An Investigation on Adding Polypropylene Fibers to Reinforce Lightweight Cement Composites (LWC)

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ABSTRACT

The influence of polypropylene fibers has been studied in different proportioning and fiber length to improve the performance characteristics of the lightweight cement composites. Fibers used in two different lengths (6mm and 12mm) and fiber proportions (0.15% and 0.35%) by cement weight in the mixture design. Hardened concrete properties such as: 7- and 28-day compressive strength, splitting tensile strength, flexural strength, water absorption, and shrinkage were evaluated.

Fiber addition was seen to enhance the physical and mechanical properties of lightweight concrete. Compared to unreinforced LWC, polypropylene (PP) reinforced LWC with fiber proportioning 0.35% and 12 mm fiber length, caused 30.1% increase in the flexural strength and 27% increase in the splitting tensile strength. Increased fiber availability in the LWC matrix, in addition to the ability of longer PP fibers to bridge on the micro cracks, are suggested as the reasons for the enhancement in mechanical properties.

Keywords: PP fiber, cement composite, concrete.

INTRODUCTION

Cement mortar and concrete made with Portland cement is a kind of most commonly used construction material in the world. These materials have inherently brittle nature and have some dramatic disadvantages such as poor deformability and weak crack resistance in the practical usage [1-3]. Also their tensile strength and flexural strength is relatively low compared to their compressive strength. Many attempts have been done to convert cementitious system to a structural material with desirable physical and mechanical properties [1, 4].

Due to rapid development of very tall buildings, larger-sized and long-span concrete structures, lightweight concrete (LWC) has been used for structural purposes for many years [5-10]. The density of light weight concretes typically varies in the ranges from 1400 to 2000 kg/m^3 compared with that of 2400 kg/m^3 for ordinary concrete [11]. Light weight concrete also can be considered as a brittle material similar to other cementitious materials. Therefore, improving the brittleness of these materials is the key point to make them suitable as structural material with desirable physical and mechanical properties.

To do away with brittle nature of light weight concrete, the application of discrete fibers has been proposed by many researchers [12-14]. Reinforcement with fibers has been proved an effective and economical way to convert cementitious material into a tough and ductile product [1, 7]. At first, asbestos fibers were used in Hatschek process to produce fiber reinforced cement sheets. They showed excellent performance in building material in various forms and styles during the last century. But this fiber can constitute a major health hazard to human safety [1]. Thereafter, by introducing the various types of synthetic fibers many efforts have been made to replace as asbestos materials. The most frequently used reinforcement's synthetic fibers in the last decades were included organic fibers (acrylic, polyvinyl alcohol, polyolefin, polyethylene and polypropylene), and inorganic fibers (alkali resistant glass and carbon) [15]. It is stated that [12-14] the most important fiber parameters which affect the mechanical behavior of the composites are geometry, distribution, orientation, and volumetric proportion of fibers in the matrix.

Brittle matrices, such as unreinforced mortar and concrete, lose their tensile load-carrying capacity almost immediately after formation of the first crack in their matrix. The addition of fibers in concrete can increase the toughness of cementitious matrices significantly. Performance improvement of fiber reinforced concrete can be attributed to the point where fibers resist cracking generation [16, 42].

It was reported that application of nylon and polypropylene fibers improves the plain concrete properties including splitting tensile strength, first-crack strength and impact resistance [17]. Alhozaimy et al. [18] observed that an additional amount of %0.1 polypropylene fibers in the plan concrete had %44 increase in flexural toughness of the concrete. Some researchers also reported evidence of small but favorable effects of fiber addition on toughness [19-23]. Mindess *et al* (1988) reported that compressive strength increased by about 25% at 0.5% volume fraction of PP fibers in the concrete mixture design [24]. Hughes and Fattuhi [25] suggested that compressive strength decreases but flexural properties are improved with increasing fiber content.

The efficacy of fiber reinforcement in the grab of cracking, which results from drying shrinkage, has been proven [26, 27]. Few research reports on high-strength fiber-reinforced lightweight concrete have been published, although the benefits of reinforcing lightweight concrete with fibers have been concluded in a research on blast-resisting structures [28].

However there are well-documented reports in the area of adding PP fibers in ordinary concrete, there are still lacks of study about the way of mixing and best volume fractions of PP fibers in the lightweight aggregate concrete. Also, it has been proved [42] that physical and mechanical properties of reinforced concrete improve with increasing the volume fraction of the fibers in cement matrix. Up to now, the upper limit volume fraction of PP fibers in cement composites is 0.3 % by cement weight and after an increase in this portion, mechanical and physical properties decrease dramatically due to ball forming of fibers in the matrix during mixing [12, 42, 43]. This study presents comprehensive experimental data and powerful statistical analyses regarding the effects of adding polypropylene fibers with different fiber lengths and volume fractions on the physical and mechanical properties of lightweight aggregate concrete. Also by applying a spin finish with bi-polarity properties on surface of the fibers, maximum volume portion (0.35%) of fibers in mixture design is achieved.

MATERIALS AND METHODS

Materials

Polypropylene fiber used in this study provided by PP Fiber Prod. Co. To improve the mixing properties of fibers in concrete, a special surface treatment was used in the laboratory on the fibers which make the surface of fibers more bipolar in liquid solution. For fiber surface treatment, fibers incubated in 5% by total fibers weight of a commercial spin finish (Schill and Seilacher GmbH Böblingen, Germany) with bio-polarity properties mixed with antistatic and lubricant spinning oil for five minutes. Two different lengths of PP fibers (6 mm and 12 mm) were employed in this study based on previous works [12, 42, 43] and common cut lengths of PP fiber used in the fiber reinforced concrete industry. *Figure 1* shows microscopic images cross-sectional and longitudinal view of used PP fibers. Also some critical properties of PP fibers are presented in *Table I*.

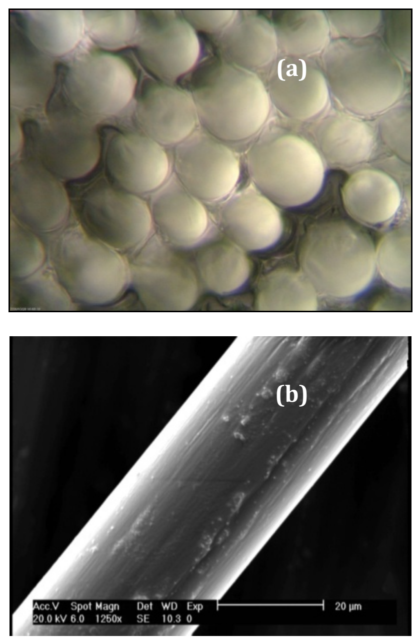

FIGURE 1. a) Cross-sectional view, b) Longitudinal view of PP fiber surface (SEM micrograph).

TABLE I. Properties of PP fiber used.

Fiber type	Diameter (µm)	Density (gram/cm^3)	Tensile strength (MPa)
Polypropylene	25	0.91	326

The cement used in this study was ordinary Portland cement, which corresponds to ASTM Type I. The chemical composition of the cement used is shown in *Table II*. According to the table the main components are being calcium oxides, silica and aluminum.

TABLE II. Chemical composition of used cement (%).

Chemical Component	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	SO_3	Others
Percentage	20.35	4.30	3.80	3.40	61.60	2.06	4.49

In this study, Light Weight Expanded Clay (LECA) with 10 mm maximum size was used as a light-weight aggregate and river sand with 5 mm maximum size was used as a coarse aggregate.

Alkali Resistance Evaluation of Fibers

Because of hydration process and the generation of $Ca(OH)_2$, Portland cement has a strong alkali environment [29, 30]. Hydration of the calcium silicates in Portland cement (C3S and C2S) yields portlandite ($Ca(OH)_2$) hydrate Eq. (1). This chemical change of cement system may cause the degradation of some fibers. The degradation of fibers decreases their tensile strength. Consequently, the mechanical performance of cementitious composites reinforced with these types of fiber decreases. It is important to investigate the alkali resistance of used fibers in cementitious materials.

$$6CaOSio_2+7H_2O \rightarrow 3CaO\ 2SiO_2 4H_2O+3Ca(OH)_2 \qquad (1)$$

To evaluate the fiber resistance, they are soaked in NaOH (=40g/l) with pH=12 to examine their strength in the alkali environments. Therefore, the tensile strength of them tested after 28 and 56 days exposing to alkali condition. Single fiber tensile test was performed under standard atmosphere on a Fafegraph HR (Monchengladbach, Germany) tensile tester machine with a constant rate of crosshead speed of 20 mm/min accordance to the requirements of ISO 527.

Specimen Preparation

In this study the following types of mixtures were prepared (*Table III*). All mixtures were mixed in a conventional rotary drum concrete mixer with a capacity of 0.04 m^3):

1. Plain lightweight aggregate concrete as control specimen.
2. Lightweight aggregate concrete reinforced specimen with 6 mm and 12 mm polypropylene fibers at two different mixture proportions by weight of the cement, 0.15% and 0.35%.

The volume fractions of various fibers used in the mixtures are given in *Table IV*. Total dosage of PP fibers in mixture was maintained up to 0.35 %, primarily from the point of view of providing good workability and without balling the fibers during mixing. After an increment of fibers volume fracture, fibers started to make balls in the mixture. The LF1 specimen is unreinforced concrete and acted as a control specimen.

TABLE III. Concrete mixture proportions (kg/m^3).

Cement (Kg/m3)	Lightweight aggregate (kg/m3)	Sand (kg/m3)	Water (kg/m3)	Super-plasticizer (kg/m3)
475	302	840	166.25	4.75

TABLE IV. Volume fractions of fibers with different proportions and lengths.

Sample code	Fiber length (mm)	Volume fraction (%)
LF1	-	0.00
LF2	12	0.15
LF3	12	0.35
LF4	6	0.15
LF5	6	0.35

The water absorption of the aggregates was determined and the water to cement quantity was adjusted accordingly. Before mixing with other materials in mixer, expanded clay lightweight aggregates (leca) were moistened with enough water and left for ten minutes to compensate the short time absorption of leca aggregates. For all specimens, water to cement ratio was 35% and amount of super-plasticizer was 1% of cement by weight.

Mixing and Casting Details

The coarse aggregate, light weight aggregate, and cement, were first mixed dry in a pan mixer of capacity 100 kg for a period of 2 min. The super-plasticizer was then mixed thoroughly with the mixing water and added to the mixer. Fibers were wetted by water then were dispersed by hand in the mixture to achieve a uniform distribution throughout the concrete, which was mixed for a total of 4 min. There were no fibers balling during mixing and placing for all the concretes after mixture. Fresh concrete was cast in steel moulds and compacted on a vibrating table. For the curing function, the specimens were kept covered in their molds for 24 h. There was less bleeding in the fiber concretes compared to that of the control concrete. After demoulding, concrete specimens were placed in 20±2 °C water for 28 days. They were removed from water and placed in the laboratory environment, 2 h before carrying out the tests. All tests were performed according to relevant ASTM standards.

Physical and Mechanical Tests

Compressive Strength

A universal testing machine of capacity 100 tones was used for testing the compressive strengths of nine 150×150×150 mm beams specimens (*Figure 2*). Cube specimens at 7, 14, and 28 days from casting were tested at a loading rate of 14 $N/mm^2/min$ according to ASTM C 39 [31]. The compressive strength interpreted by stress generated from the result of compression load per area of specimen surface. The results for each specimen are based on an average value of three replicate specimens.

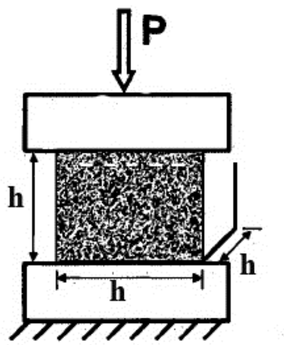

FIGURE 2. Schematic of compressive strength test.

Flexural Strength

Flexural strength at 28 days of curing test was conducted according to the requirements of ASTM C 1609 [33] using three 100 × 100 × 500 mm beams under third-point loading on a simply supported span of 400 mm.

According to ASTM standard, the results of flexural strength test are interpreted by calculating flexural stress as following:

$$R = \frac{PL}{bd^2} \quad (2)$$

where, R is flexural strength (modulus of rupture), P is maximum indicated load, L is span length, b is width of specimen, and d is depth of the specimen.

Tensile Strength

Split tensile strength at 28 days of curing test of three 150×300 mm cylinders is indirect measurement of tensile strength of concrete which were conducted according to the requirements of ASTM C496 [35]. In the split tensile strength test, cylindrical concrete specimen is placed on diametrical compressive force along its length (*Figure 3*). The load is applied continuously at a constant rate until failure of cylinder along its vertical diameter. To allow the uniform distribution of applied compressive load, strips of plywood are placed between the specimen and loading platens of the testing machine.

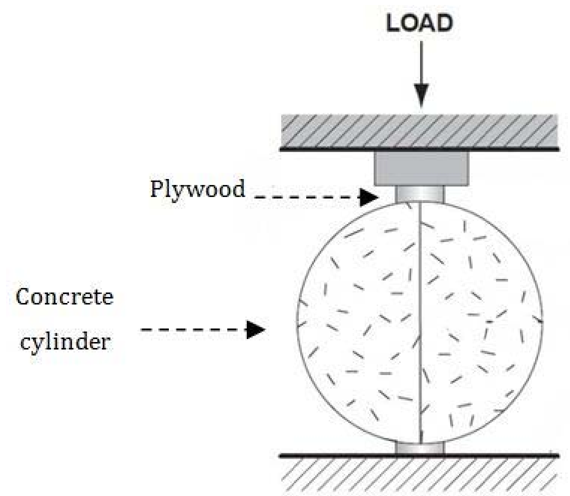

FIGURE 3. Schematic of split tensile strength test.

Splitting tensile strength of a specimen can be evaluated from the Eq. (3):

$$T = \frac{2P}{\pi l d} \quad (3)$$

where, T is tensile strength, P is compression load at failure, l is length of cylinder, and d is diameter of the cylinder.

Water Absorption

Water absorption at 28 days of curing tests of three 100×100×100 mm concrete beams were conducted according to the requirements of ASTM C1585 [36].

Concrete Shrinkage

Evaluation of concrete shrinkage at 28 days of curing of three 100×100×500 mm beams was conducted according to the requirements of ASTM C426 [39]. Concrete drying shrinkage was performed on the basis of concrete specimen longitudinal changes measurements at a period of time. The measurement was done in comparison to the initial length of concrete specimen in early ages of production.

RESULTS AND DISCUSSION

Fibers Alkali Resistance Test Result

Tensile strength test of PP fiber with different days of exposing (28 and 56 days) to the NaOH was performed. Mean value results of tensile strength are plotted in *Figure 4* for three different fiber specimens (three different tests for each specimen).

According to the results illustrated in *Figure 5*, decrease in yield strength after 28 days exposure to NaOH, and a partial recovery in the yield strength after 56 days were appeared, however statistical results (with 0.95 confidence interval) showed that there are no significant differences between the samples. In addition, the results showed that the PP fibers have excellent alkali resistance which is in good agreement with other researchers [16, 40]

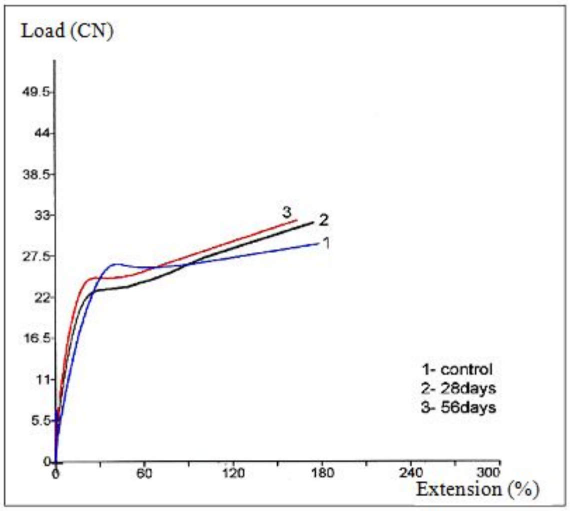

FIGURE 3. Load-extension curves of PP fibers at different days of exposing to alkali condition.

Compressive Strength Results

As it is evident from *Table V*, an enhancement in compressive strength compared to control sample occurs for the PP fiber concrete for both 12 mm and 6 mm fiber lengths.

Also an increase in the fiber content has direct effect on compressive strength. The fiber length of 12 mm showed better performance compared to 6 mm. The increase in compressive strength at 28 days of curing for LF2 and LF3 specimens is only in order of 11% and 18%, respectively. It can be seen, however, that the difference in performance of the PP fiber concrete with introducing more percentage of fibers in the specimen LF5, with respect to compressive strength is not significant at 0.95 level of confidence.

The performance of polypropylene fibers in the concrete mixture can be attributing to generation a good cohesion with other aggregates which enhances mechanical properties of the LWC [12]. This could be as a result of good distribution of fiber in LWC, which also stated by Chen et al. [32].

TABLE V. Average compressive strength of LWC specimens.

Sample code	Density (kg/m^3)	7 Days (N/mm^2)	14 Days (N/mm^2)	28 Days (N/mm^2)
LF1	1723.1± 3.8	10.5±0.07	18.2±0.14	22.2±0.13
LF2	1720.5±2.3	11.2±0.20	18.8±0.04	24.8±0.06
LF3	1783.0±1.4	12.0±0.30	19.1±0.08	26.3±0.14
LF4	1625.3±4.2	10.7±0.23	18.4±0.12	23.1±0.30
LF5	1680.0±1.6	10.9±0.16	18.7±0.61	23.5±0.28

From the compressive test results, it could be clearly found that PP fibers have no significant effect on compressive strength of concrete at 7 days and 14 days of curing. However, 28 days of curing the samples shows significant change in comparison with control specimen.

Flexural Strength Results

Results of flexural strength are shown in Figure 6. Each of the results is the average of 3 test specimens. Compared to control concrete without fibers, all fiber-reinforced concretes showed an appreciable increase in flexural strength. Also increase in the fiber content clearly shows the better performance. Among all fiber reinforced concretes, specimen containing more proportion of fiber (LF3 and LF5), showed the maximum flexural strength. Maximum increase in flexural strength for LF3 and LF5 was in order of 30.1% and 23.4%, respectively. This is due to contribution of more fibers in tensile load before fracture of the samples. In addition, the increased fiber availability makes it more efficient in delaying the growth of micro cracks [34] and thereby improving the ultimate tensile stress capacity. Also the specimens with longer length of PP fiber showed better flexural strength in compare with specimens with smaller fibers. The reason could be due to high aspect ratio of PP fibers used in the LF2 and LF3 specimens, which gives high reinforcement index.

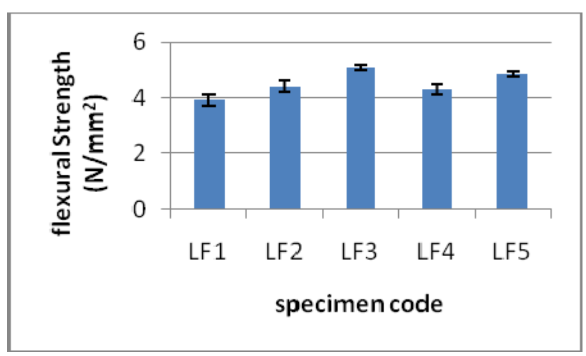

FIGURE 5. Flexural Strength of LWC specimens.

Tensile Strength Results

Results of tensile strength are shown in *Figure 6*. Each of the results was the average of 3 test specimens and mean values were statistically analyzed by ANOVA technique in SPSS software at 0.95 level of confidence. Split tensile strengths of PP fiber concretes were found to be higher compared to reference concrete. From *Figure 6*, it can be observed that the fiber concrete specimens containing longer PP fiber (LF2 and LF3) show the best split tensile strength among all concretes. Enhancement in split tensile strength is expected with increasing the fiber proportion since the plane of failure is well defined (diametric). The higher the number of fibers bridging on the diametrical 'splitting' crack, the higher would be the split tensile strength. Short length fiber reinforced specimens (LF4 and LF5), possibly owing to their short fiber lengths, did not perform as well as the other two samples.

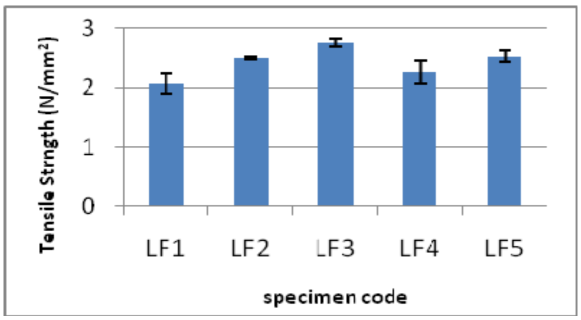

FIGURE 6. Tensile strength of LWC specimens.

Water Absorption Results

Results of water absorption of concrete specimens are shown in *Figure 7*. Each of the results was the average of 3 test specimens and mean values are reported. It is clearly shown that introducing fibers to the concrete have direct effect on the water absorption behavior of lightweight concrete. The water absorption of all specimens increases by adding polypropylene fibers although increase in water absorption for longer fibers is relatively higher than shorter fibers. It may be concluded that increase in water absorption is due to entrapment of air during the mixing and thereby generating voids in concrete. For long fibers the interlocking phenomena [37, 38] causes the formation of vacant space where are suitable location for water diffusion. By increase in the fiber proportion the water absorption increases for both fiber lengths, significantly (with 0.95 confidence interval).

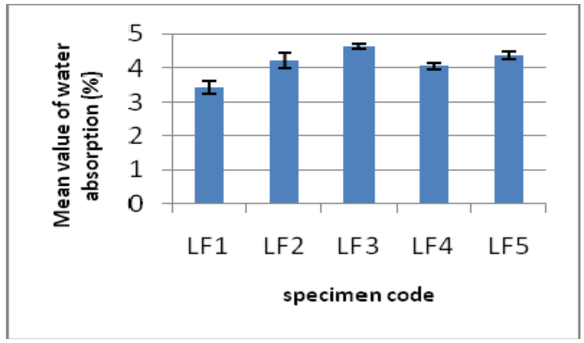

FIGURE 4. Water absorption of LWC specimens.

Concrete Shrinkage Results

The concrete is usually subjected to changes in its volume either autogenous or induced. The loss of moisture contained in hardened concrete causes one of the most detrimental properties of concrete, which affects the long-term strength and durability. This change is important from the point of view that it causes unsightly cracks in concrete. Generation of crack in the concrete structure is the major factor in destruction.

The effect of added fibers in concrete on shrinkage behavior is shown in *Figure 8*. Each of the values is the average of 3 test specimens. According to the results, shrinkage value of concrete specimens decreases by utilizing the polypropylene fibers. Among the all specimens, LF3 showed the best decrease in concrete shrinkage. Increase in fiber proportioning seemed to result in a reduction in the value of shrinkage when compared with the results of plain lightweight concrete. This reduction, however, is not statistically significant (with 0.95 confident interval).

These results could be due to the efficacy of fiber reinforcement in the arrest of cracking, which results from drying shrinkage [40, 41]. When a crack is formed in fiber-reinforced concrete, fibers that bridge the crack prevent it from opening more. With the action of shrinkage, fibers transmit forces through the crack. If loads transmitted by fibers are very small, as for composites containing either very low volumes or very short length of fibers, then the second crack will not form because the tensile stress transmitted across the crack is smaller than the tensile strength of the matrix.

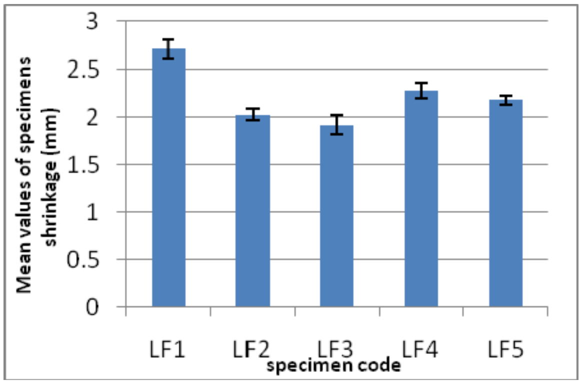

FIGURE 8. Mean value of concrete shrinkage at 28 days of casting.

With comparing the result of flexural strength (*Figure 5*) and tensile strength (*Figure 7)* with shrinkage results (*Figure 8*), it could be concluded that an advantage may therefore be obtained from including fibers in the lightweight aggregate concrete because of the improvement that the fibers impart to the tensile and flexural strength. The improvement obtained here is large enough to avoid large shrinkage in the lightweight aggregate concrete.

CONCLUSIONS

The primary objective of this study was to evaluate the action of PP fibers at different volume fractions and fiber length to obtain a good physical and mechanical behavior of light weight concrete. Fibers with two different length, 6mm and 12mm were employed for this study. Fiber reinforcement significantly increases the tensile strength of lightweight aggregate concrete. The higher tensile strength along with the higher flexural strength is believed to be effective in reducing shrinkage in lightweight aggregate concrete.

All reinforced lightweight concrete specimens display improvement in their mechanical strength as a result of fibers performance in cement matrix. Among all fiber proportions and lengths, only the PP fiber with 12 mm length and proportion 0.35 % performed better in all respects compared to the physical and mechanical properties of reinforced lightweight concrete.

The density of polypropylene fibers is lower than water, so they normally show deficiency of uniform distribution during the mixing process and thereby in concrete bulk. However the method introduced in this study gained remarkable results because of their pre-process of their mixing in concrete matrix. Consequently, by increasing the volume fraction of PP fibers up to 0.3 %, a remarkable improvement in physical and mechanical properties of light weight cement composite is achieved.

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