Bond Strength of Polymer Lightweight Aggregate Concrete

Tayfun Uygunoğlu,[1] Witold Brostow,[2] Osman Gencel,[3] İlker Bekir Topçu[4]
[1]*Faculty of Engineering, Department of Civil Engineering, Afyon Kocatepe University, 03200 Afyonkarahisar, Turkey*

[2]*Laboratory of Advanced Polymers & Optimized Materials (LAPOM), Department of Materials Science and Engineering and Center for Advanced Research and Technology (CART), University of North Texas, Denton, Texas 76203-5017*

[3]*Faculty of Engineering, Department of Civil Engineering, Bartın University, 74000 Bartın, Turkey*

[4]*Faculty of Engineering and Architecture, Department of Civil Engineering, Eskişehir Osmangazi University, 26100 Eskisehir, Turkey*

Bond strength, physical, and mechanical properties of lightweight PC were investigated with inclusion of pumice lightweight aggregate in maximum size of 12 mm. As binder material, epoxy resin-based polymer was used with its hardener. The binder to aggregate ratio was 30% by weight. In addition, steel fibers were added to lightweight PC mixtures in ratio of 0, 0.5, and 1%. After lightweight PC mixture was prepared, it was poured in the molds with different type of steel-bars in size of 100 × 100 × 100 mm^3. The steel-bars centered in the cubic molds, and they were in size of Ø12, Ø14, and Ø16. The specimens were cured at 60°C for 2 h. On the hardened polymer lightweight concrete (PLC), pull-out test for bond strength and compressive strength tests were performed. Moreover, ultrasonic pulse velocity, water absorption by weight, specific porosity, and density experiments were carried out. The relation between physical and mechanical properties showed that PLCs become more durable when using ratio of steel fibers. POLYM. COMPOS., 34:2125–2132, 2013. © 2013 Society of Plastics Engineers

INTRODUCTION

The most often used material in the world is concrete. Low costs, ease of application, and high compressive strength are the main factors to be considered for a given application. Concrete is an excellent material when subjected to compressive forces, but the tensile strength of concrete is typically only about 8–15% of its compressive strength [1]. Therefore, the tensile strength of concrete is neglected in design and reinforcing bars are needed to equilibrate the internal forces and moments. Tensile and compressive forces are transferred to bars through bond action. This load transfer is referred to as bond and is idealized as a continuous stress field that develops in the vicinity of the steel-concrete interface [2,3]. The bond mechanism between steel and concrete can be broken by adhesion, friction, and bearing. The effects of concrete–steel adhesion and friction are related to the mechanics of bond action. Adhesion is the chemical bond that forms between the reinforcing bar and the concrete surface during hydration [4]. Friction forces increase the efficiency of the force transfer because the force acts opposite to the direction of slip, but the amount of friction decreases as the tensile force increases because of Poisson effects on the bar. Adhesion increases the amount of friction because small concrete particles adhere to the steel surface, which causes the roughness of the reinforcing surface to increase [5].

concrete can absorb water or be attacked by acids; property deterioration results in either case. Further, long span bending members made with concrete may not be capable of carrying their own weight. These disadvantages can be remedied by using thermo-set polymer materials, which have lighter, hydrophobic nature, and chemical inertness [6–11]. The search for durable and sustainable construction materials inspires the developments in the world of cement concrete, as well as in the world of concrete–polymer composites [12]. In general

---

Correspondence to: Tayfun Uygunoglu; e-mail: uygunoglu@aku.edu.tr

Contract grant sponsor: Afyon Kocatepe University, Scientific Project Committee; contract grant number: 11.MUH. 01.
DOI 10.1002/pc.22621

when adding polymer it is desirable to obtain high compressive and flexural strength, high bond strength between the steel-bar and concrete, high impact and abrasion resistance, service possible in adverse environments (wind, moisture, etc.), lower weight, and lower costs. Polymer concrete (PC) materials have become a viable choice for the civil construction sector in developed countries, particularly in applications such as making reinforced slabs, overlays for highway pavements and bridge decks, or pipe coatings [13]. PCs are also used in repairing deteriorated mineral concretes (Portland cement concrete) in situations when high strength, fast cure and durability are required [14,15]. PCs are composites in which the aggregates are bound together in a polymer matrix [16]. They do not contain Portland cement. PC is a concrete-like composite, in which polymer such as epoxy resin or polyester resin, substitutes the cement binder [17].

The main disadvantages of concrete polymer materials are their cost. The higher cost of PCs makes its use almost forbidden for high volume applications except in cases where durability renders cement concrete unusable [18–20]. However, Oussama et al. [21] reported that compressive, bending, ultrasonic wave's propagation, porosity, and thermal conductivity tests show that when the polymer content is 13%, it leads to obtain the highest physical and mechanical properties at lowest cost. On the other hand, one way to minimize this limitation is the development of a lighter PC [18,22]. It can be produced easily with lightweight aggregates such as pumice. Pumice is essentially composed of solidified frothy lava which is generally rhyolitic in composition, but can also be produced in a less acidic form [23]. Aggregate strength ranges from very weak and porous, to stronger and less porous. Absorption is generally high, with the specific characteristics being largely dependent on the porosity and size of the aggregates [24,25].

Some studies were performed in terms of bond strength between reinforcing bars and concrete with lightweight aggregate. It was noted that the bond strength of structural lightweight concrete changes between 2 and 8 MPa depending on components such as binder content, water to cement ratio and steel-bar diameter, and it is lower than that of normal weight concrete [26–30]. The results of those studies also show that the lightweight concrete-steel bond strength is 30% weaker than the concrete-steel bond strength in ordinary concrete. However, the difference between the bond strength of lightweight concrete and ordinary concrete decreases when deformed steel members and steel rods with large diameters are brought into the comparison. On the other hand, unfortunately there are very limited researches on bond strength of polymer lightweight concrete (PLC) [31]. Due to the lack of studies in this field, it was performed in this research, focused on the bond strength of epoxy-based PLC with pumice.

FIG. 1. Steel fibers used in the lightweight PC.

EXPERIMENTAL STUDY

Materials Used

PLCs were produced using dry pumice aggregates and monomers (binders) that undergo polymerization (curing, hardening). Epoxy resin which has a large variety of applications was used. It exhibits good dimensional stability, high heat resistance, high mechanical strength, and chemical resistance. The selection of the type of epoxy resin was based on the requirement of curing at room temperature, heat evolved during curing on the low side and pot-life suitable for industrial applications. It has two components as A and B (hardener) in density of 1,050 kg/m^3 and 1,100 kg/m^3, respectively.

Also, steel fibers used in the production of polymer specimens. The fiber lengths (l) was 13 mm, the diameters (d) was 0.6 mm; therefore, the aspect ratio (l/d) was 21.7 (Fig. 1). All aggregates (fine and coarse) were pumice in maximum size of 12 mm. Pumice was supplied from Isparta/Turkey and its characteristic properties and grain size are presented in Tables 1 and 2, respectively.

Production of Specimens and Tests

For cubic meter 1,000 kg pumice were used. Epoxy resin ratio was 30% after pre-productions. At lower resin contents used in the mixture, the mixture was not made by stirring. Epoxy was used as a component is 285 kg and B component is 142 kg for cubic meter. Except for control series, steel fibers were added to mixture 100.6 kg and 213.3 kg, respectively, to produce the 0.5% and 1% steel fiber (by volume of concrete) PC. Before the specimens are poured, epoxy separator was sprayed on the steel molds. The fresh PLC was placed in 100 × 100 × 100 mm^3 cubic molds without shaker and they were demolded after 24 h. The specimens were cured in at 60°C for 2 h, and then they were kept for 7 days. On the specimens,

TABLE 1. Characteristic properties of pumice.

Properties	Pumice	Standard
Density (kg/m^3)	739	EN 1097-3 [32]
Water absorption (%)	28.75	EN 1097-6 [33]
Loss of wear resistance (coarse) (Los Angeles) (%)	52.62 (LA$_{53}$)	EN 1097-2 [34]

TABLE 2. Sieve analyses of lightweight aggregates.

Sieve (mm)	16	8	4	2	1	0.5	0.25
Passing (%)	100	59	46	39	27	17	9

compressive strength was defined according to EN 12390-3 [35] by compressive machine with a rate of loading controller. The loading test in compressive strength test was 0.6 MPa/s. Unit weight, specific porosity, and water absorption were defined on 7 days aged specimens according to Archimedes principle. It was made by the weight measurements of saturated specimens on air and in water, and dry weight (oven drying at 105°C to constant weight). Ultrasonic pulse velocity (UPV) was defined on the cube specimens. Dynamic modulus of elasticity was also calculated from UPV and density of testing materials at direct transmission of testing samples. Dynamic modulus of elasticity E_d (MPa) was calculated according to *Eq*. 1:

$$E_\mathrm{d}= \quad V^2\rho(1+\upsilon)(1-2\upsilon)/(1-\upsilon) \tag{1}$$

where E_d is dynamic modulus of elasticity; ρ is density (kg/m^3); V is UPV (km/s); and υ is the Poisson ratio (= 0.20).

Bond of reinforcing bars to concrete influences the behavior of structural concrete in many respects. It affects the anchorage of rebars, the strength of lap splices, and the serviceability, and ultimate states. The most commonly used test procedure is pullout tests with centric or eccentric placement of the reinforcing rebar in the concrete specimen [36]. Pull-out tests were carried out by extracting the reinforcing steel-bar of 12, 14, and 16 mm diameter from the concrete cube specimens (Fig. 2). The free extreme of the bar was connected to the grips of the universal testing machine utilized for direct tensile tests on steel bars, while the part of the bar embedded in the concrete block was fixed, though a rigid steel frame, to the fixed part of the testing machine. A controlled displacement test was carried out at a fixed displacement rate of 0.5 mm/min, and the reactive load and the corresponding slippage of the steel bar were recorded. The load was applied on the top of the concrete surface at a uniform rate as per ASTM standards [37] until failure to obtain the ultimate load. The bond stress-slip diagrams were deduced by taking the applied forces at given strip values and bond strength was determined by using the *Eq*. 2.

$$\tau=F/(\pi\Phi L) \tag{2}$$

where τ is bond strength (N/mm^2); F is applied force (N); Φ is diameter of steel-bar; and L is embedded length of steel-bar (mm).

RESULTS AND DISCUSSIONS

The development of compressive strength of PLC containing the pumice aggregate is given in Table 3, showing the strengths at 7 days depending on steel fiber content. It was observed that steel fiber addition into PC mixture produced increases compressive strength of PC. Compressive strength values were 22.5, 25.6, and 24.5 MPa for steel fiber content of 0%, 0.5%, and 1%, respectively. Sancak [38] used the steel fibers in ratio of 0, 0.5, and 1% by volume in the pumice lightweight aggregate concrete with 300 kg/m^3 Portland cement content. He used the pumice as coarse aggregate in his experiments. He reported that compressive strength of the specimens was 11, 17, and 13 MPa; density was 1,835, 1,860 and 1,742 kg/m^3; water absorption was 10, 9, and 10%; modulus of elasticity was 18,560, 22,047, and 18,526 MPa; UPV was

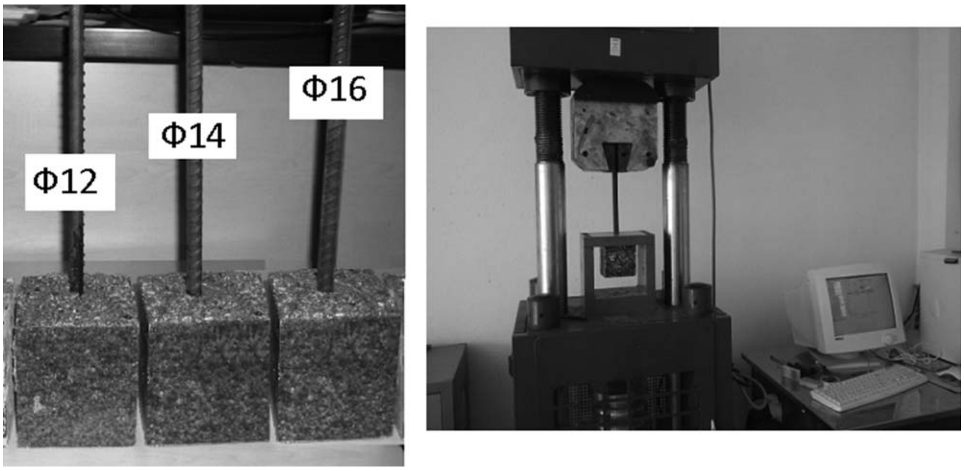

FIG. 2. Specimens with steel-bar and bond test setup.

TABLE 3. Characteristic properties of PLC specimens.

Fiber content (%)	Water absorption (%)	Specific porosity (%)	Density (kg/m^3)	UPV (km/s)	Compressive strength (MPa)	Dynamic modulus of elastic (MPa)
0.0	0.071	0.097	1,346	2.4	22.5	7,979
0.5	0.066	0.097	1,469	2.4	25.6	8,311
1.0	0.061	0.09	1,464	2.2	24.5	6,937

3.15, 3.41, and 3.23 km/s depending on steel fiber content of 0, 0.5, and 1%, respectively. As clearly seen from Table 3, when compared to PLC without steel fiber there was increase on compressive strength of PLC in ratio of about 14% and 9% by increasing of steel fiber content from 0.5 to 1%, respectively. Increase of fiber content generally resulted in decrease of compressive strength due to decreasing the workability of concrete. Earlier works reported that a variety of effects of addition of steel fibers on compressive strength ranges from marginal up to 25% increase or decrease [39–42]. But still PLC in this study has two times compressive strength values at 7 days when compared to normal lightweight concrete (NLC) with pumice in dosage of 300 at 28 days [38]. Increase in compressive strength of PLC when compared to NLC mainly depends on strength gaining of the epoxy with its hardener and temperature. Epoxy resin gains higher strength values under temperature with strong cross-links [19,20]. During the curing process, polymer chains are formed from the monomer resin. Not only do the monomers combine in chains but the chains also connect with each other in a process referred to as crosslinking [43]. In the first stage of polymerization (i.e., curing process), the resin is usually in the liquid state. Once the reaction temperature is reached, the physical state of the compound changes abruptly from liquid to gel and the crosslinking reaction slows down [44]. Also, the half-open porous structure of pumice aggregate (Fig. 3) is mostly influenced to increasing of compressive strength by improving to adherence between binder and aggregate. On the other hand, because of half-open surface structure of pumice, PC need more binding material (epoxy resin) than PC with normal aggregate. It may be a disadvantage for producing of PLC due to expensive price of epoxy.

As the another results in this study, it was observed that water absorption and specific porosity of PLC specimens are almost zero (Table 3). So, they have water absorption values as 0.071, 0.07, and 0.06% by weight although they produced with lightweight aggregate (pumice) with water absorption ability of about 28%. On the other hand, NLC specimens have 11, 9, and 10% water absorption values as mentioned before Sancak [38]. It means that PLC specimens quite durable to chemical and physical effects depending on water transportation to inside of the specimens [44].

The most important aim of using lightweight concrete is to take advantage of their densities to decrease the dead-load of structures. When the density of PLC that given in Table 3 was analyzed, it can be clearly seen that density of PLC is lower than NLC in all the steel fiber content. The density of PLC is lower in ratio of 25%, 21.6%, and 17% than NLC for 0, 0.5, and 1% fiber content, respectively [38]. In other words, dead-load of the structures may be reduced at these ratios by using PLC instead of NLC. The UPV is used as an indicator for strength of cementing materials. So, there are many studies on relationship between UPV and strength of concretes. If the UPV increases, the quality of the cement-based concrete becomes better, depending on its density or porous structure, when compared with low quality concrete. However, although the strength values of PLC are higher than NLC, the UPV values are lower than that of NLC. In addition, dynamic modulus of elasticity of PLC changes between 6.5 and 8 GPa. But, it changes between 18 to 23 GPa for NLC. As seen, dynamic modulus of elasticity of PLC is three times lower than that of NLC, too. Fiber content does not effect to dynamic modulus of elasticity in PLC. However, the highest dynamic modulus of elasticity was obtained in fiber content of 1%.

For lightweight concrete, the use of fibers is suitable, also coupled with traditional steel reinforcements, because it reduces material decay in the field of the strains exceeding those corresponding to the strength [45–47]. To determine the behavior of the bond in different tests, the slips of the reinforcing bars were measured. The bond strength of PLC with pumice can be seen in Figs. 4–6 for steel bar in size of 12, 14, and 16 mm, respectively, depending on fiber content of from 0 to 1.5%. From all

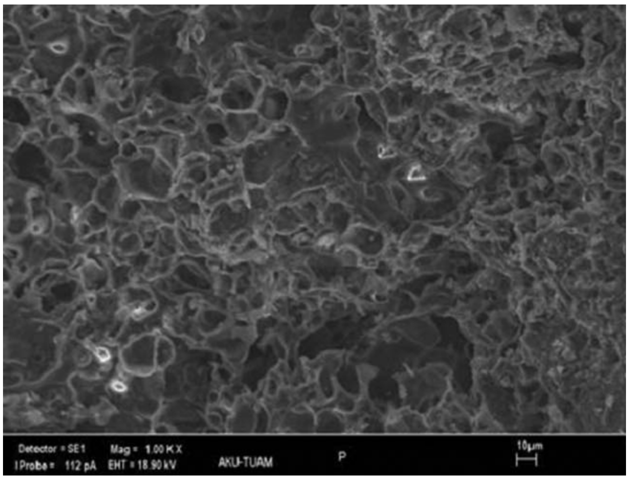

FIG. 3. Microstructure of pumice aggregate.

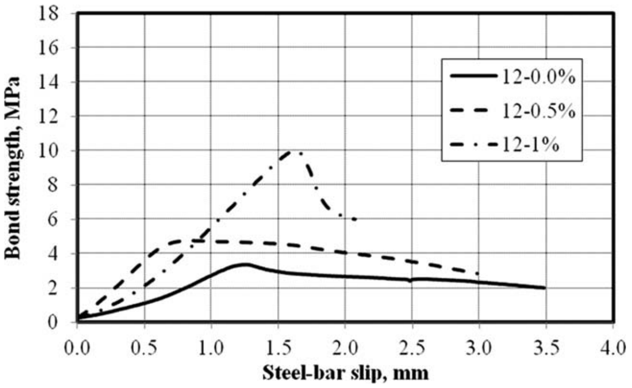

FIG. 4. Bond stress of PLC with steel-bar of 12 mm.

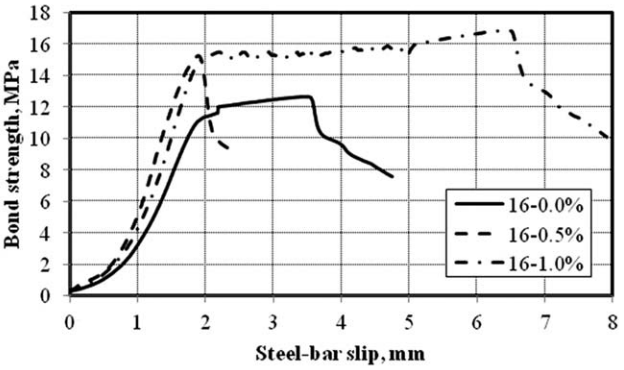

FIG. 6. Bond stress of PLC with steel-bar of 16 mm.

the graphs, it emerges that the initial stiffness of the bond stress-slip curve decreased gradually from its initial large value to zero when approaching the maximum bond strength τ_{max} corresponding to a slip value of approximately from 0.8 to 2 mm (depending on rebar diameter and fiber content) in which splitting failure with crushing cracks appears. Similar results are obtained by Campione et al. [28] for cement-based lightweight aggregate concrete with compressive strength of 34.4, 34.9, and 35.4 MPa for steel fiber content of 0, 0.5, and 1%. After passing the maximum bond strength value τ_{max}, the bond resistance decreases slowly and almost linearly until it approaches a slip of 2–8 mm depending on rebar diameter, and then the next value corresponds to the distance between the drowned ribbings of the deformed bar in the concrete. The slip values at peak bond stress and failure of PLC was increased with increase of steel fiber using ratio and rebar diameter. When the fiber content is considered, the results obtained show that the addition of fibers has an influence on the increase in the ultimate strength and on the overall response compared to the case of plain concrete. The orientations and distributions of fibers affect the properties of steel fiber reinforced concrete such as toughness, strength, ductility, and crack width [48]. Thus, the bond cracks in PLC that surrounding the steel was decreased by using steel fibers, and the friction force and adhesion was also increased between the PLC and steel surface [49]. Another reason of increase of bond-slip strength is surface area which is coated with resin in the PLC. It is well known that the surface area increases with the increase of rebar diameter. The lowest bond-slip values were obtained at the lowest diameter of rebar when the highest bond slip was observed at the highest rebar diameter. PLC has higher bond strength values when compared to cement-based normal and lightweight concrete for the similar compressive strength [26–30]. Although a crude representation of the local stress concentrations around the ribs that engage in concrete, the simple frictional model properly identifies the significance of many important design parameters for bond, that is, the higher the normal pressure, the higher the frictional force required for pullout and the higher the strength reserves of the splitting failure mechanism [50]. The relative insensitivity of strength to the confining influence of the reinforcement bar is attributed to the bar's surface texture. Thus, the bearing action of the "indentations" was marginal up to almost total cracking of the cover and substantial slip; the confining ribs were activated at advanced stages of slip, producing a pseudo-yield plateau and delayed softening in the post-peak segment of the average bond-slip relationship [47].

When the maximum bond strength was considered (Fig. 7), it was increased by increase of steel-bar diameter due to higher surface of steel-rod. Higher surface area results with higher mechanical and physical adhesion

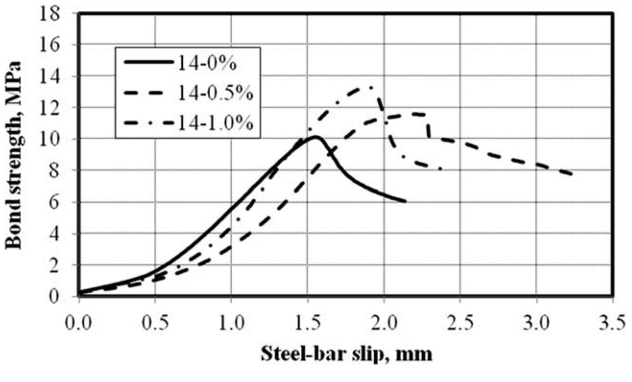

FIG. 5. Bond stress of PLC with steel-bar of 14 mm.

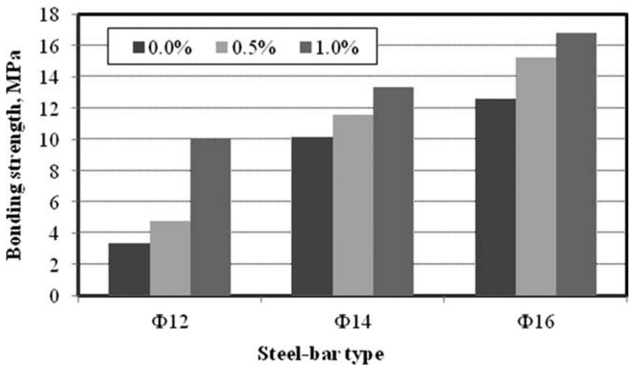

FIG. 7. Bonding strength of PLC depending on steel-bar type.

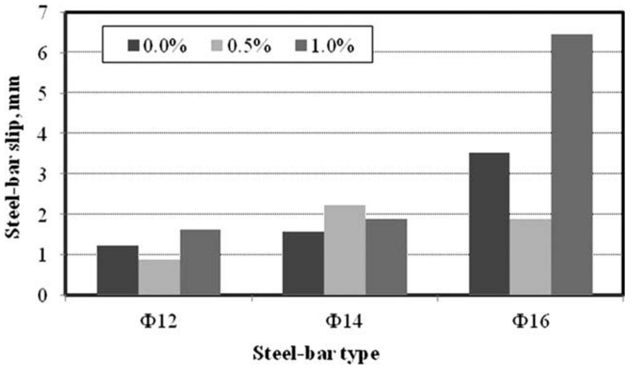

FIG. 8. Slip of steel-bars at maximum bonding stress of PLC.

between the PLC and steel surface [51]. For control series, bond strength increased in ratio of 170% and 232% for Φ14 and Φ16 when compared with Φ12, respectively. For PLC with 0.5% fiber content, it was 162% and 233% for the same steel-bar. When PLC with 1% fiber content was considered, increments in bond strength were 35% and 65% for steel-bars of Φ14 and Φ16. On the other hand, the bond strength to compressive strength ratio was 15%, 19%, and 40% for steel-bars of Φ12 depending on steel-fiber content, respectively, for 0%, 0.5%, and 1%. It was 45%, 45%, and 54% for steel-bars of Φ12, and 56%, 59%, and 69% for steel-bars of Φ16, respectively. Teo et al. [52] found that the bond strength of specimens with plain bars was approximately 10–24% of the compressive strength. Paramsivam and Loke [53] found that the ultimate bond strength for 20 mm diameter deformed bars was about 8 MPa, which is about 27% of the compressive strength of 30 MPa. The ultimate bond strength incorporating 12 mm diameter deformed bars embedded in 152 mm cube specimens were found to be in the range of 10.2–11.3 MPa for Lytag aggregate concrete. This bond strength was approximately 25–41% of the compressive strength [54]. In another study conducted on high-strength lightweight aggregate concrete produced from expanded shale, it was observed that the bond strength for specimens with 19 mm diameter deformed bars was 19.3–23.4% of the compressive strength [26]. Meanwhile, the lowest and the highest bond strength for PLC with steel-bar of Φ12 is 3.5 and 10 MPa. It was ranged between 10 and 13.3 for Φ14; and it was changed between 12.3 and 16.5 MPa for and Φ16. The bond strength for Φ12 and Φ16 steel-rod was obtained in range of 8 and 10.6 MPa in lightweight concrete with pumice and Portland cement. It can be clearly seen that the bond strength of PLC higher than Portland cement lightweight concrete. This mean is that similar bond strength can be obtained by epoxy-based polymer binder in less embedding length when compared to Portland cement concrete.

For reinforced concrete structures subjected to moderate loading, the bond stress capacity of the system exceeds the demand and there is relatively little movement between the reinforcing steel and the surrounding concrete. The principal tensile stress caused by bond stresses reach the tensile strength of concrete and micro cracks initiate at the tips of the bar deformations which allow the bar to slip [31]. The slip values of PLC at maximum bond strength can be seen in Fig. 8 depending on steel-bar and steel-fiber content. It was also increased by incase of steel-bar diameter. However, it changes with addition of steel fibers. This was because of dispersing and orientation of steel-fibers in PLC. The highest slip was observed in the highest steel-bar diameter due to enhancement of bonding surface areas. Because polymer is better binding material than ordinary cement, it gives better bong strength, too [44,55]. For PCs in particular, natural or synthetic fibers—such as carbon fibers, glass fibers, polypropylene fibers, or steel fibers—can be added to PC matrix to improve the mechanical performance. The improvement results from stretching and pulling-out of the fibers, which occurs after failure of the matrix. It is

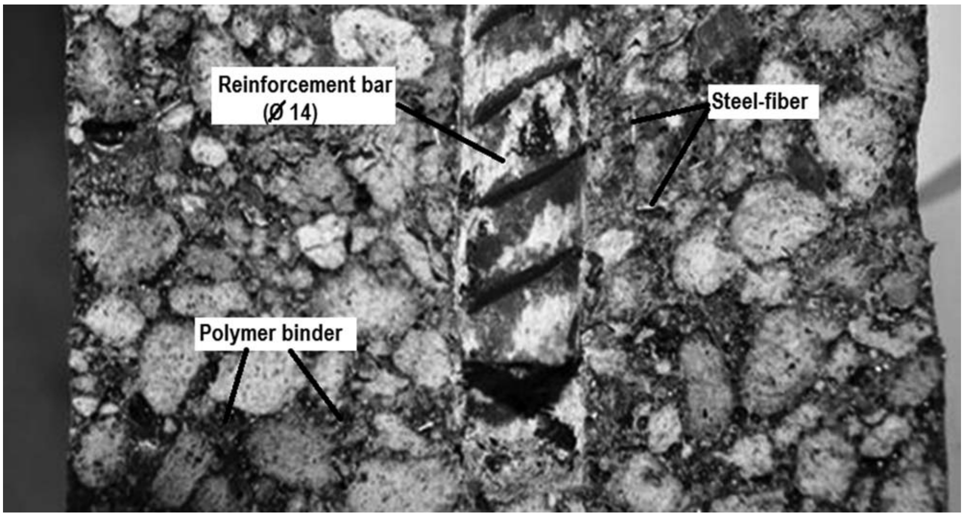

FIG. 9. Steel-bar in PLC.

clearly seen that still there was some polymer binding materials on the steel bar after pull-out test (Fig. 9). Steel fibers present a good adhesion with the polymer matrix. This reinforced the matrix. As a result of it, a reinforced matrix prevents the bar from pulling out matrix. There is also good binding between the pumice aggregates by epoxy resin and half-open surface structure of pumice. It makes stronger the PLC with pumice. This microstructure continuity, in addition to the organic nature of the binder, facilitates the PLC elements protection against atmospheric conditions, corrosion, and chemical attacks.

CONCLUSIONS

In this study, bond strength of epoxy-based polymer lightweight aggregates was investigated. Compressive strength is about twice that of Portland cement lightweight concrete with pumice. In addition, our concretes do not absorb water, with absorption values of about 0.07%. Due to the closed porosity and low water absorption ability of in PLC, this is an attractive material to obtain high durability structures. This microstructure continuity, in addition to the organic nature of the binder, facilitates the PLC elements protection against atmospheric conditions, corrosion and chemical attacks. The density is lower about 25% than that of NLC. Also, bond strength of PLC is higher than that of Portland cement concrete or lightweight concrete. In general, PLC gives better mechanical and physical properties when compared to concrete type with ordinary Portland cement due to its unique and desirable properties such as higher compressive strength, bond strength, very low/without water absorption, lower density, and lower UPV values. However, as mentioned before, epoxy is expensive. Therefore, it may be used for special applications.

REFERENCES

1. M. Gregor, G. James, and J.K. Wight, *Reinforced Concrete Mechanics and Design*, 4th ed., Pearson Prentice Hall, Upper Saddle River, New Jersey, 112–116, 328 (2005).
2. L. Bouazaoui and A. Li, *Int. J. Adhes. Adhes.*, **28,** 101 (2008).
3. J.L. Clarke and F.K. Birjandi, *Mag. Concr. Res.*, **163**, 79 (1993).
4. R. Tepfers, *Mag. Concr. Res.*, **31**, 3 (1979).
5. L. Bizindavyi, *J. Compos. Construct.*, **3**, 153 (1999).
6. G. Martínez-Barrera and W. Brostow, "Fiber-Reinforced Polymer Concrete: Property Improvement by Gamma Irradiation," in *Gamma Radiation Effects on Polymeric Materials and its Applications, Chapter 4*, Research Signpost press, 27–44, ISBN: 978-81-308-0293-0 (2009).
7. B. Bilyeu, W. Brostow, and K.P. Menard, *J. Mater. Ed.*, **21**, 281 (1999).
8. B. Bilyeu, W. Brostow, and K.P. Menard, *J. Mater. Ed.*, **22**, 107 (2000).
9. B. Bilyeu, W. Brostow, and K.P. Menard, *J. Mater. Ed.*, **23**, 189 (2001).
10. B. Bilyeu, W. Brostow, and K.P. Menard, *Polym. Compos.*, **23**, 1111 (2002).
11. B. Bilyeu, W. Brostow, and K.P. Menard, *Mater. Res. Innov.*, **10**, 110 (2006).
12. A. Beeldens, D. Van Gemert, H. Schorn, and Y. Ohama, "Integrated Model for Microstructure Building in Polymer Cement Concrete," in *Proceedings of 11th Congress on Polymers in Concrete*, Berlin, 1–10 (2004).
13. D.W. Fowler, *Cem. Concr. Compos.*, **21**, 449 (1999).
14. E.A. Bobadilla-Sanchez, G. Martinez-Barrera, W. Brostow, and T. Datashvili, *Express Polym. Lett.*, **3**, 615 (2009).
15. C.H. Chen, R. Huang, J.K. Wu, and C.H. Chen, *Construct. Build. Mater.*, **20**, 706 (2006).
16. ACI Committee 548, *Guide for the Use of Polymers in Concrete-ACI 548.1R*, American Concrete Institute, Detroit (1997).
17. L. Czarnecki, *Int. Design Constr.*, **7**, 47 (1985).
18. P.J.R.O. Nóvoa, M.C.S. Ribeiro, A.J.M. Ferreira, and A.T. Marques, *Compos. Sci. Technol.*, **64**, 2197 (2004).
19. A.E. Akınay, W. Brostow, C.M. Castaño, R. Maksimov, and P. Olszynski, *Polymer*, **43**, 3593 (2002).
20. W. Brostow, "Mechanical Properties," in *Physical Properties of Polymers Handbook*, 2nd ed., Chapter 24, Mark, Ed., Springer, New York (2007).
21. E. Oussama, G. Elhem, M. Valérie, and B.O. Mongi, *Construct. Build. Mater.*, **27**, 415 (2012).
22. A.M. Kılıc, O. Kılıc, and M.O. Keskin, *Sci. Res. Essays*, 5, (1986) (2010).
23. T. Uygunoğlu, *Properties of Self-Consolidating Lightweight Aggregate Concrete*, Suleyman Demirel University, Natural Science Institute, Ph.D. Thesis, 155 [in Turkish] (2008).
24. K.M.A. Hossain and M. Lachemi, *ACI Mater. J.*, **104**, 449 (2007).
25. İ.B. Topcu and T. Uygunoğlu, *J. Concr. Prefab.*, **8**, 5 (2008).
26. A. Mor, *ACI Mater. J.*, **89**, 76 (1992).
27. J.V. Cox, K. Bergeron, and J. Malvar, "A Combined Experimental and Numerical Study of the Bond Between Lightweight Concrete and CFRP Bars," in Sessions on Interface Degradation 14th ASCE Engineering Mechanics Conference, The University of Texas at Austin, 1–5 (2000).
28. G. Campione, C. Cucchiara, L. La Mendola, and M. Papia, *Eng. Struct.*, **27**, 881 (2005).
29. E. Sancak and O. Şimşek, "The Bond Strength of Structural Lightweight Pumice Aggregate," in International Balkans Conference on Challenges of Civil Engineering, BCCCE, Epoka University, Tirana, Albania, 1–12, May 19–21 (2011).
30. S. Pul, *Iranian J. Sci. Technol. Trans. B: Eng.*, **34**, 397 (2010).
31. J.T. San-Jose, I.J. Vegas, and M. Frias, *Construct. Build. Mater.*, **22**, 2031 (2008).
32. *EN 1907-3 Tests for Mechanical and Physical Properties of Aggregates—Part 3: Determination of Loose Bulk Density*

and Voids, Turkish Standard Institute, Ankara/Turkey (1999).

33. *EN 1907-6 Tests for Mechanical and Physical Properties of Aggregates—Part 6: Determination of Particle Density and Water Absorption*, Turkish Standard Institute, Ankara/Turkey (2007).
34. *EN 1907-2 Tests for Mechanical and Physical Properties of Aggregates—Part 2: Methods for the Determination of Resistance to Fragmentation*, Turkish Standard Institute, Ankara/Turkey (2010).
35. *TS EN 12390-3 Testing Hardened Concrete—Part 3: Compressive Strength of Test Specimens*, Turkish Standard Institute, Ankara/Turkey (2010).
36. D.A. Abrams, *Test of Bond Between Concrete and Steel*, Vol. **71**, *University of Illinois, Bull*. Urbana (1913).
37. ASTM E1512-01, *Standard Test Methods for Testing Bond Performance of Bonded Anchors*, Annual Book of ASTM Standards (2007).
38. E. Sancak, *The Effect of the Use of Steel Fibres on Mechanical Properties of Lightweight Aggregate Concrete Blocks*, Süleyman Demirel Üniversity, Natural Science Institute, Master Thesis, Isparta, 79 pages (1998).
39. M.C. Nataraja, N. Dhang, and A.P. Gupta, *Cem. Concr. Compos.*, **21**, 383 (1999).
40. D.A. Fanella and A.E. Naaman, *ACI J.*, **82**, 475 (1985).
41. N. Balaguru and S. P. Shah, *Fiber Reinforced Cement Composites*, McGraw-Hill, New York (1992).
42. O. Gencel, W. Brostow, D. Tea, and M. Thedford, *Compos. Interfaces*, **18**, 169 (2011).
43. Z. Jelcic, P. Hedvig, F. Ranogajec and I. Dvornik, *Radiat. Phys. Chem.*, **20**, 309 (1982).
44. G. Martinez-Barrera, E. Vigueras-Santiago, O. Gencel, and H.E. Hagg-Lobland, *J. Mater. Ed.*, **33**, 37 (2011).
45. P. Balaguru and A. Foden, *ACI Struct. J.*, **93**, 62 (1996).
46. G. Campione, N. Miraglia, and M. Papia, *Mater. Struct.*, **34**, 201 (2001).
47. G. Campione, C. Cucchiara, L. La Mendola, and M. Papia, "Experimental Investigation on Local Bond-Slip Behavior in Lightweight Fiber Reinforced Concrete Under Cyclic Actions," in 13th World Conference on Earthquake Engineering Vancouver, B.C., Canada, Paper No. 2087, August 1–6 (2004).
48. P.S. Song and S. Hwang, *Construct. Build. Mater.*, **18**, 669 (2004).
49. S.P. Shah and B.V. Rangan, *ACI J.*, **68**, 126, (1971).
50. T. Uygunoğlu, *Mater. Struct.*, **41**, 1441 (2008).
51. J.A. Rossignolo and M.V.C. Agnesini, *Cem. Concr. Res.*, **32**, 329 (2002).
52. D.C.L. Teo, M.A. Mannan, V.J. Kurian, and C. Ganapathy, *Build. Environ.*, **42**, 2614 (2007).
53. P. Paramasivam and Y.O. Loke, *Int. J. Lightweight Concr.*, **2**, 57 (1978).
54. C.O. Orangun, *Build. Sci.*, **2**, 21 (1967).
55. J.A. Rossignolo and M.V.C. Agnesini, *Cem. Concr. Compos.*, **26**, 375 (2004).