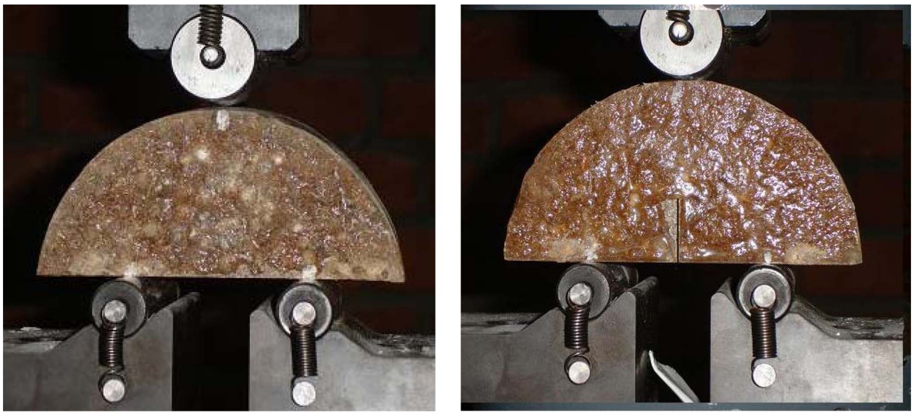
Using the procedure described above, several cracked and un-cracked SCB specimens were fabricated from the PC material. Meanwhile, in order to compare the strength and fracture resistance properties of the PC material with conventional cement concretes, some test specimens were also manufactured from 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 SCB specimens were selected to be the same. Table 2 summarizes the geometry and dimensions of the whole manufactured specimens. It should be noted that three specimens were tested for each case in Table 2.

3.3 Mechanical tests

After preparation of the test samples, they were 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. The SCB specimens were tested using a three-point bend fixture with the loading span of $2S = 65$ mm (i.e., $S/R = 0.5$). Fig. 2 shows the test setup and the fixtures used for the experiments. For conducting the tests, the SCB specimens were placed carefully inside the fixtures and then were loaded until the

Table 2 Dimensions of manufactured SCB specimens

Specimens	a (mm)	R (mm)	t (mm)	a/R	S/R
PC un-cracked SCB	-	65	40	-	0.5
Conventional concrete un-cracked SCB	-	65	40	-	0.5
PC cracked SCB	20	65	40	0.3	0.5
Conventional concrete cracked SCB	20	65	40	0.3	0.5



(a) Un-cracked SCB (b) Cracked SCB

Fig. 2 Experimental setup used for the PC testing

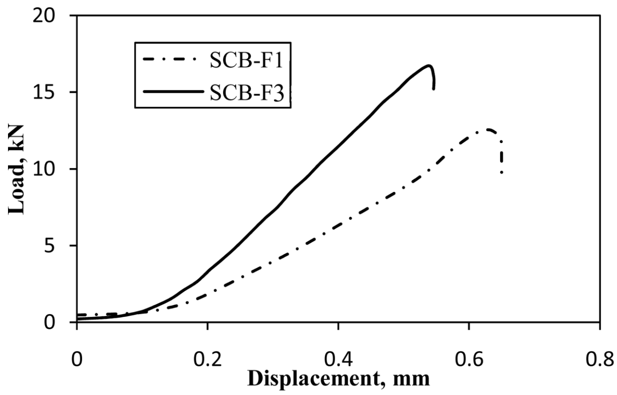


Fig. 3 Typical load-displacement curves of tested SCB specimens made of PC material

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.

4. Results

4.1 Fracture toughness results

Mode-I fracture toughness (K_{Ic}) was determined for each cracked SCB specimen from the following equation (Ayatollahi and Aliha 2006)

$$K_{Ic}(\mathrm{SCB}) = Y_{SCB}\frac{P_f}{2Rt}\sqrt{\pi a} \quad (1)$$

where P_f and Y_{SCB} are maximum fracture load and geometry factor for the SCB specimen, respectively. Y_{SCB} is a function of the crack length to radius ratio (a/R) and the loading span to radius ratio (S/R). Some analytical and numerical solutions are available for obtaining Y_{SCB} (Atkinson *et al.* 1982, Ayatollahi and Aliha 2006). For example, for the tested mode-I samples, the corresponding geometry factor has been determined by Ayatollahi and Aliha (2006) using finite element analysis as: Y_{SCB} = 2.55 (for a/R = 0.3 and S/R = 0.5). By recording the final fracture loads from the experiments, the corresponding values of K_{Ic} for the tested concretes were calculated from Eq. (1). The obtained data together with their mean values are presented in Table 3 where SCB-F*i* stands for the cracked SCB specimens and *i* is the specimen number.

The average values of K_{Ic} obtained from the SCB specimens were found as 1.69 $\mathrm{MPa}\sqrt{\mathrm{m}}$ for PC and 0.51 $\mathrm{MPa}\sqrt{\mathrm{m}}$ for the conventional concrete. The obtained values for fracture toughness are also in good agreements with those values of K_{Ic} reported for other similar concrete materials tested with different test methods like rectangular beam subjected to three-point bending (Reis and Ferreira 2003, 2004, Reis 2006). Moreover, in order to investigate the validity of the suggested semi circular bend specimens, a series of fracture toughness experiments were also conducted on the conventional and frequently used test configurations (i.e., center cracked Brazilian disc specimen subjected to diametral compression and the edge cracked rectangular beam specimen under three point bend loading) made of the same polymer concrete and conventional concrete materials used for SCB testing in this research. The fracture toughness values obtained from the Brazilian disc configuration were about 1.5 $\mathrm{MPa}\sqrt{\mathrm{m}}$ and 0.45 $\mathrm{MPa}\sqrt{\mathrm{m}}$ for the polymer concrete and conventional concrete, respectively (Aliha *et al.* 2012). Similarly Shokrieh *et al.* (2012) reported the average value of K_{Ic} = 1.8 $\mathrm{MPa}\sqrt{\mathrm{m}}$ for the fracture toughness of the same polymer concrete tested with three point bend beam. The mentioned results are in good agreement with the values obtained for the fracture toughness of the SCB specimen which reveals the suitability of the SCB specimen for fracture toughness testing of concrete materials.

Table 3 Critical fracture load (P_f) and fracture toughness (K_{Ic}) obtained for the cracked SCB specimens made from PC and conventional concrete materials

Materials	Specimens	P_f (kN)	K_{Ic} ($\mathrm{MPa}\sqrt{m}$) (±SDV)
PC	SCB-F1	12.7	1.56
	SCB-F2	11.5	1.41
	SCB-F3	17	2.1
	Avg.	13.73	1.69 (±0.36)
Conventional Concrete	SCB-F1	4.3	0.49
	SCB-F2	5.3	0.60
	SCB-F3	3.8	0.44
	Avg.	4.47	0.51 (±0.08)

4.2 Tensile strength results

The tensile strength of tested materials can also be determined using the un-cracked SCB specimen from the following equation (Aliha *et al.* 2007)

$$\sigma_t\,(\text{SCB}) = \frac{P_f}{\pi t R}\left[0.073\left(\frac{t}{R}\right) + 0.8896\right]\left[2.01\left(\frac{S}{R}\right) + 1.052\right] \quad (2)$$

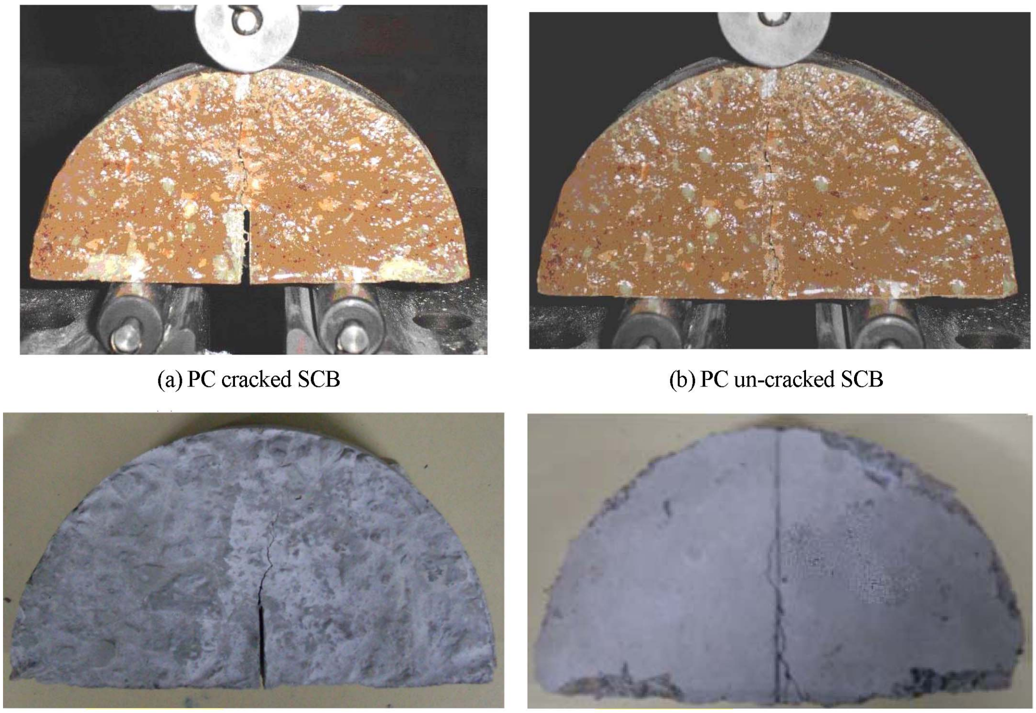
By using the peak load for each un-cracked SCB specimen, the corresponding value of σ_t was calculated from Eq. (2) for both polymer and conventional concrete materials. The obtained results are presented in Table 4, where SCB-T*i* indicates the un-cracked SCB specimens and *i* is the specimen number.

According to the test results, the average value of σ_t was found about 11.22 MPa and 2.51 MPa for the polymer concrete and the conventional concrete, respectively. Using the un cracked Brazilian disc specimen and the same concrete materials (manufactured with the same composition and procedure used for SCB specimens), Aliha *et al.* (2012) obtained the values of 8.3 and 2 MPa for tensile strength of polymer and conventional concretes, respectively. These values are also in the range reported by other researchers for similar concretes (Swaddiwudhipong 2003, Golestaneh 2010).

Since for both cracked and un-cracked SCB samples, the maximum tensile stress takes place along the symmetry line, it is expected that the cracking trajectory would be in this direction for both specimens. This phenomenon is consistent well with the cracking path observed for the tested specimens (see Fig. 4 for typical fracture paths observed in the experiments). It was observed that the fracture trajectory in the cracked SCB specimens started from the crack tip and then extended along the direction of initial crack and terminated at the location of applied load. Similarly, for the un-cracked samples, a tensile crack was initiated from the middle of flat edge of the SCB specimens and then extended towards the top loading point. The fracture paths for all the tested samples were generally straight (even passing through the silica particles) without any significant curving.

Table 4 Results of the splitting load (P_f) and tensile strength (σ_t) of the un-cracked SCB specimens made of PC and Conventional concrete materials

Materials	Specimens	P_f (kN)	σ_t (MPa) (±SDV)
PC	SCB-T1	33	11.5
	SCB-T2	36.5	12.5
	SCB-T3	31.7	9.65
	Avg.	33.57	11.22 (±1.45)
Conventional concrete	SCB-T1	6.9	2.105
	SCB-T2	9.38	2.86
	SCB-T3	8.4	2.56
	Avg.	8.23	2.51 (±0.38)



(a) PC cracked SCB (b) PC un-cracked SCB

(c) Conventional concrete cracked SCB (d) Conventional concrete un-cracked SCB

Fig. 4 Typical fracture paths observed for the cracked and un-cracked SCB specimens

5. Discussion

As mentioned earlier, the assessment of the tensile strength and crack growth resistance for newly developed engineering materials such as polymer concretes is an important issue before using them in practical applications. In this research, the application of two simple test methods for determination of σ_t and K_{Ic} in the PC materials was investigated. It was shown that the suggested semi-circular shape specimens can be successfully used for determination of both the tensile and fracture strength of the PC and conventional concrete materials. Several advantages can be mentioned for these specimens, such as: the simple geometry of test specimens, the convenience of specimen casting or coring, the easy test setup, the ability of testing with ordinary test machines and fixtures, the significant saving in the volume of material required for manufacturing the test samples, and finally the practical applicability of the SCB specimens as shown in this research. Therefore, the use of cracked and un-cracked SCB specimens is recommended for determining the values of σ_t and K_{Ic} for polymer and conventional concrete materials. Indeed, the SCB specimen can be used as an alternative test specimen to the conventional rectangular beam specimens, which has been widely used in the past for concrete materials.

Moreover, a comparison between the test data obtained for the polymer and conventional concretes (as presented in Tables 3 and 4) reveals that the averages of the tensile strength and fracture toughness of the tested PC are about 4.5 and 3.5 times the values corresponding to the conventional concrete, respectively. The unidirectional compressive strength of the tested PC was also about 64 MPa (Shokrieh *et al.* 2011) which is about twice the corresponding value of 31 MPa obtained for the conventional concrete. This shows significantly improved strength properties of the newly developed polymer concretes in comparison with the conventional concretes. Although the cost of PC materials are greater than the conventional concretes, larger strength/weight ratio of the PC materials with respect to cement concretes makes them good candidates for those applications in which the weight and durability of structure are important issues for civil and infrastructure designers.

6. Conclusions

The practical applicability of semi-disc test specimens was investigated experimentally for obtaining the tensile strength (σ_t) and fracture toughness (K_{Ic}) of polymer concrete materials. It was shown that both cracked and un-cracked SCB 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 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.

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