Arabian Journal of Geosciences (2022) 15: 1213
https://doi.org/10.1007/s12517-022-10466-y

ORIGINAL PAPER

Investigation of the effect of components on tensile strength and mode-I fracture toughness of polymer concrete

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Received: 7 February 2022 / Accepted: 10 June 2022 / Published online: 27 June 2022
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Abstract
Polymer concrete is a relatively new type of concrete in which polymer is used as a binder. This paper investigates the effect of compositions on the tensile strength and mode-I fracture toughness of polymer concrete (PC) and fiber-reinforced polymer concrete (FRPC). According to the literature, the range of compounds (in unit weight) is selected 15 to 25% for resin, 0 to 2% for fibers, 45 to 55% for fine aggregates, and 25 to 35% for fine and coarse aggregates. Using a design of experiment software, 198 specimens made of 66 different mixture designs have been designed, prepared, and tested. The results show that reducing the size of aggregates, increasing fiber content, and increasing resin content increase the tensile strength and fracture toughness. Results show that fiber reinforcement effect on mixtures with higher resin and smaller aggregates content is more promising. In addition, the minimum resin content for PC and FRPC materials is about 12.5%. In addition, the results show that the optimal percentage of fiber depends on the percentage of resin; in a mixture with 15%, optimum resin content is equal to 1.5%, and in a mixture, with 25%, optimum resin content is equal to 4.0%.

Keywords Polymer concrete · Tensile strength · Mode-I fracture behavior · Aggregate size · Glass fiber

Introduction

Different kinds of concretes are widely used in the construction industry. As the most widely used type of concrete, cement concrete has noticeable disadvantages, such as poor tensile strength, high porosity, and sensitivity to environmental conditions. Polymer concrete (PC) is a relatively new generation of concrete; manufactured by mixing a polymeric adhesive and aggregates (Asdollah-Tabar et al. 2021; Mehmet et al. 2017; Huang et al. 2017). In comparison with ordinary cement concrete, PC properties such as strength, adhesion, water tightness, chemical resistance, freeze–thaw durability, and abrasion resistance improved noticeably; hence, this is a suit material for the construction and repairing of many structures and infrastructures such as hydraulic or offshore structures or even road pavements and overlays (Martínez-Barrera et al. 2019; Seco et al. 2020; Ohama 2008; Sun et al. 2018). Fiber-reinforced polymer concrete (FRPC) is a polymer-based concrete composite that randomly distributed short fibers are used to strengthen its matrix. FRPC is stronger and more durable and has higher tensile and flexural strength values than polymer concrete (Küçük et al. 2019; Ghassemi and Toufigh 2020; Ferdous et al. 2020).

Such as cement in cement concrete and bitumen in asphalt concrete, in PC and FRPC materials, polymer binders, or liquid resin provide a firm matrix and create a strong bond between the aggregates and fibers (Hajiloo, et al. 2022; Saed et al. 2022; Dong et al. 2014; Seco et al. 2020). Considering the cost, availability of materials, and required mechanical and strength properties, different polymeric resins are usually used

Responsible Editor: Zeynal Abiddin Erguler

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for manufacturing polymer concrete materials (ACI Committee 548 1997; Anand et al. 2019; Zhang et al. 2020). Epoxy, polyester, methacrylate, and polyurethane resin are among the commonly used polymers for manufacturing PC and FRPC materials (Huang et al. 2021; Heidarnezhad et al. 2020; Reis 2009).

Large proportions of resin in polymer concrete mixtures are not common, because the high price of resins makes structures uneconomical. To overcome this issue, adding high proportions of aggregates is a common method. In this condition, PC strength affects by aggregate (especially reduction of tensile strength and cracking resistance), so the addition of fiber appears as a solution (Ohama 2008; Golestaneh et al. 2010).

Mineral admixtures and industrial aggregates (i.e., limestone, basalt, silica, quartz, granite, fly ash, slag, or silica fume) can be added to a polymeric matrix, and by using them, properties of PC in liquid and hardened states (i.e., shrinkage deformation, density, or strength) can be controlled. However, due to the excellent characteristics of the epoxy resin matrix, the added aggregate must be very durable and has suit mechanical behavior (Marinela et al. Jul. 2010; Shams and El-Hajjar 2013; Reis and Ferreira 2003a). A suitable gradation of aggregates is also important; it results in fewer air voids, minimizes the amount of resin required to generate proper adherences between the aggregate particles, and results in a more economical PC (Ohama 2008; Muthukumar and Mohan 2004; Castro et al. 2020).

As said, fiber addition is a common method for reinforcing polymeric concrete mixtures (Moreira et al. 2016; Nunes and Reis 2012); however, the influence of fibers may strongly depend on the type, shape, and percentage of fibers used in the mixture. The two main types of fibers commonly used in the mixture of polymeric concrete materials are glass fibers and carbon fiber (Reis and Ferreira 2006a; Naser et al. 2019; Belnoue et al. 2021; Lee et al. 2016).

Cracking is one of the major failure modes in brittle and quasi-brittle materials. Along with the compressive and tensile strength as two primary parameters to evaluate the behavior of a material, fracture toughness as a parameter that describes the resistance of a material to cracking is an important mechanical characteristic (Chen et al. 2011; Aliha et al. 2022a; Reis and Jurumenh Sep. 2011; Reis et al. 2011).

Several researchers have investigated the effect of ingredients on the behavior of PC and FRPC materials. For example, Niaki et al. (Niaki et al. 2018) investigated the effect of clay nanoparticles and basalt fiber on the mechanical behavior (compressive, flexural, splitting, and impact strength) of polymer concrete (PC) made of epoxy resin. Results showed basalt fiber increased the mechanical strength and increased the thermal stability of FRPC. At the same time, clay nanoparticles improve the compressive strength, flexural strength, and impact strength but decrease the tensile strength of the PC.

Seco et al. (2020) investigate the effect of adding alumina filler and ladle slag as two metallurgical wastes on the fresh and cured properties of polyester-based polymer concretes. The consistency test showed low representativeness of the recycled fresh mix's workability. The mixtures containing alumina filler and ladle slag showed higher shrinkages than those containing sand. In addition, the density of the cured samples was measured in the range of 1.59–1.91 g/cm^3. Results also show that the flexural strength of polyester polymer concretes containing alumina filler and sand reached 10.93 and 11.02 kN, respectively, while the ladle slag contained mixture showed 19.31 kN flexural strength. The alumina filler and sand contained mixture compressive strength reached 104.2 and 106.2 MPa, respectively, while the ladle slag contained mixture achieved 160.5 MPa.

Bulut and Sahin (2017) investigated the effects of electronic plastic waste (e-plastic) addition on the mechanical properties of unsaturated polyester-based polymer concrete. E-plastic was used as a part of the filler and fine-graded materials. The ratio of resin to filling material has been assumed as 10–90%, 15–85%, and 20–80%, and the e-plastic to aggregates ratio has been decided to be 0%, 5%, 15%, and 25%. Results show that an increase in resin content increases the compressive strength but does not cause a significant increase or decrease in the flexural and splitting tensile strength. Compressive, flexural, and splitting tensile strength values decrease as the amount of e-plastic content increases. In contrast, increases in electronic plastic waste increase the polymer concrete ductility.

Simsek and Uygunoglu (2016) used a multi-response optimization method to achieve an acceptable level of compressive strength of PC material. In their study workability, mechanical and thermal properties with different polymer binders (thermoplastic polyurethane, polycarbonate, and polybutylene terephthalate) were analyzed and optimized using a full-factorial design-based desirability function approach. The results show that polycarbonate-based PC has the lowest thermal conductivity, and thermoplastic polyurethane and polycarbonate significantly reduce the percentage of water absorption. It was concluded that experimental designs, which take into account interaction effects, such as full factorial design, should be used to determine the optimal mixture parameters of polymer concrete.

Among the researchers, Reis and Ferreira (2004a, b, 2003b) comprehensively studied the fracture behavior of PC and FRPC mixtures. Reis and Ferreira studied the fracture parameters of different glass fiber reinforced polymer concrete materials. Results have shown that fracture resistance can be improved due to the addition of short fibers. For example, according to their findings, the glass fiber reinforcement can improve the fracture toughness and modulus of elasticity up to 13 and 39%, respectively. Their study also shows that unlike conventional PC materials (which behave completely brittle), the fiber addition can change the behavior from brittle to quasi-brittle and noticeably the post-peak failure behavior. Reis and Ferreira (2006b) also evaluated the effect of environmental conditions (atmospheric exposure, freeze–thaw cycle, and temperature cycles) on the fracture properties of polymer concrete materials. Results show that the glass fiber reinforcement enhanced the resistance of FRPC against exposure, and almost no degradation is seen. The flexural elasticity decreases by increasing the temperature, and the failure becomes more ductile and enhances fracture toughness value (after 100 thermal cycles, the fracture toughness of epoxy polymer concrete increases up to 33%). Reis (2006) also studied the effect of chopped natural fibers on FRPC materials. Results showed that coconut fiber and sugar cane bagasse fiber increase fracture toughness and fracture energy of PC, but banana pseudostem fiber does not enhance fracture toughness and only increases fracture energy value.

Aliha et al. (2012a) investigated the tensile strength and fracture toughness of polymer concrete (epoxy-based polymer concrete reinforced chopped glass fiber) using cracked and un-cracked semi-circular bend (SCB) specimens. They showed that cracked and uncracked SCB specimens are suitable specimens for measuring tensile strength and fracture toughness. They state that the SCB samples need less material than the rectangular bend beam specimen previously used by researchers.

In the most recent research by Karimi and Aliha (2021) and Aliha et al. (2022a, b), the mode-I and mode-II fracture parameters for PC and FRPC materials were investigated. They used SCB specimens made of several mixed designs to formulate the relationship between fracture toughness and fracture energies in pure mode-I and mode-II conditions using statistical methods such as trend and cluster analysis. Their study shows that there is a strong relationship between mentioned parameters. Also, they showed that the fiber reinforcement significantly affects the fracture behavior of FRPC material, especially in mode-I conditions.

Generally, polymer concrete is made of at least 3 or 4 ingredients (i.e., resin, fine aggregates, coarse aggregate, and sometimes fiber or additives). Such ingredients have different shapes, percentages, and different mechanical behaviors. Same as other composite materials, each ingredient affects the mechanical properties of the final material; indeed, increasing or decreasing the percentages of the compositions changes properties such as ductility or brittleness and can affect significantly (Reis et al. 2003; Douba et al. 2612; Aliha et al. 2012; Nunes and Reis 2014). However, most of the previous research used fixed or limited mix designs to characterize the mechanical properties of the PC materials, and the effect of PC mix-design on the mechanical parameters and fracture toughness of PC materials has not been comprehensively investigated.

In this research using experimental design software, 66 PC mixtures with different percentages of ingredients were designed, prepared, and tested. In these mix designs, the percentage of resin, fine and coarse aggregate, and fiber materials are assumed as variable parameters to investigate their effect on mechanical and fracture behaviors. In the current study, both fracture toughness and tensile strength values are evaluated using SCB specimen (in pre-cracked and intact conditions), while pre-cracked SCB specimen as a simple and easy to prepare specimen used by many researchers to obtain fracture toughness, but intact SCB specimen is used less frequently to obtain tensile strength. Besides typical evaluations such as evaluation of the effect of resin content or fiber content on strength parameters of mixture which enable the comparison of data with other researches, in this study, some firstly conducted evaluations such a determination of minimum resin content required to develop the matrix or the effect of size of the aggregates is reported.

Experimental procedure

The epoxy resin produced by Iranian Mokarrar Co. with a commercial code of M-20 was used in current research for manufacturing the PC material. Table 1 shows the properties of resin (presented by the manufacturer) used for manufacturing the samples.

In PC materials, high-strength aggregates must be used to prevent the matrix from weakening due to the addition of aggregates. In the current study, siliceous aggregate as a high-strength material was used. This aggregate was supplied from Kavyan Industry and Stone Company (Iran). Aggregates were sorted as two fine and coarse graded aggregates. The aggregate gradation is given in Fig. 1.

Based on data presented by the producer company, the chemical composition of aggregates has been given in Table 2.

E-glass fibers used for reinforcing the PC mixture has a diameter of 13 μm and chopped in the length of 6 mm. Same as other ingredients, the fibers are randomly distributed in

Table 1 Mechanical and technical properties of used epoxy resin

Property	Value/unit	ASTM standard
Compressive strength	88.3 MPa	D695M
Compressive modulus	824 MPa	D695M
Flexural strength	81.6 MPa	D790M
Tensile strength	62.4 MPa	D638M
Tensile modulus	3081 MPa	D638M
Hardness	87 Shore D	D2240
Impact resistance	6257 kJ/m^2	D256
Adhesion resistance to shear	42.9 MPa	D1002
Viscosity	13 Pa.s	D445
Flashpoint	250 °C	D92
Moisture content	0.02%	D1744

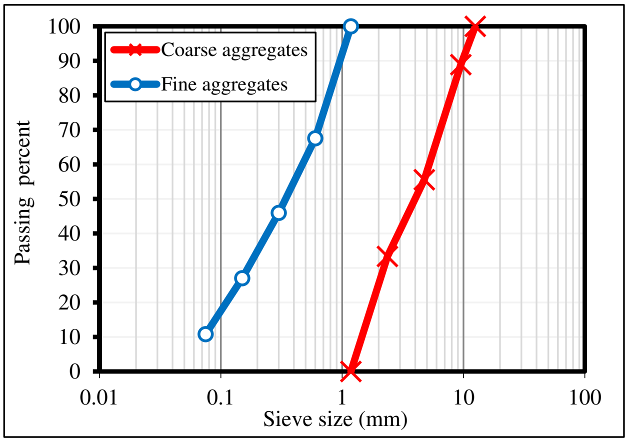

Fig. 1 Silica aggregate gradation used in the current investigation

Table 2 Chemical composition of used aggregates

Percentage	Chemical composition
98.11 ~ 96%	SiO_2
1.65 ~ 0.51%	Al_2O_2
0.7 ~ 0.4%	CaO
0.7 ~ 0.2%	Fe_2O_2
0.08 ~ 0.03%	Na_2O
0.15 ~ 0.09%	K_2O

the mixtures. The chopped glass fibers and silica aggregates are shown in Fig. 2.

To investigate the effect of ingredients on the behavior of PC and FRPC materials, suitable ranges of resin, aggregate, and fiber ingredients should be considered. Some researchers have focused on obtaining the acceptable range of input mix design parameters and optimum percentages of ingredients. For example, by performing some mechanical tests, Shokrieh et al. obtained the optimum percentages of ingredients: epoxy resin 19%, coarse aggregates 48.3%, fine aggregates 32.2%, and glass fiber 0.5% of weight unit (Shokrieh et al. 2011). Other researchers such as Karimi and Aliha, Aliha et al., Ribeiro et al., or Reis and Ferreira also state the similar optimum mix design with nearly the same ranges for the percentages of PC ingredients (Aliha et al. 2022a, b; Reis and Ferreira 2003b; Karimi and Aliha 2021; Ribeiro et al. 2003; Heidari-Rarani and Bashandeh-Khodaei-Naeini 2018).

This paper chose the minimum and maximum range of variables to oscillate ± 5% of the optimum percentage values reported in the previous works. Therefore, percentages of ingredients were varied in the ranges of coarse aggregates 45 to 55% of weight unit, fine aggregates 25 to 35% of weight unit, epoxy resin 15 to 25% of weight unit, and e-glass fibers 0 to 2% of weight unit.

The range of ingredients was used as input variables to design several PC and FRPC mixtures. Considering the percentages of ingredients in the mentioned ranges, mix designs must satisfy the following design requirement:

$$\begin{gathered} \text{Resin} + \text{fine aggregates} + \text{coarse aggregates} + \text{glass fiber} = 100 \\ 15\% \le \text{Resin} \le 25\% \\ 0.45\% \le \text{fine aggregate} \le 55\% \\ 25\% \le \text{coarse aggregate} \le 35\% \\ 0\% \le \text{glass fiber} \le 2\% \end{gathered} \tag{1}$$

To achieve this purpose, the design of experiment (DOE) module of the Minitab software was used. Besides the design of experiments based on input variables, DOE programs were used to assess the effects of input variables on output variables. Such experiments mainly consist of a series of tests that make purposeful changes to the input variables. According to the percentages mentioned in the previous section, mixing designs were obtained from the full factorial design by considering the percentage of resin,

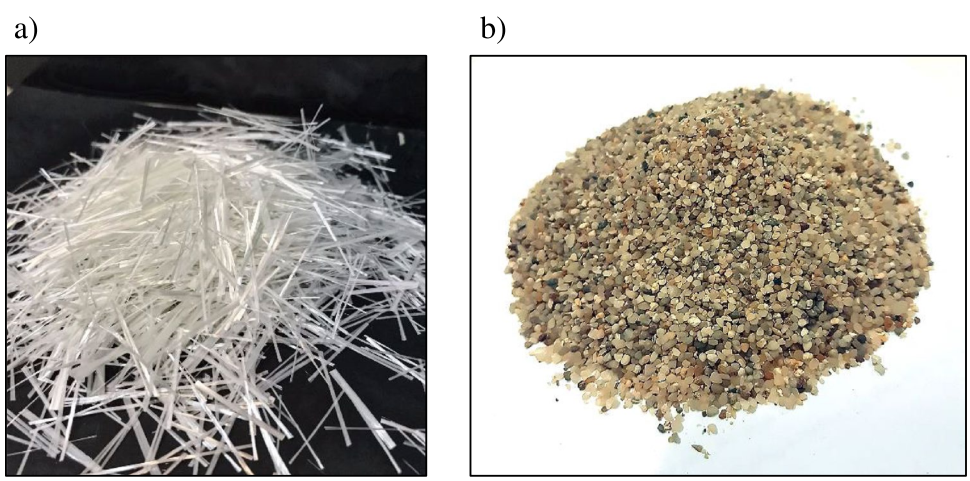

Fig. 2 Materials used in the current study; **a** E-glass fibers chopped in the length of 6 mm, and **b** silica aggregates

fibers, and coarse and fine aggregates as variable factors. To investigate the effect of aggregate sizes on the results, a parameter called the aggregate coarseness ratio (β) is defined as follows. The higher the β value, the finer the granulation in the mixture.

$$\beta = \frac{\text{Fine aggregate percentage}}{\text{Coarse aggregate spercentage}} \tag{2}$$

Among the feasible PC mix-designs obtained from the requirements and constraints, a total number of 66 mix-designs was chosen (shown in Table 3) for manufacturing the PC specimens (after eliminating invalid mixing designs) and conducting the experiments. The mixture ID was chosen as two parts, letters and a number. The letters are present the resin content, including ultra-low (UL) for mixtures with 15% resin content, low (L) and moderate-low (ML) for mixtures with 17 and 19% resin content, and also moderate-high (MH), high (H), and ultra-high (UH) for mixtures with 21, 23, and 25% resing content respectively. The following number in the mixture's ID shows the mixture aggregate coarseness ratio (previously defined by β).

Test configuration

Experimental studies on actual components are often expensive and challenging, so researchers prefer to use laboratory specimens. There are several specimens to investigate the behavior of brittle materials such as edge-notched disc bend (ENDB) specimen (Aliha and Pour 2020; Mansourian et al. 2018; Fuan et al. 2021; He et al. 2021; Haghighat Pour et al. 2018; Aliha et al. 2018, 2016; Pirmohammad and Bayat 2016, 2017; Motamedi et al. 2020; Najjar et al. 2020; Eghbali et al. 2019), edge-notched diametrically compressed (ENDC) disc specimen (Aliha et al. 2017a; Bahmani et al. 2021), edge crack torsion (ECT) specimen (Ahmadi-Moghadam and Taheri 2015), Modified compact tension specimen (Feng et al. 1993; Wang et al. 2020), compact, double notch diametral compression (DNDC) specimen (Mohammad Aliha et al. 2021), U-notch diametral compression (UNDC) specimen (Mohammad Aliha et al. 2021), rectangular beams subjected to three or four-point bend loading (Reis and Ferreira 2004a, 2003b; Guzlena and Sakale 2021; Avci et al. 2005; Krause and Fuller 1984; Kim et al. 2011; Aliha et al., 2021), semi-circular bend (SCB) specimen (Aliha et al. 2012a), and Brazilian disc (BD) specimen (Asdollah-Tabar et al. 2021; Martínez-López et al. 2016). However, a suitable fracture specimen has a simple geometry, easy preparation, and simple test setup. In this study, the SCB specimen is used for obtaining the mechanical and fracture parameters of the PC and FRPC material. The SCB specimens are

Table 3 Different mix designs contain resin, glass fiber, and fine and coarse aggregates (obtained using DOE software)

Mixture ID	Fine aggregates (%)	Coarse aggregates (%)	Resin (%)	Glass fiber (%)	β
UL1	50	33	15	2	1.5
	51	33	15	1	
	52	33	15	0	
UL2	52	31	15	2	1.7
	53	31	15	1	
	54	31	15	0	
UL3	54	29	15	2	1.9
	55	29	15	1	
	56	29	15	0	
L1	48	33	17	2	1.5
	49	33	17	1	
	50	33	17	0	
L2	50	31	17	2	1.7
	51	31	17	1	
	52	31	17	0	
L3	52	29	17	2	1.9
	53	29	17	1	
	54	29	17	0	
L4	54	27	17	2	2.1
	55	27	17	1	
	56	27	17	0	
ML1	48	31	19	2	1.5
	49	31	19	1	
	50	31	19	0	
ML2	50	29	19	2	1.7
	51	29	19	1	
	52	29	19	0	
ML3	52	27	19	2	1.9
	53	27	19	1	
	54	27	19	0	
ML4	52	25	19	2	2.1
	53	25	19	1	
	54	25	19	0	
MH1	44	33	21	2	1.5
	45	33	21	1	
	46	33	21	0	
MH2	46	31	21	2	1.7
	47	31	21	1	
	48	31	21	0	
MH3	48	29	21	2	1.9
	49	29	21	1	
	50	29	21	0	
MH4	50	27	21	2	2.1
	51	27	21	1	
	52	27	21	0	

Table 3 (continued)

Mixture ID	Fine aggregates (%)	Coarse aggregates (%)	Resin (%)	Glass fiber (%)	β
H1	44	31	23	2	1.5
	45	31	23	1	
	46	31	23	0	
H2	46	29	23	2	1.7
	47	29	23	1	
	48	29	23	0	
H3	48	27	23	2	1.9
	49	27	23	1	
	50	27	23	0	
H4	50	25	23	2	2.1
	51	25	23	1	
	52	25	23	0	
UH1	44	29	25	2	1.5
	45	29	25	1	
	46	29	25	0	
UH2	46	27	25	2	1.7
	47	27	25	1	
	48	27	25	0	
UH3	48	25	25	2	1.9
	49	25	25	1	
	50	25	25	0	

favorite because of their advantages, such as ease of casting and introducing the pre-crack, ease of testing, and lesser amount of material required for manufacturing the test sample. This type of specimen is suitable for conducting experiments on other construction and building materials such as asphalt concrete, polymer concrete, and cement concrete (Aliha et al. 2012a, 2020, 2017b; Fuan et al. 2021; He et al. 2021; Fattahi Amirdehi et al. 2019; Ameri et al. Jul. 2016; Fakhri et al. 2018a, 2020, 2018b; Aliha 2019; Mirsayar et al. Jan. 2017; Razmi and Mirsayar 2017; Yang et al. 2021; Somé et al. 2018; Aliha et al. Mar. 2020; Ziari et al. 2020; Xiongzhou et al. 2021; Mahdavi et al. 2020) and also geo-materials such as rocks (Aliha et al. 2012b, 2021; Aliha and Ayatollahi 2011; Mirsayar et al. 2018; Akbardoost et al. 2014; Aliha and Ayatollahi May 2013). In addition, the previously used test samples for investigating the behavior of PC materials are rectangular beams subjected to three or four-point bend loading (Reis and Ferreira 2004a, 2003b; Guzlena and Sakale 2021; Avci et al. 2005; Krause and Fuller 1984; Kim et al. 2011), semi-circular bend (SCB) specimen (Aliha et al. 2012a), and Brazilian disc (BD) specimen subjected to diametral compression (Asdollah-Tabar et al. 2021; Martínez-López et al. 2016).

Figure 3 illustrates two SCB specimens with and without pre-crack to measure fracture and tensile strength, respectively. Previously, Aliha et al. used these specimens to investigate the tensile strength and fracture resistance of a PC material with a fixed composition and mixture (Aliha et al. 2012a).

Although applied load for the test of SCB specimen is compressive, the stresses in specific locations of specimen become tensile (i.e., middle of the bottom edge of the SCB specimen in un-cracked SCB and tip of the crack in pre-cracked SCB). Due to these tensile stresses, the specimen is split into two halves at a critical level of the applied load. Consequently, the maximum critical tensile stress can determine material tensile strength. The mentioned method is called the indirect test method, and such method is often used for brittle and quasi-brittle materials, weak against the direct tensile loads.

Mode-I fracture is simulated by test in symmetric loading conditions. Due to load application, the stresses in the crack tip become tensile, and at a certain level of applied load, the specimen splits. The critical stress intensity factor of this specimen under mode-I condition that is known

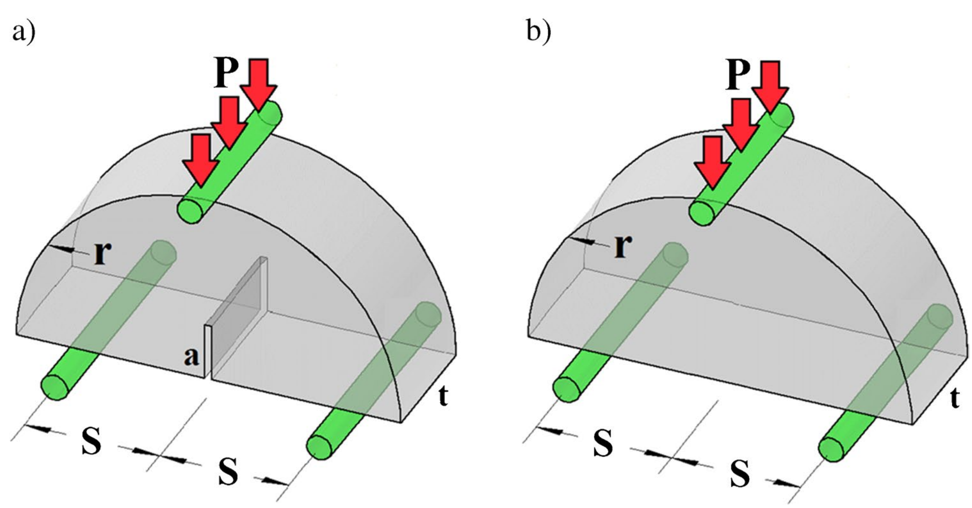

Fig. 3 Schematic illustration of semi-circular (SCB) test specimens, **a** pre-craked SCB for fracture test, **b** un-cracked SCB for the tensile strength test

as fracture toughness (K_{Ic}), is determined from the following equation based on the framework of linear elastic fracture mechanics (LEFM) concept (Ayatollahi and Aliha 2006):

$$K_{Ic} = Y_{SCB}\left(P_f/2rt\right)\sqrt{\pi a} \tag{3}$$

where r and t are the radius and thickness of the specimen, and a is the length of the crack; also P_f is the fracture load, and Y_{SCB} is the geometry factor for the SCB specimen that is a function of a/R and S/R (S is the span of supports). Based on Ayatollahi and Aliha (2006), the corresponding value of Y_{SCB} for the testing conditions ($a/R = 0.3$ and $S/R = 0.6$) was equal to 3.3.

The tensile strength of materials using the uncracked SCB specimen can be determined (Aliha et al. 2012a). Using the maximum load for un-cracked SCB specimen, the tensile strength (σ_t) value can be calculated from Eq. (4).

$$\sigma_t = \left(\frac{P_f}{\pi rt}\right)\left[0.073\left(\frac{t}{r}\right) + 0.8896\right]\left[2.01\left(\frac{S}{r}\right) + 1.052\right] \tag{4}$$

The ingredients with the given percentages were adequately mixed and then cast inside the PVC molds for manufacturing the test specimens. The diameter and heights of semi-circular specimens were 100 and 30 mm, respectively. After hardening the samples (24 h), the specimens were de-molded and cured in an 80 °C oven for 1 h. In fracture test specimens, a pre-crack of length 15 mm was introduced in the middle of the flat surface of each specimen using a narrow saw blade. A servo-hydraulic test machine loaded the samples with a constant span of 2S = 60 mm and a 1 mm/min loading rate for conducting the tests. Figure 4 shows the specimen placed in the loading machine.

Results and discussion

As expected, for the tensile strength and mode-I fracture tests, a vertical crack was developed in all tested specimens (e.g., Fig. 5). Close observations of fracture surface show that a suit number of fibers appear and fail on crack propagation surface. The crack path majorly crossed the resin region, and a small number of aggregates were fractured; this indicates the strength of silica aggregates.

Based on the loads obtained by the fracture and tensile strength tests, the fracture toughness and tensile strength of each mix-design are calculated and presented in Table 4.

Figure 6 shows the influence of fiber and resin values on the fracture toughness and tensile strength of PC materials. In this figure, order-2 polynomial trend lines were drawn on the data points for further evaluation. As seen, the fracture toughness and tensile strength of mixtures increase with the addition of glass fiber; however, this increase depends on resin content. With the increase of resin content, the optimum percentage of fiber rises, so that in mixtures with 15% resin content, the optimum fiber percentage is about 1.5%, while with an increase of resin percentage to 25%, the optimum fiber content is obtained as about 4%. In explaining such behavior, it can be said that, in mixtures with low resin content, the amount of

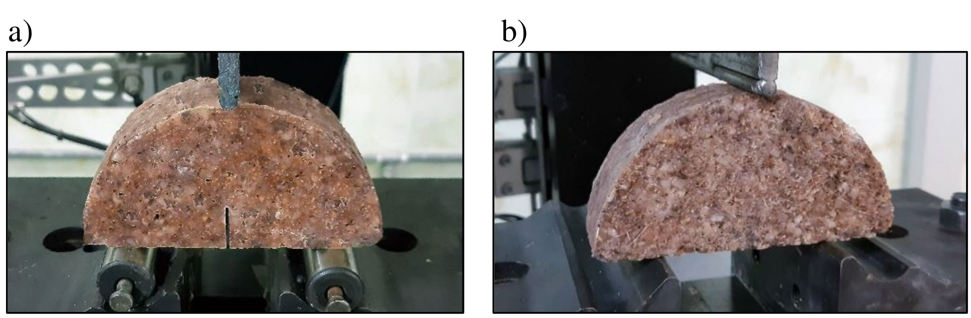

Fig. 4 SCB specimens placed in a three-point bend loading fixture which is mounted into the loading machine. **a** Pre-craked SCB for fracture test, **b** un-cracked SCB for the tensile strength test

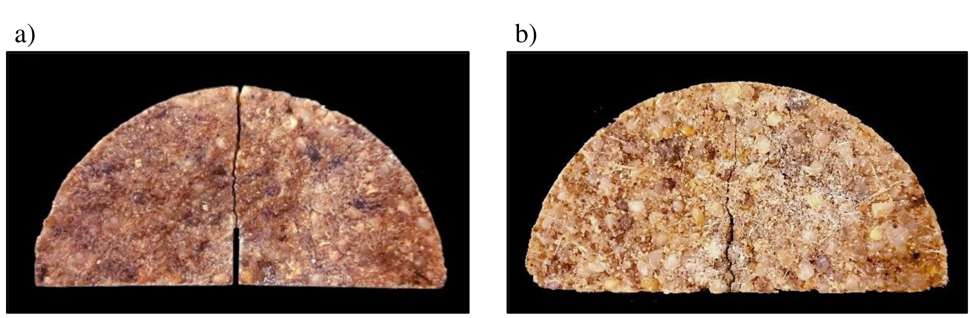

Fig. 5 Examples of observed crack propagation of specimens; **a** pre-craked SCB for fracture test, **b** un-cracked SCB for the tensile strength test

Table 4 Average loads and related standard deviation values obtained from tests and the calculated fracture toughness and tensile strengths

ID	Load obtained by fracture toughness test (N)		fracture toughness (MPa$\sqrt{m}$)	Load obtained by tensile strength test (N)		Tensile strength (MPa)
	Average	STDV		Average	STDV	
UL1	2717	134	0.65	11,139	1515	5.25
	2671	252	0.64	11,585	1390	5.46
	2022	91	0.48	9491	1167	4.47
UL2	3426	351	0.82	10,808	1153	5.09
	3190	340	0.76	10,027	1241	4.72
	2121	130	0.51	8211	588	3.87
UL3	3232	287	0.77	13,377	1175	6.30
	3297	349	0.79	11,821	1486	5.57
	2515	234	0.60	8987	744	4.23
L1	4145	233	0.99	21,141	1528	9.96
	4069	235	0.97	17,179	2539	8.09
	3461	225	0.83	15,475	1321	7.29
L2	4455	282	1.06	19,922	1644	9.39
	3674	285	0.88	14,486	2179	6.83
	3226	358	0.77	13,579	1246	6.40
L3	4615	439	1.10	19,054	1371	8.98
	4137	346	0.99	17,147	1187	8.08
	3360	291	0.80	15,453	1350	7.28
L4	4849	404	1.16	18,255	1914	8.60
	4724	350	1.13	19,878	2961	9.37
	3463	299	0.83	16,005	1690	7.54
ML1	6150	516	1.47	28,710	2196	13.53
	5210	447	1.24	25,266	3636	11.90
	4841	348	1.16	21,627	2498	10.19
ML2	6855	467	1.64	30,151	1957	14.21
	6430	495	1.54	29,788	2400	14.03
	4729	464	1.13	21,343	2823	10.06
ML3	6315	542	1.51	30,177	4442	14.22
	5840	463	1.39	26,424	4180	12.45
	5417	444	1.29	21,390	3152	10.08
ML4	7338	530	1.75	33,717	2740	15.89
	5851	488	1.40	28,537	3736	13.45
	5423	499	1.29	24,589	3559	11.59
MH1	6991	637	1.67	33,811	2867	15.93
	6182	526	1.48	28,786	4111	13.56
	5322	398	1.27	28,102	3921	13.24
MH2	7311	497	1.75	36,397	4350	17.15
	6528	608	1.56	30,839	2042	14.53
	5564	476	1.33	26,550	2246	12.51
MH3	7534	664	1.80	35,351	5020	16.66
	7074	488	1.69	34,262	3281	16.14
	5960	568	1.42	29,120	4437	13.72
MH4	7847	558	1.87	37,990	3271	17.90
	7613	512	1.82	36,074	4617	17.00
	6502	605	1.55	32,225	2338	15.18
H1	7869	640	1.88	35,581	4193	16.76
	7144	526	1.71	34,826	3193	16.41
	6396	435	1.53	30,149	3400	14.20

Table 4 (continued)

ID	Load obtained by fracture toughness test (N)		fracture toughness (MPa $\sqrt{m}$)	Load obtained by tensile strength test (N)		Tensile strength (MPa)
	Average	STDV		Average	STDV	
H2	8541	699	2.04	38,811	3563	18.29
	7729	604	1.85	38,517	4282	18.15
	6515	437	1.56	32,971	3537	15.53
H3	8940	663	2.13	43,008	5239	20.26
	7760	683	1.85	38,350	3678	18.07
	6630	572	1.58	32,489	4600	15.31
H4	9610	812	2.29	46,022	6949	21.68
	8778	746	2.10	43,249	3759	20.38
	6895	598	1.65	32,548	2450	15.33
UH1	9209	816	2.20	43,730	6027	20.60
	8546	714	2.04	39,434	3222	18.58
	7152	616	1.71	34,771	2149	16.38
UH2	9355	667	2.23	44,693	5672	21.06
	8418	672	2.01	39,692	2702	18.70
	7213	498	1.72	34,962	5085	16.47
UH3	9890	793	2.36	47,704	4515	22.48
	8909	696	2.13	42,958	3240	20.24
	7693	662	1.84	37,343	2676	17.59

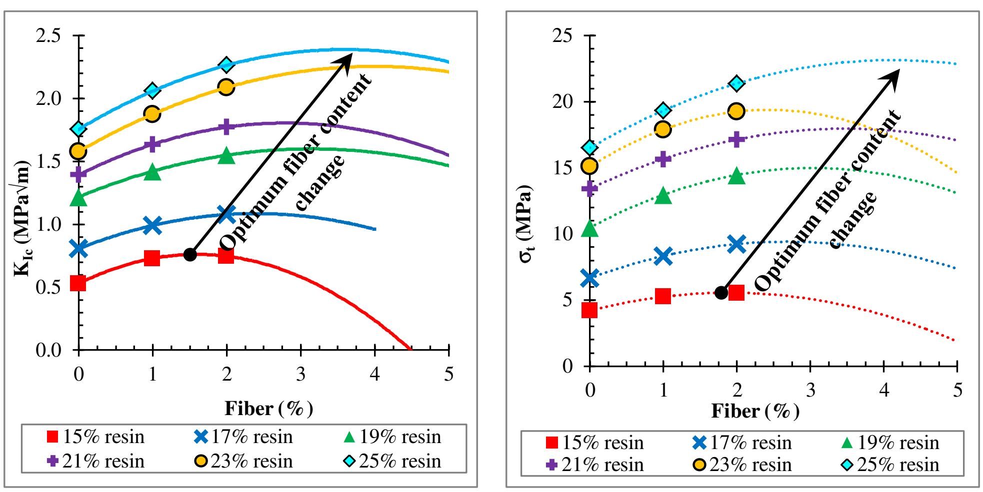

Fig. 6 Fracture toughness (**a**) and tensile strength (**b**) change due to fiber addition based on resin content (resin content of 15, 17, 19, 21, 23, and 25%), and the trend of optimum fiber content changes due to change in resin content

resin to cover the outer surface of the fiber is limited, and adding more fiber does not increase the strength. While with the increase of resin, the amount of resin to cover the outer surface of the fiber has increased, and a higher percentage of fiber can be used.

Figure 7 shows the trends of optimum fiber percentage obtained from Fig. 6. This figure shows that the trend of optimum fiber percentage obtained from both fracture toughness and tensile strength are similar. From the trends, it can be understood that the maximum fiber content that positively influences the FRPC mixture is about 4.1%.

Figure 8 shows resin percentage influence on fracture toughness and tensile strength of PC materials with different fiber percentages. The figure shows that the fracture toughness and tensile strength increase with the increase of resin content. However, this increase has a nonlinear relationship with resin content based on fiber percentage. The highest fracture toughness measured in the mixture without

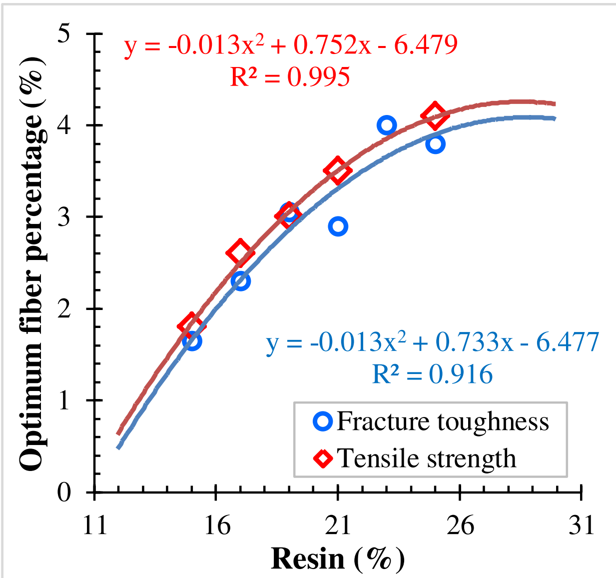

Fig. 7 The trend of optimum fiber content obtained from fracture toughness and tensile strength data

the fiber is limited to 1.75 MPa$\sqrt{m}$ (seen in the mixture with 25% resin). On the other hand, the highest fracture toughness measured in a mixture with 1% and 2% fiber reached 2.06 and 2.26 MPa$\sqrt{m}$, respectively. Also, the highest tensile strength measured in the mixture without the fiber is 17 MPa, (seen in the mixture with about 25% resin). On the other hand, the highest tensile strength measured for mixtures with 1 and 2 fiber percentages reaches 19.2 and 21.4 MPa, respectively.

Based on extrapolations, fracture toughness and tensile strength of mixtures can be increased further by increasing the resin content to about 30%. In addition, it can be seen that the minimum resin content in both PC and FRPC materials is about 13%; and the resin content below this percentage is unable to develop a proper matrix between ingredients.

Observation of specimens and their fracture surface shows the effect of resin content on the resulted mixture and specimens. As seen in Fig. 9a, an H specimen made with 23% resin content has a more uniform state with lower air voids than an L specimen with 17% resin content. This increase in air voids due to a decrease in resin content can also be seen in the fractured surface of specimens, so as can

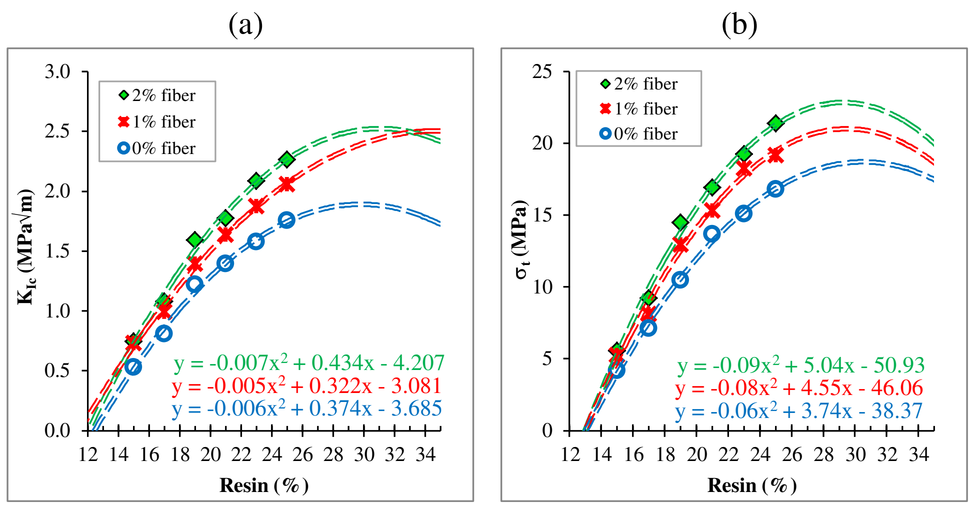

Fig. 8 Fracture toughness (**a**) and tensile strength (**b**) versus resin percentage based on fiber content (i.e., 0, 1, and 2%), the extrapolation shows the minimum resin content required for the development of matrix based on fiber content

Fig. 9 **a** View of specimens with high and low resin contents (left: an H series specimen and right: an L series specimen), **b** fractured surface of an L series specimen and the air voids

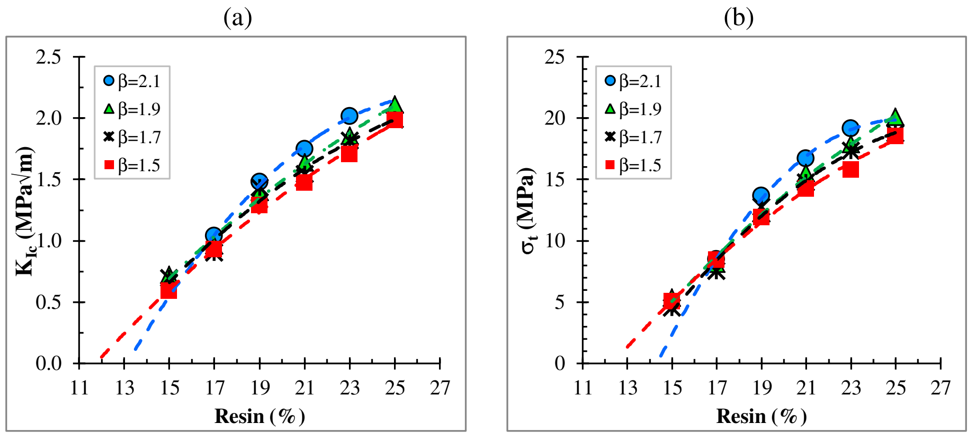

Fig. 10 Fracture toughness (**a**) and tensile strength (**b**) versus aggregates coarseness ratio ($\beta = 2.1$, $\beta = 1.9$, $\beta = 1.7$, $\beta = 1.5$), the extrapolation shows the minimum resin content required for the development of matrix based on aggregate size

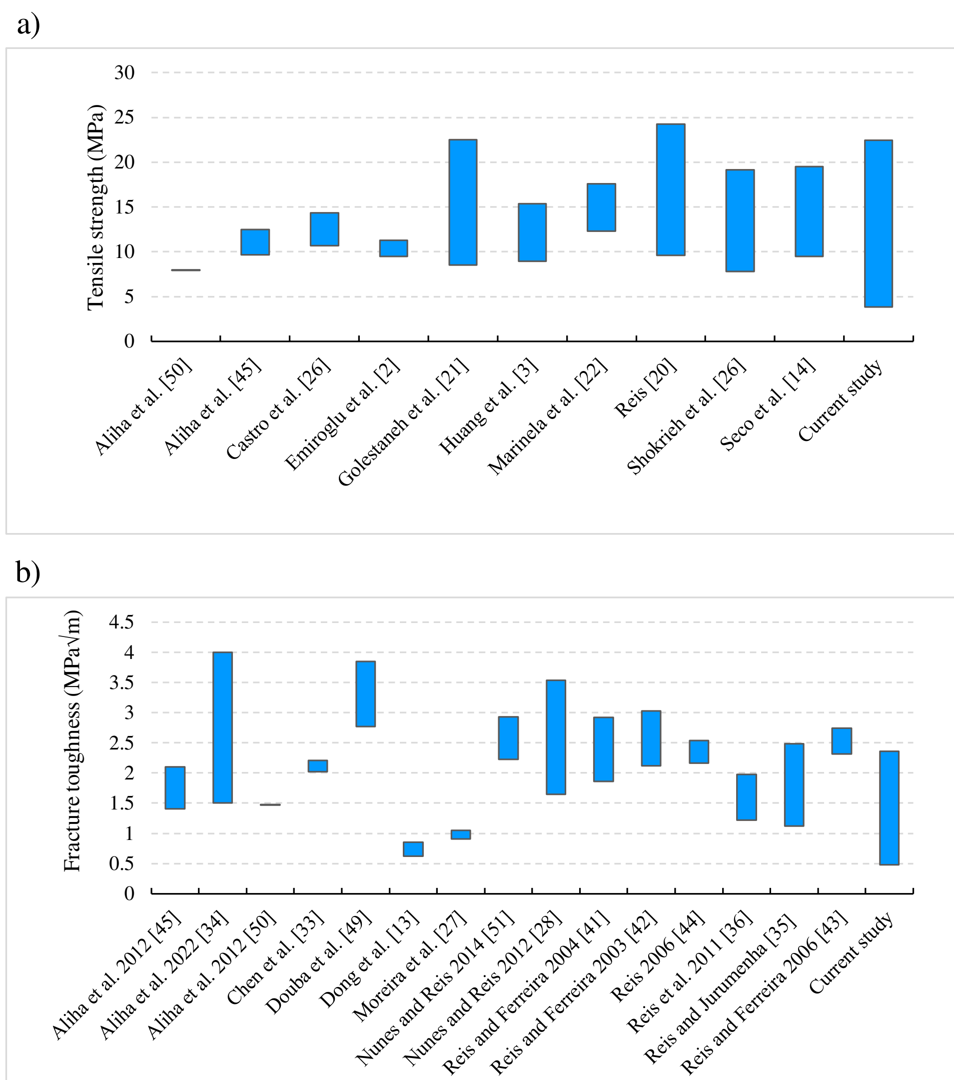

Fig. 11 Compression of the results obtained by the test of different PC materials in current and other studies. **a** Tensile strength, **b** Fracture toughness

be seen in Fig. 9b, a considerable number of air voids can be seen in the mid-section of an L series specimen.

Figure 10 shows the influence of aggregate size on fracture toughness and tensile strength of PC materials with different resin percentages. From this figure, it can be understood that with the decrease in aggregate sizes (lower β value), the fracture toughness and tensile strength of the mixture increase. However, increasing the outer surface due to the reduction of aggregate size increases the minimum resin content (13% for $\beta = 1.5$ and 14% for $\beta = 14\%$). In other words, although the minimum resin content for PC made of finer aggregates is slightly higher, in mixtures with higher resin contents, the strength of the mixture made of finer aggregates is higher.

Comparison with other studies

For decades, several researchers have evaluated the mechanical strength of polymer concretes containing different types, sizes, or percentages of aggregates, fillers, and fibers. To assess the mechanical characteristics of PC material evaluated in the current study, the results of some of the related investigations are compared with data obtained in the current study (Fig. 11). These researchers used different types of epoxy resin to produce polymer concrete with different fibers or fillers. As seen, most of these researches obtained the tensile strength and fracture toughness in the same range (about 5 to 25 MPa for tensile strength and 0.62 to 4.0 MPa$\sqrt{m}$ for fracture toughness), which is in agreement with the range of results of the current study (about 3.9 to 22. MPa for tensile strength and 0.48 to 2.36 MPa$\sqrt{m}$ for fracture toughness).

Conclusion

The current paper studied the effect of percentages of ingredients (i.e., resin, fine and coarse silica aggregates, and E-glass fibers) on tensile strength and fracture toughness experimentally. Using SCB specimen, different mixes made of 15 to 25% resin, 45 to 55% coarse aggregate, 35 to 45% fine aggregate, and 0 to 2% short fiber were tested. Based on the results, the following conclusions can be drawn:

- The experimental results show the noticeable influence of mixture compositions on the fracture load and tested polymer concrete materials. All the compositions affect resulted strengths; however, the effect of resin content is more significant.
- Results showed that the FRPC fracture toughness and tensile strength values increase with increasing the fiber percentages and resin percentage; however, the addition of fiber more than a certain amount (optimum percentage) has a negative effect on the strength of the mixture. Results show that with the increase of resin content from 15 to 25%, fracture toughness and tensile strength increase by about 250 and 325%, respectively.
- The optimum fiber percentage is highly dependent on resin content. In mixtures with 15% resin content, the optimum fiber content is about 1.5%, and with the increase of resin content to 25%, the optimum fiber content increase to about 4.0%. In other words, by increasing the proportion of the matrix relative to the other ingredients, the acceptance of the fiber in the matrix increases.
- The minimum resin content for PC and FRPC material is about 12%. However, the size of the aggregate affects the minimum resin content required for the development of the matrix, so that the minimum resin content for the mixture made of fines aggregates (used in the current study) is about 2% higher than the minimum resin content for the coarsest aggregates used in the current study. Such behavior can be related to the higher outer surface of the finer aggregates and the higher required resin content to develop a firm matrix.

Acknowledgements We would like to thank Khorramshahr University of Marine Science and Technology for supporting this work under research grant No.181.

Declarations

Competing interests The authors declare no competing interests.

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