

## **A NOVEL POLYMER CONCRETE MADE FROM FINE SILICA SAND AND POLYESTER**

**M. M. Shokrieh,\* S. Rezvani, and R. Mosalmani**

***Keywords:** polymer concrete, silica sand, polyester, compression strength, flexural strength, micromechanics*

*In order to improve the mechanical properties and decrease the manufacturing costs of traditional polymer concrete, a new concrete mix is presented, where fine silica sand is used instead of common large and small aggregates. In addition, to decrease manufacturing costs, a polyester resin is employed instead of epoxy matrix. By performing compression and three-point bending tests, it was found that the new polymer concrete had a higher compression strength than the traditional polymer concrete and a similar bending strength. Also, a two-phase micromechanical model was used to analytically estimate the compressive strength of the new material, and a rather good agreement between experimental data and theoretical calculations was found to exist.*

### **1. Introduction**

Polymer concrete (PC) is a composite material made from such mineral aggregates as sand and gravel in combination with a polymer. It has a very high compression strength, which is higher than that of the ordinary cement concrete [1]. Also, due to the adequate bonding between the aggregates and resin, this type of concrete exhibits higher tensile and bending strengths than the ordinary cement concrete [2]. The high permeability, low abrasion resistance, low frost resistance, long curing time, and such phenomena such as cavitation and corrosion due to chlorine infiltration are some of drawbacks of the ordinary cement concrete; but in PCs, all these weaknesses are reduced considerably [3]. Also, because of its lower density, polymer concrete can withstand dynamic loads better than the ordinary cement concrete [4]. One of the most prominent characteristics of polymer concrete is its very high resistance to corrosive and chemical environments [5]. With these fine characteristics, polymer concrete has been increasingly substituting cement concrete in many applications, including construction industry and such structural engineering applications as coverings of highway surfaces, bridge deckings, pavement overlays, sewer

---

Composites Research Laboratory, Center of Excellence in Experimental Solid Mechanics and Dynamics, School of Mechanical Engineering, Iran University of Science and Technology, Tehran, 16846-13114, Iran

\*Corresponding author; tel.: +9821-7720-8127; e-mail: shokrieh@iust.ac.ir

---

Russian translation published in *Mekhanika Kompozitnykh Materialov*, Vol. 51, No. 5, pp. 807-820, September-October, 2015. Original article submitted October 31, 2014.

pipes, structural and decorative panels, and repairs of concrete cracks [6]. For example, as a practical application, drinking water filtration slabs for the Tehran water distillation plant recently have been designed and manufactured using PC [7].

The increase in construction costs and the restriction in using it at elevated temperatures due to the resin involved are the drawbacks of polymer concrete. Also, since the resins utilized in this type of concrete are not water-soluble, production of a polymer concrete is much more difficult than of cement concrete. Many researchers have attempted to improve the strength of polymer concrete. Some of these attempts are briefly described in the following section.

Different compositions of polymer concrete and their properties and applications have been reported extensively [8-12]. The most important factors having a significant influence on the application and performance of polymer concrete are the specific polymeric binder and the type of aggregate and its gradation [13]. In order to obtain a dense packing, the distribution of aggregates should be such as to secure a minimum volume of voids in dry packed aggregates [14]. To achieve a dense packing of aggregates in the polymeric matrix, which results in better properties of concrete, either the void content in the aggregate mix can be minimized [15] or a loosely packed aggregate mix with a higher binder content can be used. Though the aggregate and microfiller form the major component of the total mass of polymer concrete, there has not been much emphasis on the aggregate and microfiller mix proportion used in such systems. A review of the literature shows that the aggregates used in polymer concretes are either fine particles [16] or the distribution of particle sizes is chosen on a theoretical basis [17] suitable for Portland cement concretes. The effect of aggregate mix proportion on the void content and a method to optimize the mix proportion to have a minimum void content are reported [18].

Vipulanandan and Mantrala [19] investigated the performance of a polymer concrete made with polyester resin and of a polymer concrete reinforced with glass fibers. In their research, the static properties, including stress-strain equations, elastic modulus, Poisson's ratio, and the maximum stresses and strains, of the concretes were studied. On adding 6 wt.% of glass fibers to the PC, their compressive strength increased to 16%. Using different percentages of resin and various types of resins, Abdelfattah and El-Hawary [20] explored the bending strength of polymer concretes. Reis and Ferreira [21] utilized carbon and glass fibers to improve the fracture and bending properties of polymer concrete. The addition of the fibers in low amounts (up to 2%) increased the fracture resistance of concrete by 13%. Reis [22] also studied the improvement of the bending characteristics of polymer concrete by means of natural fibers. A comparison between polymer concretes with and without these fibers was carried out. It was found that the addition of certain natural fibers (e.g., coconut fibers) led to an increased bending strength of concrete. Heidari-Rarani, et al. [23] investigated the mechanical durability of an optimized epoxy PC, focusing on the tensile strength and mode I fracture toughness, under three different freeze-thaw cycles. The fracture toughness and tensile strength of the tested PC materials decreased with increasing mean temperature of the thermal cycles.

In most of the existing research works regarding the estimation of the elastic and strength properties of PC, the models of cement concrete are employed. Aitcin and Neville [24] demonstrated that the strength of a regular-strength concrete is controlled by the strength of cement paste. Aitcin and Mehta [25] showed that the compressive strength of a high-strength concrete is limited by the strength of its aggregates. Ouaar [26] studied the mechanical properties of multiphase composite materials independent of loading rate. Pasa Dutra et al. [27] used micromechanics equations to estimate the elastic and viscoelastic properties of a cement concrete reinforced with microfibers.

In the present paper, a new compound is proposed for producing polymer concrete, where, instead of using ordinary large- and small-size aggregates and mixing them in a suitable proportion, fine silica sand can be employed as the aggregate. In addition, a polyester resin was taken instead of epoxy matrix. The compression and bending strengths of the newly developed PC were obtained by testing. Also, a two-phase micromechanical model is employed to predict the compressive properties of the PC. In order to evaluate the micromechanical model presented, predictions are compared with experimental data.

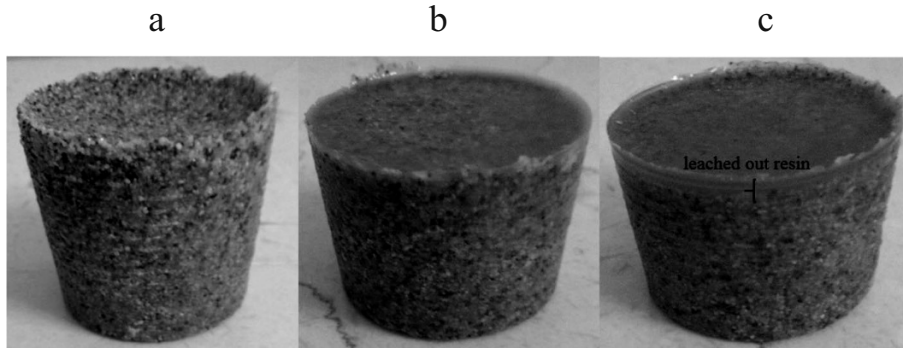


Fig. 1. Polymer concrete samples made with (a) 20, (b) 25, and (c) 30 wt.% of resin.

## 2. Experimental Procedures

### 2.1. Materials

The polymer concrete investigated in this research was produced by combining fine silica and a Bushepol 751129 polyester resin made by the Bushehr Chemical Industries. One of the important properties of this resin is its exceptional corrosion resistance to sea water; it is basically used in the structural components of boats, pipes, sanitary equipment, swimming pools, Jacuzzis, etc. The monomer of this resin is styrene; for every 100 g of resin, 1.1 ml of peroxide and 0.09 ml of cobalt must be combined with this monomer at a temperature of 25°C. The mechanical and physical specifications of this resin are as follows: strength 75 MPa, flexural strength 100 MPa, elastic modulus 3.5 GPa, Poisson's ratio 0.4, elongation at break 4 %, density 1050 kg/m<sup>3</sup>, viscosity 600 mP · s (at 25°C), gel time 27 min, shelf life 6 mth, and heat deflection temperature 80°C.

It should be mentioned that, in this study, the compressive strength of concrete  $\sigma_{\max}^c$  is considered to be 1.6 times its tensile strength  $\sigma_{\max}^t$ . This value was obtained from the equation [28]

$$\log \frac{\sigma_{\max}^c}{\sigma_{\max}^t} = 2.2 - 5\nu,$$

where  $\nu$  is Poisson's ratio of the polymer.

The major aggregate used in polymer concretes is siliceous compounds, because they are compatible with the common resins used in PCs and make good adhesion to polymeric resins. The aggregate used in this research is fine silica sand, with the maximum diameter of grains of 5 mm, produced by the Damavand Casting Sand Co. This is the strongest type of sand known in the market of construction materials and includes 96-98.11% SiO<sub>2</sub>, 0.2-0.7% Fe<sub>2</sub>O<sub>3</sub>, 0.51-1.65% Al<sub>2</sub>O<sub>3</sub>, 0.4-0.7% CaO, 0.03-0.08% Na<sub>2</sub>O, and 0.09-0.15% K<sub>2</sub>O.

Since the same type of sand was utilized both in this research and in [4], the values of its elastic modulus 4.5 GPa, Poisson's ratio 0.2, and yield strength 69 MPa were taken from the reference cited.

### 2.2. Manufacturing method

To produce samples, first, the sand was washed and dried. The resin was completely mixed with cobalt, and then an acid was added to the mixture. The compound obtained was poured over the sand and thoroughly blended to uniformly disperse sand grains in the resin. The sand-resin mixture was poured into molds and cured at room temperature for seven days. The inner surfaces of these composite molds were covered with a thin release film before molding the concrete mixture.

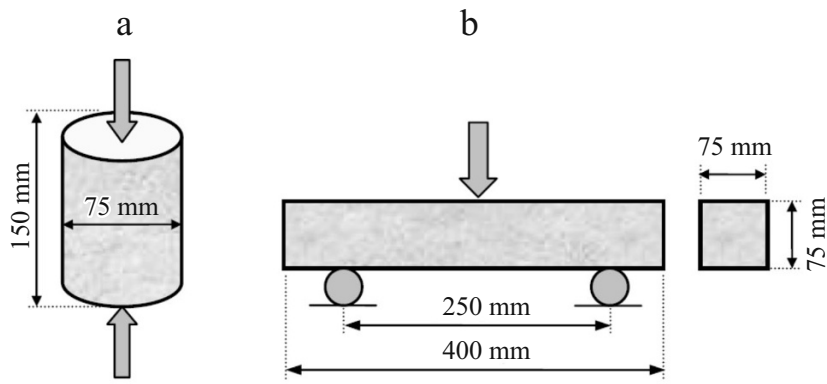


Fig. 2. Compression and bending test specimens.

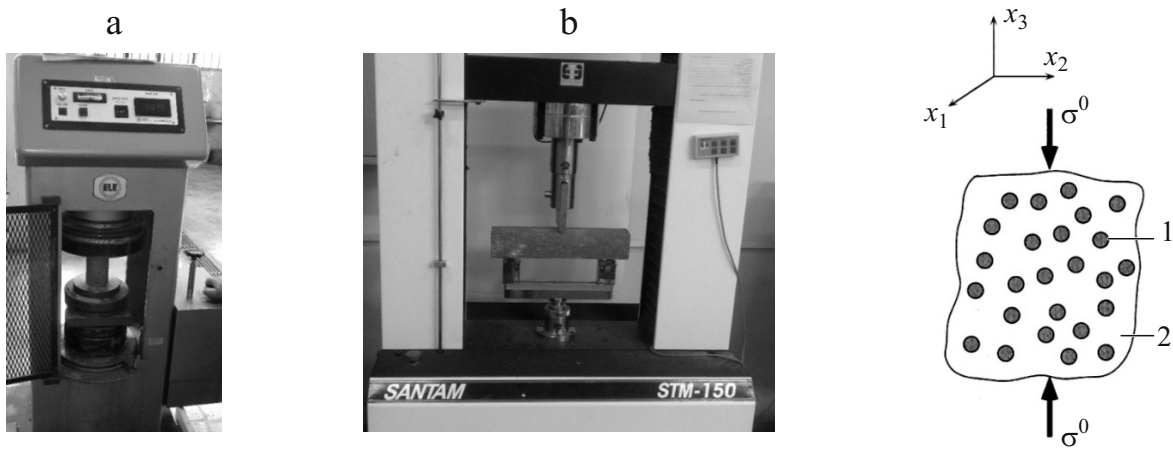


Fig. 3. Compression (a) and three-point bending (b) test setups.

Fig. 4. Spherical inclusions (1) embedded in an isotropic infinite body (2) subjected to a uniaxial compression stress  $\sigma^0$ .

The weight percent of resin normally used in making polymer concrete is usually between 10 and 20 wt.%. However, since, in this research, only sand was used, the resin had to coat a larger total surface of aggregates than in the case of larger aggregates. Therefore, after making several samples and qualitatively examining the amount of the leached-out resin and the bonding of sand grains to one another, 25 wt.% of resin was used in this research. As shown in Fig. 1a, in the sample made with 20 wt.% resin, the sand grains did not have sufficient adhesion, and the surfaces were rough and uneven. In the sample made with 30 wt.% resin (Fig. 1c), there was a large amount of leached-out resin, which indicated that an excessive quantity of resin had been used. But in the sample made with 25 wt.% resin (Fig. 1b), the surfaces were smooth, the bonding between sand grains was adequate, and a negligible amount of resin had leached out.

### 2.3. Mechanical tests

In this research, compression and bending tests were carried out to investigate the mechanical properties of polymer concrete samples. The compression test was performed according to the ASTM C39-49 standard [29]. In this test, the upper jaw of the testing machine compresses a cylindrical sample with a diameter of 75 mm and height of 150 mm at a speed

TABLE 1. Results of Compression Tests

Sample number	Maximum applied load, kN	Area, cm <sup>2</sup>	Compression strength, MPa
1	325.3	44.41	73.24
2	328.7	44.53	73.18
3	340.8	44.06	77.35
4	359.5	44.18	81.37

\*Average value — 76.44 MPa.

of 5 mm/min. To obtain the bending strength, the three-point bending test was used according to the ASTM C293-554T standard [30]. In this test, rectangular prismatic samples with dimensions of 400 × 75 × 75 mm are subjected to bending. Figure 2 shows the dimensions of samples and loadings in the compression and three-point bending tests.

Figure 3 illustrates the testing machines and the way the samples are placed in these machines in compression and bending tests, respectively.

### 3. Two-Phase Micromechanical Model for Estimating the Compression Strength of PC

The two-phase model presented by Yang and Huang [31] for estimating the compression strength of cement concrete is a micromechanical model in which the average stress field of inhomogeneities and matrix is expressed by using the inclusion method [32] and the Mori–Tanaka theoretical concept [33]. This model is used in this paper for the polymer concrete under investigation. Polymer concrete can be considered as a composite material; therefore, its compression strength is obtained as a function of properties of its constituent materials and the volume fraction of aggregates. The compression strength of concrete is controlled by the strength of its weakest component. Moreover, in this model, it is assumed that there is a perfect bonding between the aggregates and matrix and that the geometry of the inhomogeneity for determining the Eshelby tensor is spherical.

Considering the fact that the spherical inhomogeneities ( $\Omega = \sum_{i=1}^N \Omega_i$ ) with an elastic moduli  $\tilde{C}^*$  and volume fraction  $V_f$  are randomly located in an infinite matrix with an elastic moduli  $\tilde{C}$  (according to Fig. 4), the distribution of the stress generated by an applied compressive stress  $\tilde{\sigma}_0$  can be simulated by the eigenstress caused by a fictitious misfit strain. Actually, a fictitious misfit strain i.e., the eigenstrain  $\varepsilon^*$  is introduced to simulate the effect of inhomogeneity.

Using the equivalent inclusion method and the Mori–Tanaka theory, the ultimate stress in an inhomogeneity is obtained as follows:

$$\tilde{\sigma}_0 + \langle \tilde{\sigma} \rangle_{\Omega} = \tilde{C} \left\{ \tilde{C}^{-1} (\tilde{\sigma}_0 + \langle \tilde{\sigma} \rangle_M) + \langle \widetilde{\Delta\gamma} \rangle - \langle \varepsilon^* \rangle \right\} \quad (1)$$

or

$$\tilde{\sigma}_0 + \langle \tilde{\sigma} \rangle_{\Omega} = \tilde{C}^* \left\{ \tilde{C}^{-1} (\tilde{\sigma}_0 + \langle \tilde{\sigma} \rangle_M) + \langle \widetilde{\Delta\gamma} \rangle \right\}, \quad (2)$$

where  $\tilde{\sigma}_0 + \langle \tilde{\sigma} \rangle_{\Omega}$  is the average stress in an inhomogeneity,  $\langle \tilde{\sigma} \rangle_M$  is the average stress in the matrix, and  $\langle \widetilde{\Delta\gamma} \rangle$  is the average distribution of the strain produced by the eigenstrain  $\langle \varepsilon^* \rangle$  in an inhomogeneity, which is related to the eigenstrain in the following way:

$$\langle \widetilde{\Delta\gamma} \rangle = S^{es} \langle \varepsilon^* \rangle, \quad (3)$$

where  $S^{es}$  is the Eshelby tensor for a single inhomogeneity located in an infinite homogeneous material. The Eshelby tensor is a function of geometry of the inhomogeneity and the Poisson's ratio of matrix.

The average disturbance stress ( $\tilde{\sigma}$ ) is zero [34], i.e.,

$$V_f \langle \tilde{\sigma} \rangle_{\Omega} + (1 - V_f) \langle \tilde{\sigma} \rangle_M = 0. \quad (4)$$

The average disturbance stress in the inhomogeneity,  $\langle \tilde{\sigma} \rangle_{\Omega}$ , is obtained by solving Eq. (1) and Eq. (3), i.e.,

$$\langle \tilde{\sigma} \rangle_{\Omega} = \langle \tilde{\sigma} \rangle_M + \tilde{C}(S^{es} - I) \langle \varepsilon^* \rangle, \quad (5)$$

where  $I$  is the unit tensor. The second term in Eq. (4),  $\tilde{C}(S^{es} - I) \langle \varepsilon^* \rangle$ , is the average stress field in the inclusion when only one inclusion is considered. The average stress in the inclusion is taken as the sum of the average stress in the matrix and the stress in a single inclusion. This corresponds to the basic assumption in the Mori–Tanaka theory.

Inserting Eq. (5) into Eq. (4), the average disturbance stress in the matrix  $\langle \tilde{\sigma} \rangle_M$  is calculated as

$$\langle \tilde{\sigma} \rangle_M = -V_f \tilde{C}(S^{es} - I) \langle \varepsilon^* \rangle. \quad (6)$$

Using Eqs. (5) and (6), the average disturbance stress in the inhomogeneity  $\langle \tilde{\sigma} \rangle_{\Omega}$  is rewritten as

$$\langle \tilde{\sigma} \rangle_{\Omega} = (1 - V_f) \tilde{C}(S^{es} - I) \langle \varepsilon^* \rangle. \quad (7)$$

Inserting Eqs. (6) and (7) into Eq. (2) and solving it for  $\langle \varepsilon^* \rangle$ , we have

$$\langle \varepsilon^* \rangle = \alpha^{-1} (\tilde{C} - \tilde{C}^*) \tilde{C}^{-1} \tilde{\sigma}_0, \quad (8)$$

where

$$\alpha = (1 - V_f)(\tilde{C}^* - \tilde{C})S^{es} - V_f(\tilde{C} - \tilde{C}^*) + \tilde{C}.$$

Inserting Eq. (8) into Eqs. (6) and (7), the average total stresses in the matrix and in the inhomogeneity are obtained as

$$\tilde{\sigma}_0 + \langle \tilde{\sigma} \rangle_M = [I - V_f \tilde{C}(S^{es} - I) \alpha^{-1} (\tilde{C} - \tilde{C}^*) \tilde{C}^{-1}] \tilde{\sigma}_0$$

and

$$\tilde{\sigma}_0 + \langle \tilde{\sigma} \rangle_{\Omega} = [(1 - V_f) \tilde{C}(S^{es} - I) \alpha^{-1} (\tilde{C} - \tilde{C}^*) \tilde{C}^{-1} + I] \tilde{\sigma}_0.$$

The ultimate stresses applied to the matrix and inhomogeneity,  $\sigma_{0_m}$  and  $\sigma_{0_{\Omega}}$ , respectively, are obtained when the average stress reaches the strength of matrix or inhomogeneity. Now, if the ultimate stress applied to the matrix is lower than the ultimate stress applied to the inhomogeneity ( $\sigma_{0_{\Omega}} > \sigma_{0_m}$ ), the compression strength of the composite material  $f_c$  is controlled by the strength of matrix,  $f_m$ . If the ultimate stress applied to the matrix is higher than the ultimate stress applied to the inhomogeneity ( $\sigma_{0_{\Omega}} < \sigma_{0_m}$ ), the compression strength of the composite material  $f_c$  is controlled by the strength of inhomogeneity  $f_{\alpha}$ .

When the average stress of matrix  $\tilde{\sigma}_0 + \langle \tilde{\sigma} \rangle_M$ , reaches the compression strength of matrix  $f_m$ , the ultimate compressive stress  $\sigma_{0_m}$  is obtained by the

$$\sigma_{0_m} = [I - V_f \tilde{C}(S^{es} - I) \alpha^{-1} (\tilde{C} - \tilde{C}^*) \tilde{C}^{-1}]^{-1} f_m. \quad (9)$$

When the average stress of inhomogeneity  $\tilde{\sigma}_0 + \langle \tilde{\sigma} \rangle_{\Omega}$  reaches the compression strength of inhomogeneity  $f_{\alpha}$ , the ultimate compression stress is obtained by the equation

$$\sigma_{0_{\Omega}} = [(1 - V_f) \tilde{C}(S^{es} - I) \alpha^{-1} (\tilde{C} - \tilde{C}^*) \tilde{C}^{-1} + I]^{-1} f_{\alpha}. \quad (10)$$

Therefore, the compression strength of the composite material  $f_c$  is equal to the lower of the value of  $\sigma_{0_m}$  and  $\sigma_{0_{\Omega}}$ . The compression strength of concrete is not always limited to the compression strength of its constituents — it may be higher in certain cases.

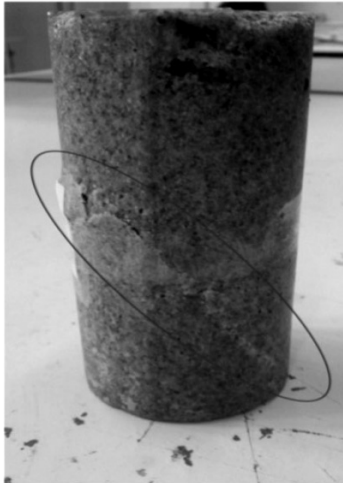


Fig. 5. Fracture surface in a polymer concrete sample subjected to compression.

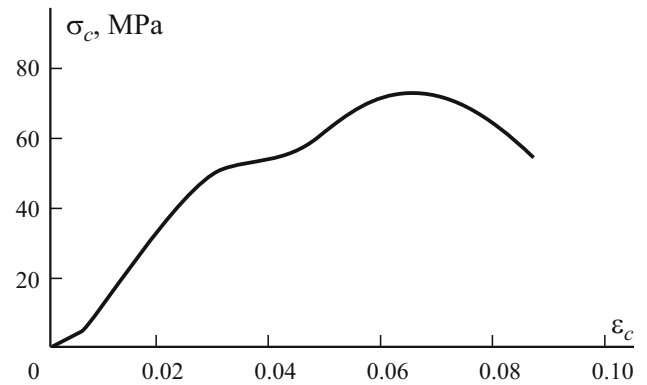


Fig. 6. Compression stress  $\sigma_c$  vs. strain  $\varepsilon_c$  for a concrete sample.

TABLE 2. Results of Three-Point Bending Tests

Sample number	Maximum applied load, kN	Width	Height	Bending strength*, MPa
		cm		
1	23	7.42	7.55	20.39
2	21	7.43	7.55	18.59
3	23	7.41	7.58	20.26
4	22	7.44	7.54	19.50

\*Average bending strength — 19.69 MPa.

## 4. Results

### 4.1. Compression test

The results of compression tests performed on four polymer concrete samples made of 25 wt.% polyester resin and 75 wt.% silica sand are listed in Table 1. The density of the concrete was 1834 kg/m<sup>3</sup>.

Figure 5 shows the fracture surface of a polymer concrete sample subjected to compression. As seen, the test piece fractured appropriately (at the maximum shear load), and the slope of the fracture surface was almost 45°.

Figure 6 illustrates the diagram of compression stress  $\sigma_c$  vs. strain  $\varepsilon_c$  for a concrete sample.

Comparing the densities and compression strengths of the PC and common cement concretes (density of 2400 kg/m<sup>3</sup> and compressive strength of 28 MPa [35]), it can be concluded that the present PC by 24% lighter and 2.73 times stronger than the cement concrete.

### 4.2. Bending test

The results of bending tests on four polymer concrete samples made by combining 25 wt.% polyester resin with 75 wt. % silica sand are listed in Table 2. The bending strength was obtained by using the equation presented in the test standard.

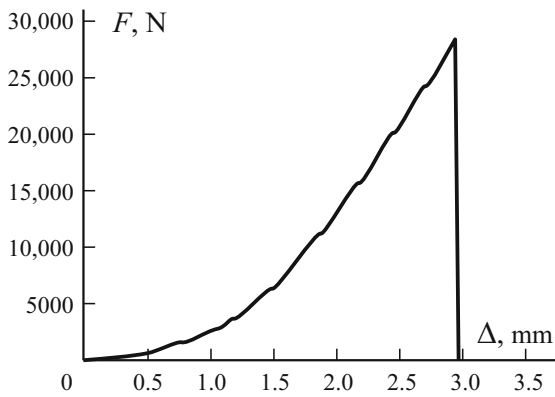


Fig. 7. Bending force  $F$  vs. midspan displacement  $\Delta$  for a test sample.

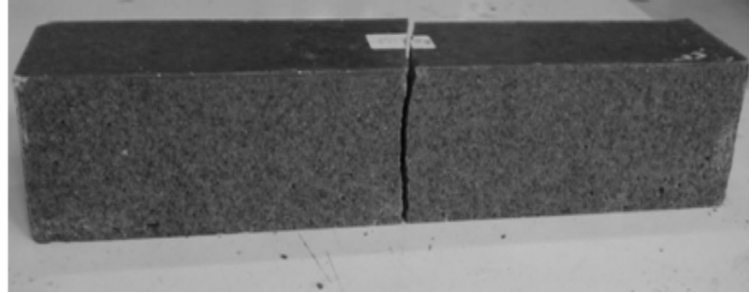


Fig. 8. Fracture surface of a polymer concrete sample broken in bending.

From this table, it is seen that the bending strength of the PC was significantly higher than that of cement concrete. The bending strength of cement concrete is usually considered to be 10-20% of its compression strength.

Figure 7 shows the diagram of bending force  $F$  vs. midspan displacement  $\Delta$  for a test sample.

Figure 8 shows the fracture surface of a polymer concrete sample broken in bending.

#### 4.3. Estimating the compression strength by means of the two-phase model

By calculating the volumes of aggregate and resin and the total volume of a concrete sample, the volume fractions of sand and resin were found to be 0.554 and 0.446, respectively. Considering the mechanical properties of the resin and aggregate and using Eqs. (9) and (10), the compression strength of the polymer concrete produced was estimated at 71.20 MPa by using the two-phase micromechanical model, which by 6.8% deviated from the average strength obtained from tests. According to this model, the compression strength of concrete is limited by that of aggregate, because, when the average stress of inhomogeneity  $\tilde{\sigma}_0 + \langle \tilde{\sigma} \rangle_{\Omega}$  reaches the compression strength of inhomogeneity  $f_{\alpha}$ , the ultimate compression stress is approximated as 71.20 MPa. When the average stress of matrix  $\tilde{\sigma}_0 + \langle \tilde{\sigma} \rangle_M$  reaches the compression strength of matrix  $f_m$  the ultimate compression stress is approximated as 86.68 MPa, which is considerably higher than 71.20 MPa. Therefore, if aggregates with a higher strength are used, the resin will be able to withstand even greater loads.

#### 4.4. Comparison with results for an epoxy PC

In order to clarify how much the mechanical characteristics of the concrete produced exceed those of other common polymer concretes, a comparison was made between the mechanical properties of the polymer concrete investigated and the epoxy concrete considered in [36]. The results of this comparison are presented in Table 3. The concrete studied in [36] was a mixture of 19 wt.% epoxy resin, 0.5 wt.% glass fibers, and 80.5 wt.% aggregate (including 40 wt.% siliceous fillers and 60 wt.% aggregates with diameters of 2 to 4 mm).

From the data given in Table 3, it can be concluded that, although the epoxy resin has a higher strength than the polyester resin, the use of fine-grain aggregates in the PC proposed, by reducing the density and porosity of concrete and stress concentrations in it, has led to a compression strength exceeding that of the epoxy PC considered in [36] and a bending strength almost equal to that of the latter one. Also, the PC considered in this paper has a lower density and a greater fracture strain, which is due to the higher weight percent of resin than that in the epoxy concrete [36].



TABLE 3. Comparison Between the Mechanical Properties of the PC Investigated and the Epoxy Concrete Considered in [36]

PC	Compression strength $\sigma_c$ , MPa	Bending strength $\sigma_b$ , MPa	Midplane displacement at break in bending, mm	Density, kg/m <sup>3</sup>
Present	76.44	19.69	2.96	1834
Epoxy [36]	63.32	19.51	1.40	2020

## 5. Conclusion

In this research, in order to improve the mechanical properties and to reduce the production cost of the traditional polymer concrete, a new formulation of polymer concrete with fine silica sand and polyester resin is proposed. The compression and bending strengths of the new PC were determined by performing relevant tests. A comparison of the results obtained with data for the traditional polymer concrete compounds pointed to a 20% higher strength, a 9.2% lower density, and reduced brittleness of the concrete proposed, while the bending strengths were almost the same. The compression strength of the present PC was estimated by using a two-phase micromechanical model, and an error of only 6.8% was obtained. This small error indicates that the two-phase model used is able to estimate the strength of polymer concretes with two phases — aggregates and a polymer.

## REFERENCES

1. B. W. Jo, S. K. Park, and J. C. Park, "Mechanical properties of polymer concrete made with recycled PET and recycled concrete aggregates," *Construction and Building Materials*, **22**, 2281-2291 (2008).
2. A. Blaga and J. J. Beaudoin, *Polymer Concrete*, Division of Building Research, National Research Council Canada, Canadian Building Digest **241**, Ottawa, 1985.
3. Y. Ohama, "Recent progress in polymer mortar and concrete in Japan," *Proc. of the Second East Asia Symp. on Polymers in Concrete (II - EASPIC)*, London, 21-30 (1997).
4. M. Elahi, *Estimation of Elastic Behavior of Polymer Concrete Using Micromechanical Methods*, MSc Thesis, Department of Mechanical Engineering, Iran University of Science and Technology, Tehran, 2011.
5. E. Kashizadeh, *Effect of Heating and Cooling Cycles on Mechanical Properties of Polymer Concrete*, MSc Thesis, Department of Mechanical Engineering, Iran University of Science and Technology, Tehran, 2008.
6. A. Camille and D. Pauls, "Experimental study of epoxy repairing of cracks in concrete," *Construction and Building Materials*, **21**, 157-63 (2007).
7. M. M. Shokrieh and M. Heidari-Rarani, *Design and manufacturing of drinking water filtration slabs using polymer concrete*, "Proc. of 1th Int. Conf. on Non-Osmosis Concrete & Water Storage Tanks, Iran, May, pp. 25-27, 2011.
8. ACI Committee 548. *Guide for polymer concrete overlays*, ACI 548.5R. Detroit, American Concrete Institute, pp. 1-26, 1998.
9. ACI Committee 548. *Polymer concrete-structural applications state of the art report*, ACI 548.6R. Detroit, American Concrete Institute, pp. 1-23, 1996.
10. D. W. Fowler, "Polymers in concrete—a vision for the 21st century," *Cement and Concrete Composites*, **21**, 449-452 (1999).
11. L. C. Muszynski, *Polymer concrete*, *Encyclopedia of polymer science and engineering*, New York: Wiley, **12**, 462-470, 1988.
12. Y. Ohama, "Recent progress in concrete polymer composites," *Cement and Concrete Composites*, **5**, 31-40 (1997).
13. V. V. L. K. Rao and S. Krishnamoorthy, "Influence of resin and microfiller proportions on strength, density and setting shrinkage of polyester polymer concrete," *ACI Structural*, **95**, 153-162 (1998).
14. Y. A. Abdel-Jawad and W. S. Abdullah, "Design of maximum density aggregate grading," *Construction and Building Materials*, **16**, 495-508 (2002).

15. V. V. L. K. Rao, "Aggregate mixtures for least void content for use in polymer concrete," *Cement and Concrete Aggregates*, **15**, 97-103 (1993).
16. Y. S. Soh, Y. K. Jo, and H. S. Park, "Effect of fillers on the mechanical properties of unsaturated polyester resin mortar," *Polymers in Concrete*, 67-74 (1997).
17. W. B. Fuller and E. T. Sanford, "The laws of proportioning concrete," *Trans ASCE*, **59**, 67-143 (1907)?.
18. M. Muthukumar, D. Mohan, and M. Rajendran, "Optimization of mix proportions of mineral aggregates using Box Behnken design of experiments," *Cement and Concrete Composites*, **25**, 751-758 (2003).
19. C. Vipulanandan and S. K. Mantrala, "Behavior of fiber reinforced polymer concrete," *Proc. of the 1996 4th Materials Engineering Conf.*, pp. 1160-1169, 1996.
20. H. Abdelfattah and M. M. El-Hawary, "Flexural behavior of polymer concrete," *Construction and Building Materials*, **13**, 253-262 (1999).
21. J. M. L. Reis and A. J. M. Ferreira, "Assessment of fracture properties of epoxy polymer concrete reinforced with short carbon and glass fibers," *Construction and Building Materials*, **18**, 523-528 (2004).
22. J. M. L. Reis, "Fracture and flexural characterization of natural fiber-reinforced polymer concrete," *Construction and Building Materials*, **20**, No. 9, 673-678 (2006).
23. M. Heidari-Rarani, M. R. M. Aliha, M. M. Shokrieh, and M. R. Ayatollahi, "Mechanical durability of an optimized polymer concrete under various thermal cyclic loadings – An experimental study," *Construction and Building Materials*, **64**, 308-315 (2014).
24. P. C. Aitcin and A. Neville, "High performance concrete demystified," *Concrete Int.*, **15**, 21-26 (1993).
25. P. C. Aitcin and P. K. Mehta, "Effect of coarse aggregate characteristics on mechanical properties of high-strength concrete," *ACI Materials J.*, **87**, 103-107 (1990).
26. A. Ouaar, *Micromechanics of rate-independent multi-phase composites. Application to Steel Fiber-Reinforced Concrete*, Ph.D. thesis, Université Catholique de Louvain Faculté des Sciences Appliquées, 2006.
27. V. F. Pasa Dutra, S. Maghous, A. C. Filho, and A. R. Pacheco, "A micromechanical approach to elastic and viscoelastic properties of fiber reinforced concrete," *Cement and Concrete Research*, **40**, 460-472 (2010).
28. D. W. Van Krevelen and K. Te Nijenhuis, *Properties of Polymers*, Fourth Edition, pp. 456-459, Amsterdam, Elsevier, 2009.
29. ASTM C 39-49, *Compressive strength of molded concrete cylinders*, 2002.
30. ASTM C 293-54T, *Flexural strength of concrete using simple beam with center-point loading*, 2002.
31. C. C. Yang and R. Huang, "A two-phase model for predicting the compressive strength of concrete," *Cement and Concrete Research*, **26**, No. 10, 1567-1577 (1996).
32. J. D. Eshelby, "The determination of the elastic field of an ellipsoidal inclusion, and related problems," *Proc. of the Royal Society A: Mathem. Phys. and Eng. Sci.*, **241**, No. 1226, 376-96 (1957).
33. T. Mori and K. Tanaka, "Average stress in matrix and average elastic energy of materials with mis-fitting inclusions," *Acta Metallurgica*, **21**, No 5, 571-574 (1973).
34. T. Mura, *Micromechanics of Defects in Solids*, Second Revised Edition, Martinus Nijhoff Publishers, 1987.
35. R. Dorf, *Engineering handbook*, New York, CRC Press, 1996.
36. M. M. Shokrieh, M. Heidari-Rarani, M. Shakouri, and E. Kashizadeh, "Effects of thermal cycles on mechanical properties of an optimized polymer concrete," *Construction and Building Materials*, **25**, 3540-3549 (2011).