WARSAW UNIVERSITY OF TECHNOLOGY Index 351733
FACULTY OF CIVIL ENGINEERING
COMMITTEE FOR CIVIL AND WATER ENGINEERING
POLISH ACADEMY OF SCIENCES ISSN 1230-2945

DOI: 10.24425/ace.2022.141894

ARCHIVES OF CIVIL ENGINEERING

Vol. LXVIII ISSUE 3 2022

pp. 411 –428

Research paper

Influence of micro synthetic fibers confinement on properties of lightweight foamed concrete

Md Azree Othuman Mydin[1]

Abstract: In this investigation, the confinement effects of micro synthetic fibers on lightweight foamed concrete (LFC) were examined. The parameters evaluated were porosity, water absorption, shrinkage, compressive strength, flexural strength and tensile strength. Three densities were cast which were 600 kg/m^3, 1100 kg/m^3, and 1600 kg/m^3. Besides, the number of layers (1 to 3 layers) of micro synthetic fibers was also being examined. Based on the result obtained, the porosity improved by 8.0% to 16.3%, 13.8% to 25.6%, and 9.3% to 24.5% for the LFC with densities of 600 kg/m^3, 1100 kg/m^3, and 1600 kg/m^3 confined with 1 layer, 2 layers, and 3 layers of micro synthetic fibers, respectively. Besides, for the water absorption test, the enhancements were 6.9% to 15.6%, 20.0 to 27.1%, and 12.2 to 29.6% for the respective densities and number of layers of micro synthetic fibers employed, while the drying shrinkage improved by 48.5% to 76.8%, 57.4% to 72.1%, and 43.2 % to 68.2% for the respective densities and number of layers of micro synthetic fibers employed. For the strength properties, a confinement with 3 layers of micro synthetic fibers showed significant results, where enhancements of 153% (600 kg/m^3), 97% (1100 kg/m^3), and 102% (1600 kg/m^3) were obtained for the compression strength; 372% (600 kg/m^3), 258% (1100 kg/m^3), and 332% (1600 kg/m^3) for the bending strength; and 507% (600 kg/m^3), 343% (1100 kg/m^3), and 332% (1600 kg/m^3) for the splitting tensile strength, respectively, compared to the control LFC.

Keywords: foamed concrete, shrinkage, porosity, water absorption, compressive strength, flexural

[1]Associate Professor, PhD., Civil Engineering, School of Housing, Building and Planning, Universiti Sains Malaysia, 11800, Penang, Malaysia, e-mail: azree@usm.my, ORCID: 0000-0001-8639-1089

1. Introduction

Generally, lightweight foamed concrete (LFC) is produced using four main materials, which are cement, sand, water, and stable foam or foaming agent. The air voids entrapped in the matrix cause its unit weight (density) to be lower (i.e., two times lighter) than that of normal concrete. The Draft International Standard Model Code for concrete construction classifies lightweight concrete as having a density of between 1200 kg/m^3 to 2000 kg/m^3 [1]. Deijik [2] defined LFC as a cementitious material with a minimum of 20% (by volume) of mechanically entrained foam in the mortar mix, where air voids are entrapped in the matrix by utilizing a suitable foaming agent. Nambiar and Ramamurthy [3] stated that LFC is a lightweight material consisting of a Portland cement paste or cement filler matrix (mortar) with a homogeneous void or pore structure created by introducing air in the form of small bubbles. Besides, Jalal et al. [4] also clarified that LFC is generally concrete that is extremely light in weight and contains no large aggregates, only fine sand mixed with cement, water, and foam [5,6].

There is growing interest in emerging concrete bonded fiber composites with enhanced mechanical and durability properties. These fibers provide a superior contact surface with the cement matrix, which considerably improves its bond, gaining a more homogeneous material, hence, having superior mechanical properties. The inclusion of natural fibers as reinforcement in LFC, has been studied to part substitute the synthetic counterparts, particularly glass and polymeric fibers in construction materials. Though, in addition to the problem of mechanical performance, there is the issue of the interface between the fibers with the cementitious matrix. Additionally, the mechanical features of cement-based composites strengthened with natural fibers not only depend on the properties of the fiber itself but also on the degree to which an applied load is spread to the fibers by the matrix phase [7]. Moreover, variations in the mechanical properties over time can transpire due to microstructural instabilities in the fiber-matrix boundary and bulk, as a sign of the continued hydration process in the fiber surroundings. First, though, the growing porosity value of the cement composite in the interfacial region arises, as there is a variation of the water to binder proportion. Then, there is a further encounter for the fiber-cement; the natural fibers' hydrophilic nature hinges on the lumens, sorptivity, irregularity, chemical compounds, and superficial energy in the fiber–matrix boundary. Therefore, it is crucial to control the fiber-matrix interface with natural fiber, unlike synthetic fibers such as glass fiber. Therefore, this study focuses on determining the properties of LFC with the confinement of micro synthetic fibers.

2. Literature review

Shabbar et al. [8] defined porosity as the sum of the entrained air pores and voids within a paste, measured by vacuum saturation, which is approximately four times that which is measured by the water absorption method. A study by Kearsley & Wainwright [9] into the porosity of LFC proved that it is mainly dependent on the dry density of LFC rather than the content or types of fly ash. Based on the results presented by Narayanan and Ramamurthy [10], the larger pores in LFC can be considered as zero-density aggregates, and a transmission zone exists in the void-paste interface. According to Visagie and Kearsley [11], at higher densities of LFC, the distribution of air voids does not seem to influence the compressive strength, which is related more to the uniform distribution of air voids at higher densities. Luping [12] also mentioned that bigger pores influence the concrete strength rather than smaller pores, whereas, for materials with the same matrix and porosity, the strength is lower for those that contain larger-sized pores. A higher percentage of porosity was obtained at a lower density of LFC [13]. The pore size and microstructure of LFC influence its strength, durability, toughness, heat transfer, and moisture transport properties [14]. The properties of LFC are mainly influenced by the pore structure, where a total pore size distribution ranging between 5 and 47 nm results in only small changes to the porosity, with no significant effects on the compressive strength and absorbency of the cellular concrete [15]. The water absorption of cement base materials is affected by many factors, namely, the concrete mixture proportions, the entrained air content, the type and duration of curing, and the presence of water absorption on LFC obtained at lower-density mixtures. Thakrele [16] emphasized that the water absorption of LFC is low due to its closed cellular structure, although the water absorption was increased with a higher air content. Drying shrinkage is one of the drawbacks faced in LFC. This problem causes the LFC structure to shrink and reduced volume then leads to the decrease of LFC strength. Since the drying shrinkage of LFC is higher compared to normal strength concrete, then by confinement of micro synthetic fibers in LFC, can decrease the drying shrinkage percentage of LFC [17]. The typical range of drying shrinkage value in LFC is between 0.1% to 0.35% of the total volume of the hardened concrete matrix.

Based on a study by Yasser [18] into the contribution of LFC to the cross-sectional strength of a composite, it was discovered that LFC is not able to satisfactorily resist a bending load because of the brittle properties of the material. According to Zhu [19], LFC is a combination of soft and brittle materials, and as such, it contains many microcracks. Thus, when it is compressed, these microcracks will propagate and cause failure. Amran et al. [20] highlighted that the compressive strength of LFC is directly related to its density, where a reduction in unit weight affects the compressive strength both exponentially and adversely. According to Thakrele [21], the compressive strength of LFC will continue to increase indefinitely due to the reaction with the existing carbon dioxide (CO2) in the surrounding air, but the increasing strength with age is essentially linear over the first 12 months. Based on a study by Dawood and Hamad [22], plain concrete is a brittle material that has poor fracture toughness, weak resistance to crack propagation, and low impact strength. However, Jones and McCarthy [23] explained that LFC can still be used as a structural material. According to the research conducted by Narayanan and Ramamurthy [24], the flexural strength of LFC ranges between 15% to 35% of its axial compressive strength. Besides, Kozłowski and Kadela [25] discovered that the flexural strength of LFC can be increased by increasing its density as the apparent density of hardened LFC is strongly associated with the foam content in the mix. The tensile strength of LFC can be as high as 0.24 times its compressive strength, with an ultimate strain of about 0.1% [21]. Splitting tensile strength for self-compacting concrete is lower than normal vibrated concrete due to the absence of aggregate-paste bonds in the matrix [20].

3. Materials and mix design

3.1. Materials

Ordinary Portland cement was used throughout this study. This OPC, which was Type 1 Portland cement, was applied according to ASTM C150-04. The cement, produced by the Cement Industry of Malaysia under the label, "Castle". Fine sand was used as a filler to produce LFC. The sand utilized in this research was sieved manually using a no. 16 sieve (1.18 mm), in compliance with ASTM C778-06, where 50% to 85% of the graded sand must be able to pass through the sieve. Next, potable or non-potable water can be used to mix concrete. For this study, clean water was used in the production of LFC. Based on a previous study, the water-to-cement ratio for LFC ranges between 0.4 and 1.25. Thus, in this experiment, the water-to-cement ratio was fixed at 0.45 to produce LFC with reasonable workability. Foam is added to control and obtain a desirable density for the LFC. Thus, for this study, a protein-based foaming agent, was used to produce a stable foam. The density of the foam applied in this study ranged between 65–75 g/L. The micro synthetic fibers used were provided by TKS Bio Sdn. Bhd. Table 1 visualizes the micro synthetic fibers physical properties. As shown in Fig. 1, the micro synthetic fibers were cut and laid according to

Fig. 1. The micro synthetic fibers were cut and laid according to the dimensions of the moulds

Table 1. Physical properties of micro synthetic fibers

Mesh size	4.0 × 5.0 mm
Colour	white
Coating Type	alkali resistant
Mass (g/m^2)	145 ± 5
Ignition point	784.4°F (398°C)
Melting point	316.4Â°F (158Â°C)
Tensile strength (MPa)	1325
Elongation at break (%)	3.41%

the dimensions of the moulds. The LFC specimen was confined with these micro synthetic fibers and placed in the matrix, as shown in Table 1.

Table 2 shows the mix proportions for LFC with densities of 600 kg/m^3, 1100 kg/m^3, and 1600 kg/m^3. The mix ratios for all the mixes were fixed, where the cement-to-sand ratio was 1:1.5, while the water-to-cement ratio was constant at 0.45. The control sample represents the LFC specimen without any confinement with micro synthetic fibers, 1L-LFC stands for the 1-layer micro synthetic fibers, 2L-LFC stands for the 2-layer micro synthetic fibers, and 3L-LFC indicates the 3-layer micro synthetic fibers. A slump test was performed until reading in the range of 21 to 26 cm was achieved.

Table 2. LFC mix proportions

Sample	Micro synthetic fibers (layer)	Density (kg/m^3)	Mix ratio		Mix proportion (kg)		
			Cement to sand	Water to cement	Cement	Sand	Water
Control	–	600	1:1.5	0.45	23.02	34.54	10.36
	–	1100	1:1.5	0.45	41.08	61.62	18.49
	–	1600	1:1.5	0.45	59.30	88.70	26.61
1L-LFC	1	600	1:1.5	0.45	23.02	34.54	10.36
	2	1100	1:1.5	0.45	41.08	61.62	18.49
	3	1600	1:1.5	0.45	59.30	88.70	26.61
2L-LFC	1	600	1:1.5	0.45	23.02	34.54	10.36
	2	1100	1:1.5	0.45	41.08	61.62	18.49
	3	1600	1:1.5	0.45	59.30	88.70	26.61
3L-LFC	1	600	1:1.5	0.45	23.02	34.54	10.36
	2	1100	1:1.5	0.45	41.08	61.62	18.49
	3	1600	1:1.5	0.45	59.30	88.70	26.61

4. Experimental program

4.1. Porosity test

A porosity test was performed using the vacuum saturation method as developed by. Cabrera and Lynsdale at the University of Leeds [26]. This test was carried out on day-28 by immersing the specimen into a vacuum desiccator. The purpose of this test was to determine the percentage of air voids in the LFC specimens of different densities, which will influence their strength. The lower the percentage of porosity in LFC, the higher its strength. This is because the presence of more air voids in the cement matrix will cause it to be more brittle and susceptible to cracks. Thus, the confinement of LFC in micro synthetic fibers will improve its porosity. Therefore, 3 specimens of LFC, with a diameter of 45 mm and height of 50 mm, were placed in an oven at a temperature of 105°C to remove moisture for 72 hours or until no changes in weight were recorded.

4.2. Water absorption test

The water absorption test was carried out as prescribed in BS 1881-12 [27]. Cylindrical-shaped specimens (Ø 75 mm $\times h$ 100 mm) were used in this study. On the aging day of the test, 3 specimens were unwrapped and oven-dried for 72 hours. Then, the weight of each cooled oven-dried specimen was recorded, and it was fully submerged in a water tank for 30 minutes. Next, a dry cloth was used to remove any excess water present on the test specimen and its weight was recorded in a saturated condition.

4.3. Shrinkage test

This test was conducted by using Mitutoyo brand digital indicator with 298 mm of reference bar. Drying shrinkage test was performed according to ASTM C157/C157M [28] where three specimens of the prism (75 × 75 × 285 mm) were installed with a pair of steel screw and cap nut. After demoulding, LFC specimens were placed in the length comparator and rotated anti-clockwise to get the data. The readings were taken and recorded as L_i. Then, the steps were repeated for the next age of testing, which is at days 1, 3, 7, 14, 21, 28, and 56.

4.4. Compression test

The compressive strength of the LFC specimen was tested on a cube measuring 100 × 100 × 100 mm. The test was carried out in a concrete laboratory via a universal testing machine, GOTECH GT-7001, with a load capacity of 3000 KN. The test was conducted at a load speed of 0.6 MPa/sec, corresponding to BS EN 12390-3 [29]. Three specimens were tested at each curing period (day-7, day-28, day-60 and day-180), and the average of the three readings was verified as the compressive strength.

4.5. Flexural test

For the flexural test, a prism measuring 100 × 100 × 500 mm was employed according to ASTM C293/C293M [30]. A three-point bending test was selected to obtain the bending strength of the FC. Three specimens were prepared for the test, and the average result of the flexural test was taken as the final result.

4.6. Splitting tensile test

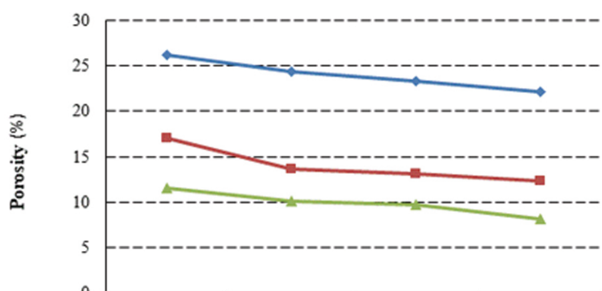
A cylinder with a diameter of 100 mm and a height of 200 mm was utilized for the splitting tensile strength test, which was performed according to ASTM C496/C496M [31].

Three specimens were cast and tested, and the average reading from these 3 results was taken. The tensile strength of concrete can be determined by the application of direct tensile stress or indirect tensile strength. In this study, the indirect tensile strength was applied. Three cylindrical specimens measuring 100 Ø mm × 200 mm were tested at day-7, day-28, day-60, and day-180.

5. Results and discussion

5.1. Porosity

Fig. 2 depicts the porosity results of LFC confined with a different number of layers of 160 g/m^2 of micro synthetic fibers. Overall, the porosity showed a decreasing trend with an increase in the density of LFC. For the control specimens of three different densities, the LFC with a density of 600 kg/m^3 obtained the highest increase in porosity of 66.4%, while the lowest increase in porosity of 32.2% was obtained by the LFC with a density of 1600 kg/m^3. The porosity decreased by 23.5% and 35.6% for the control specimens with densities of 1100 kg/m^3 and 1600 kg/m^3, respectively compared to the control specimen with a density of 600 kg/m^3. Jiang et al. [32] also reported that the higher porosity of LFC is due to the addition of pre-foam to the cement paste or mortar. Theoretically, when a high volume of foam is added into the mortar, more air voids will be created in the mortar slurry, thereby inducing a higher porosity in the LFC. Besides, the porosity of LFC depends on its density. At a density of 600 kg/m^3, the porosity of LFC was lessened by 8.0%, 12.2%, and 16.3% with 1 layer, 2 layers, and 3 layers of micro synthetic fibers confinement, respectively. The same could be said of the LFC with a density of 1100 kg/m^3, where the percentage decrease of porosity was 13.8%, 15.6%, and 25.6% with 1 layer, 2 layers, and 3 layers of micro synthetic fibers confinement, respectively, while for the LFC with a density of 1600 kg/m^3, the percentage decrease was 9.3% (1 layer), 12.7% (2 layers),



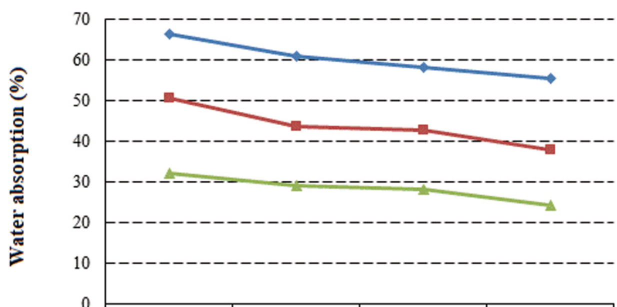
	CONTROL	1L-FM	2L-FM	3L-FM
600 kg/m³	26.2	24.4	23.3	22.1
1100 kg/m³	17.0	13.6	13.1	12.4
1600 kg/m³	11.5	10.1	9.7	8.1

Fig. 2. The porosity of LFC specimens confined with different layers of micro synthetic fibers

and 24.5% (3 layers). The reduction in the porosity was due to the confinement with the micro synthetic fibers, which lessen the rate of the water absorbed into the air void in LFC. From the previous studies, no research has yet been done to investigate the porosity of LFC confined by micro synthetic fibers. In this experimental investigation, it was observed that the LFC that was confined with micro synthetic fibers showed the same decreasing pattern for porosity as with the inclusion of fibers in the LFC. For instance, based on a study conducted by Zamzani [33], the inclusion of 0.6% fibers in LFC (1450 kg/m^3) was able to decrease the porosity by up to 21% at day-28 compared to the control. This result was approximately similar to the result obtained in the current research, where the confinement of LFC with a density of 1600 kg/m^3 with 3 layers of micro synthetic fibers (160 g/m^2) improved the porosity by 24.5% compared to the control, which was without any confinement.

5.2. Water absorption

Fig. 3 presents the water absorption results for LFC confined with 160 g/m^2 of micro synthetic fibers and for the unconfined (control) LFC with three different densities (600 kg/m^3, 1100 kg/m^3, and 1600 kg/m^3) at day-28. As shown in Fig. 3, the water absorption capacity decreased as the density of LFC increased. A water absorption capacity of 26.2% was obtained for LFC with a density of 600 kg/m^3, while the capacity was 17.0% for LFC with a density of 1100 kg/m^3, and 11.5% for LFC with a density of 1600 kg/m^3 for the control specimens. This showed that the decrease in water absorption capacity across the densities induced a better performance in the LFC, where there was a reduction of 35% in the water absorption capacity of the LFC with a density of 1100 kg/m^3, and a reduction of 56% with a density of 1600 kg/m^3 compared to the LFC with a density of 600 kg/m^3. This occurrence is related to the volume of foam that is added to the mortar. The larger the volume of foam added, the higher will be the number of pores and capillaries that will be



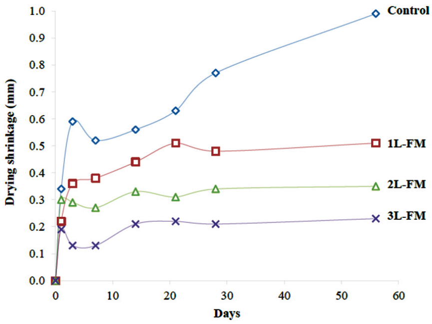
	CONTROL	1L-FM	2L-FM	3L-FM
600 kg/m³	66.4	61.1	58.3	55.6
1100 kg/m³	50.8	43.8	42.9	37.8
1600 kg/m³	32.2	29.2	28.1	24.3

Fig. 3. The water absorption capacity of LFC confined with different layers of micro synthetic fibers

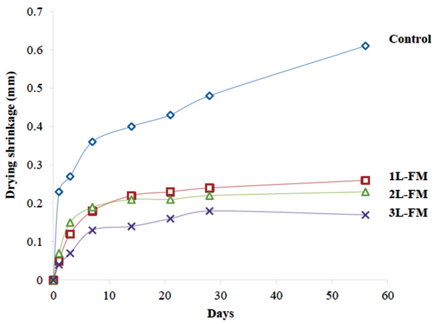
produced in the cement paste, which will lead to higher penetration of water into the LFC. Water absorption is a process whereby the concrete absorbs or draws water into its pores and capillaries. Besides, as proven in this research, the water absorption capacity of LFC was reduced with the confinement of micro synthetic fibers. The water absorption capacity of the LFC specimens with densities of 600 kg/m^3, 1100 kg/m^3, and 1600 kg/m^3 and confined with 1 layer of micro synthetic fibers lowered by 6.9%, 20.0%, and 12.2%, respectively. There was also a noticeable reduction of 11.1% (600 kg/m^3), 22.9% (1100 kg/m^3), and 15.7% (1600 kg/m^3) when the confinement was with 2 layers of micro synthetic fibers, while there was a reduction of 15.6%, 27.1%, and 29.6% when the confinement was with 3 layers of micro synthetic fibers for the respective densities. The presence of micro synthetic fibers in the cement matrix managed to prevent the penetration of water into the LFC due to the hydrophobicity of the fibers. Hydrophobic materials offer an alternative solution for inhibiting the diffusion of water molecules into LFC, where higher water absorption will lead to swelling of the LFC, thereby indirectly decreasing its mechanical performance. On the other hand, hydrophilic fibers tend to attract water molecules, resulting in the higher penetration of water, not only into the cement matrix but also into the fibers themselves to induce the debonding of the fibers and matrix due to the expansion of the swollen fibers.

5.3. Shrinkage

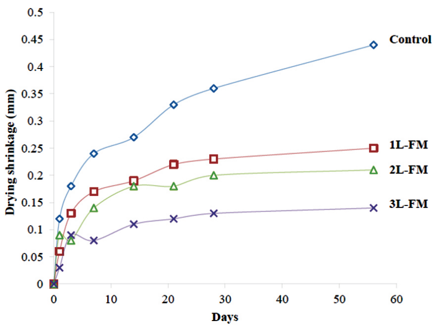
Fig. 4 depict the development of drying shrinkage for LFC confined with micro synthetic fibers. The confinement with micro synthetic fibers significantly reduced the drying shrinkage of the LFC. For the LFC with a density of 600 kg/m^3, the confinement with 1 layer of micro synthetic fibers decreased the drying shrinkage of the LFC by 48%, while the drying shrinkage of the LFC with a density of 1100 kg/m^3 was reduced by 57%, and by 43% for the LFC with a density of 1600 kg/m^3 compared to the unconfined specimens at day-56. When the number of layers for the micro synthetic fibers was increased to 2 layers and 3 layers, the drying shrinkage behaviour also decreased by 52% and 77%, respectively compared to the control specimens. At the early stage of the test, all the specimens showed inconsistent drying shrinkage measurements as they had not fully hardened yet and the hydration process still occurs. However, at day-30 and above the graph showed only a slight increase in drying shrinkage for the confined LFC, while the control specimens showed noticeable increases. Besides, Karim et al. [34] also clarified that the rapid increase in drying shrinkage at the early stage is due to the rapid loss of moisture from the surface of the specimen, while for the later stages, the rate of increase in the 125 drying shrinkage is reduced with time depending on the removal of moisture from the concrete. As mentioned previously, the reduction in the drying shrinkage strain of the confined LFC was due to the role of the micro syntheric fibers, which impeded the evaporation of moisture from the cement paste, thereby altering the dimensions of the LFC. The micro syntheric fibers not only prevented the water from diffusing into the cement matrix, but also prevented the loss of the existing water in the LFC. Falliano et al. [35] also proved that unreinforced specimens exhibit a shrinkage that decreases with increasing dry density. The addition of fibre can reduce the risk of shrinkage and stabilize the fresh mix.



(a) 600 kg/m^3



(b) 1100 kg/m^3

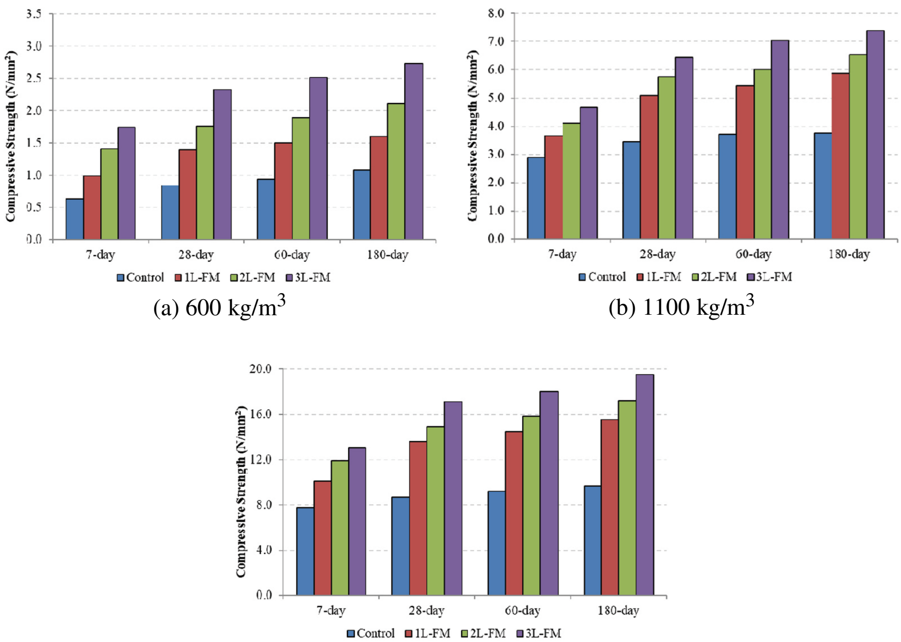


(c) 1600 kg/m^3

Fig. 4. Shrinkage of LFC confined with different layers of micro synthetic fibers

5.4. Compressive strength

Fig. 5 demonstrate the compressive strength results for LFC with densities of 600 kg/m^3, 1100 kg/m^3, and 1600 kg/m^3 confined with different number of layers of micro synthetic fibers. The three figures show the same pattern of strength development, where all the LFC mixes were enhanced with increasing curing time. As the density of the LFC increased, its compressive strength also increased significantly. For instance, for the control LFC at day-180 and with a density of 600 kg/m^3, the compressive strength achieved was 1.1 N/mm^2, while for the LFC with a density of 1100 kg/m^3, the compressive strength obtained was 3.8 N/mm^2, which was 248% higher than that of the LFC with a density of 600 kg/m^3, and an increase of 157% (9.7 N/mm^2) was obtained for the LFC with a density of 1600 kg/m^3 compared to a density of 1100 kg/m^3. Shawnim and Mohammad [36] highlighted that at the higher densities, the compressive strength is not influenced by the distribution of air voids, but rather by the more uniform distribution of voids. Lim et al. [37] also mentioned that the production of LFC with finer sand results in a more uniform distribution of air voids compared to coarse sand. Due to the brittleness of LFC, a reinforcing element is needed to boost its compressive strength. The addition of fibers improves the compressive strength of LFC by preventing microcracks. Therefore, the confinement of LFC with 160 g/m^2 of micro synthetic fibers enhanced the compresive strength of LFC. As can be observed, the confinement of LFC with a density of 600 kg/m^3 with 1 layer of micro synthetic fibers increased the compressive strength by 48% compared to the control LFC with the same density and increased the compressive strength of LFC with a density of 1100 kg/m^3 by 56%, while an increase of 61% was achieved for the comprssive strength of LFC with a density of 1600 kg/m^3. Notable improvements of 95%, 74%, and 78% were also obtained for the LFC specimens with densities of 600 kg/m^3, 1100 kg/m^3, and 1600 kg/m^3, respectively confined with 2 layers of micro synthetic fibers. Furthermore, the highest increase in compressive strength that was found in this investigation was for the confinement of LFC with 3 layers of micro synthetic fibers. The remarkable enhancements of 153%, 97%, and 102% in the compressive strength compared to the control at the respective densities proved that the micro synthetic fibers has the potential to be utilized as a reinforcing element in LFC. In addition, the micro synthetic fibers also acted to prevent microcracks and retard the widening of cracks on exposure to a higher applied load. Improved resistance and ductility are governed mainly by the fibers, which delay cracks in the matrix. The good bonding between the micro synthetic fibers and cement matrix is one of the reasons for the improvement in the compressive strength of LFC. Besides, the number of layers of confinement in concrete also contribute to the compressive strength, where an augmentation of 54% was achieved by the application of between 1 to 2 layers of



(a) 600 kg/m^3

(b) 1100 kg/m^3

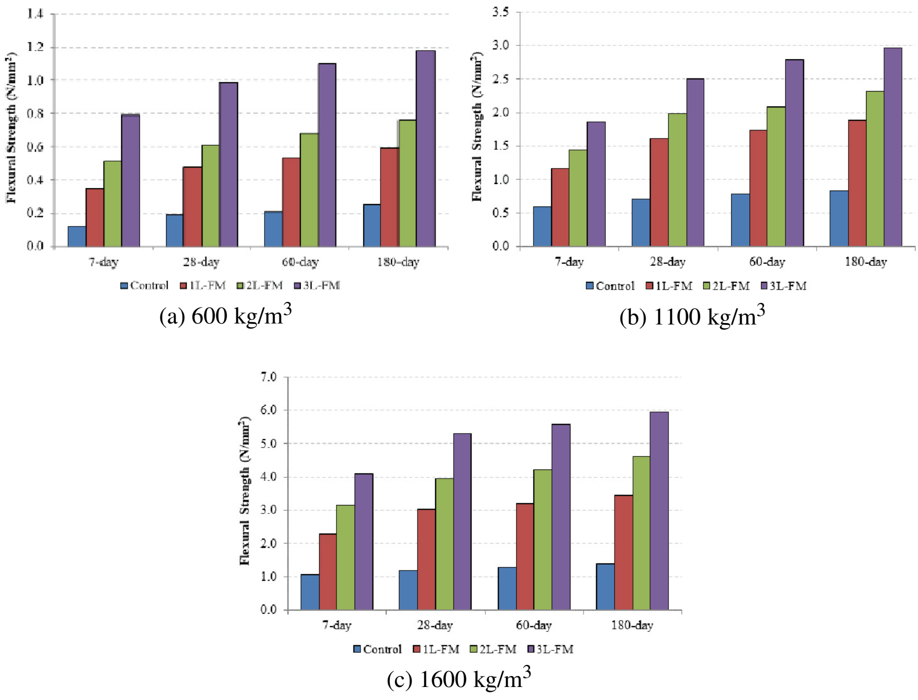
(c) 1600 kg/m^3

Fig. 5. Compressive strength of LFC confined with different layers of micro synthetic fibers

micro synthetic fibers. Huang et al. [38] also justified that the use of micro synthetic fibers jackets improves the compressive strength of plain concrete, and an increase in the number of micro synthetic fiber layers will lead to an effective confinement due to the increase in the deformation capacity. Moreover, an improvement in the load bearing capacity of concrete leads to a higher ultimate crack stress. Therefore, the highest compressive strength obtained from this study was for LFC with a density of 1600 kg/m^3 that was confined with 3 layers of micro synthetic fibers for 180 day.

5.5. Flexural strength

Fig. 6 show the results of the flexural strength for LFC with densities of 600 kg/m^3, 1100 kg/m^3, and 1600 kg/m^3. The confined LFC was embedded with 1 layer, 2 layers, and 3 layers of micro synthetic fibers placed 2 mm from the bottom layer, while the unconfined (control) specimens did not have any reinforcement in the tensile zone. Based on observations from these three figures, all the specimens gained load-carrying capacity in bending with increasing curing time. The strength development increased steadily for 180 days. Besides, it could be seen that the bending strength decreased with decreasing density. The strength of concrete is affected by the volume of voids, which is related to the porosity. An increase in porosity reduces the strength of concrete, but the magnitude of



(a) 600 kg/m^3 (b) 1100 kg/m^3

(c) 1600 kg/m^3

Fig. 6. Flexural strength of LFC confined with different layers of micro synthetic fibers

this effect depends significantly on the size, shape, and distribution of the pores. There was a noticeable increase in the load-carrying capacity in bending of the LFC from a density of 600 kg/m^3 to 1600 kg/m^3.

As described by Falliano et al. [35], this occurred because of the very low strength values corresponding to the lower densities of LFC. Moreover, it was noticed that the control specimens for the three respective densities displayed very poor bending behaviours. The reason for this was that the control specimens had zero reinforcement in the tensile zone, where the sudden failure occurred as soon as a load was applied. A reinforcement strategy is needed to ensure that LFC with lower densities can be utilized as semi-structural or even more advanced structural elements in construction work. In Fig. 6a, 1 layer of micro synthetic fibers laid 2 mm from the bottom layer increased the bending strength of LFC by 136%, but when the number of layers was doubled (2 layers), the bending strength was boosted by up to 204%, and it was effectively increased by 372% when 3 layers of micro synthetic fibers were added compared to the unreinforced specimens. This trend of increase was also almost the same for the LFC specimens with densities of 1100 kg/m^3 and 1600 kg/m^3.

As expected in Fig. 6c, the highest bending strength among all the specimens was achieved within 180 days by the LFC specimen with a density of 1600 kg/m^3 and embedded with 3 layers of micro synthetic fibers in the tensile zone of the cement matrix. The significant increase in the load-carrying capacity in bending of LFC was due to the higher flexibility of the micro synthetic fibers, which caused a higher strain in the cement matrix. Naaman [39] explained that when the cementitious composites crack under bending tension, the reinforcement in the cracked zone will contribute to both stiffness and strength, while the matrix will be cracked. The higher stiffness behavior of the micro synthetic fibers will lead to the debonding of the fibers in the matrix due to the limited release of energy by the micro synthetic fibers. Gencoglu and Mobasher [40] clarified that AR-glass reinforcement provides suitable resistance in impact loading as it absorbs less energy (20–40% of potential energy). Vogel et al. [41] also verified in their study that the specimen that had been reinforced with a micro synthetic fiber was able to transfer more energy to its supports than the unreinforced specimen without the creation of large cracks. This was because the unreinforced specimen absorbed almost double the amount of impact energy (64%) compared to the reinforced specimen, which only absorbed 39% of the impact energy, with the rest of the energy being transferred to the supports. The structure of the micro synthetic fibers itself was also the reason for the increase in the bending strength of the LFC. Basically, micro synthetic fibers is produced by combining several fibers to form a continuous fibre with a warp and weft structure, either in a coil or a layered fashion. The additional enhancement of the bonding of the fabric is due to another mechanical anchoring provided by the fill yarns in the weft direction when the fabric is embedded in the cement matrix. This micro synthetic fiber is not only able to resist fractures because of sudden loading but is also capable of withstanding high fracture toughness with high impact strength. Reddy et al. [42] also claimed that the good bonding of glass fabric produces higher impact strength. Moreover, Wong et al. [43] also mentioned that glass fiber poses high tensile strength and interfacial strength, resulting in the best impact strength compared to natural fibers.

5.6. Splitting tensile strength

The results of the splitting tensile strength obtained in this study, which showed a similar trend as that of the compressive strength, as shown in Fig. 7. These three figures demonstrated that the splitting tensile strength of the unconfined and confined LFC grew increasingly as the curing age progressed. The volume of foam also significantly affected the load carrying capacity in tension. For instance, the splitting tensile strength obtained for the control specimen with a density of 600 kg/m^3 at day-180 was 0.14 N/mm^2, and this splitting tensile strength increased by 229% after the foam volume was reduced to obtain the desired density of 1150 kg/m^3. An increase of 122% in the splitting tensile strength was also achieved for the LFC specimens with a density of 1600 kg/m^3 as only a small amount of foam was needed to achieve this preferred density compared to a density of 1100 kg/m^3. However, the results of the splitting tensile strength obtained for the control specimens were low due to the absence of a reinforcing element in the matrix. Thus, the confinement of LFC with different number of layers of micro synthetic fibers improved the performance of the LFC in terms of its splitting tensile strength. When the LFC was wrapped in 1 layer of micro synthetic fibers, the splitting tensile strength increased by 186%, 157%, and 150% for the specimens with densities of 600 kg/m^3, 1100 kg/m^3, and 1600 kg/m^3, respectively, compared to the unconfined specimens. For the confinement with 2 layers of micro synthetic fibers, the increases in the splitting tensile strength, which were 279%,

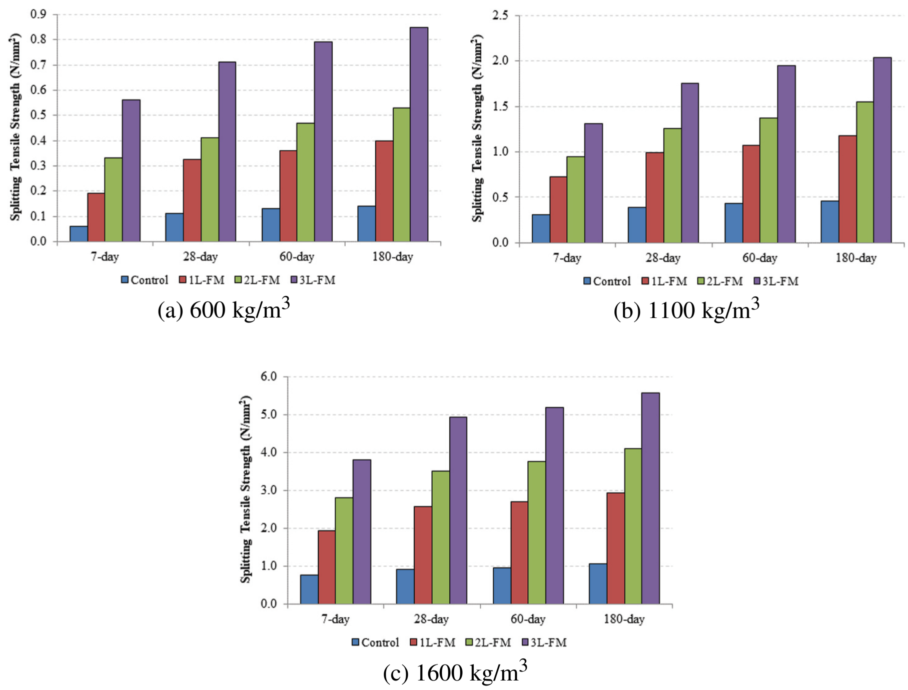


Fig. 7. Splitting tensile strength of LFC confined with different layers of micro synthetic fibers

237% and 234% for the respective densities, were double those of the specimens confined with 1 layer of micro synthetic fibers. Superior augmentations of 507%, 343%, and 332% in splitting tensile strength were accomplished when the LFC specimens with densities of 650 kg/m^3, 1150 kg/m^3, and 1650 kg/m^3, respectively were confined with 3 layers of micro synthetic fibers. The incredible enhancement of the splitting tensile strength in LFC proves that micro synthetic fibers has the potential to be used as a reinforcing element in LFC. This performance also improved as the number of layers of micro synthetic fibers for the confinement was increased. The micro synthetic fibers not only had strong fiber-to-matrix bonding, but also exceptionally strong fiber-to-fiber bonding, which enabled stretching and prevented the LFC from collapsing. The enhancement of splitting tensile strength is due to the holding capacity of the fibers, which can aid in the splitting of the concrete [44].

6. Conclusions

In this study, the hardened properties of LFC with the confinement of different layers of micro synthetic fibers were investigated and discussed. Three different densities of LFC were used in this study, namely, 600 kg/m^3, 1100 kg/m^3, and 1600 kg/m^3. This was because the variance from a lower to a higher density of LFC gave better results and various considerations for analysis. The properties evaluated were porosity, water absorption, shrinkage, compressive strength, flexural strength and splitting tensile strength. The results indicate that the confinement of LFC with micro synthetic fibers lead to substantial improvement to the properties of LFC considered in this researh.

The unreinforced LFC had a high porosity, water absorption capacity, and drying shrinkage. An increase in the foam volume caused a reduction in the density of the LFC but led to higher values for the respective tests at the given curing age. The results showed that the porosity reduced by 8.0% to 16.3%, 13.8% to 25.6%, and 9.3% to 24.5% for the LFC with densities of 600 kg/m^3, 1100 kg/m^3, and 1600 kg/m^3 confined with 1 layer, 2 layers, and 3 layers of micro synthetic fibers, respectively. Besides, for the water absorption test, the reduction were 6.9% to 15.6%, 20.0 to 27.1%, and 12.2 to 29.6%, while the drying shrinkage reduced by 48.5% to 76.8%, 57.4% to 72.1%, and 43.2 % to 68.2% for the respective densities and number of layers of micro synthetic fibers employed. The presence of micro synthetic fibers managed to prevent the penetration of water into the LFC due to the hydrophobicity of the fibres. Hydrophobic materials provide an alternative solution for inhibiting the diffusion of water molecules into LFC.

For the strength properties, the confinement of LFC with micro synthetic fibers lead to massive improvement of compressive, flexural and splitting tensile strengths. The maximum compressive strength values achieved were 2.73 N/mm^2, 7.39 N/mm^2, and 19.5 N/mm^2 for 600 kg/m^3, 1100 kg/m^3 and 1600 kg/m^3 densities, respectively. Significant improvements of 48% to 153%, 56% to 97%, and 61% to 102% were observed for the LFC specimens with densities of 650 kg/m^3, 1100 kg/m^3 and 1650 kg/m^3, respectively. The load-carrying capacity in flexural also showed a similar trend, where it increased as the density of LFC increased. The maximum load carrying capacity in bending values obtained at the respective densities were 1.18 N/mm^2, 2.97 N/mm^2, and 5.96 N/mm^2. The percentage increase in the load carrying capacity in flexural with different number of layers of micro synthetic fibers compared to the control specimens was 136% to 372% for a density of 650 kg/m^3, 127% to 258%, and 149% to 332%, for densities of 1150 kg/m^3 and 1650 kg/m^3, respectively. Finally, the maximum splitting tensile strength values obtained were 0.85 N/mm^2, 2.04 N/mm^2, and 4.41 N/mm^2 with enhancements of 186% to 567%, 157% to 343%, and 150% to 332%, respectively for the various densities. All the enhancements that were achieved were due to the confinement with micro synthetic fibers in the form of a jacket, and the increase in the initial elastic stiffness of LFC. When the lateral deformation was developed because of the applied load, the tension in the jacket (micro synthetic fibers) was activated due to the lateral expansion of the LFC. In addition, the micro synthetic fibers also acted to prevent microcracks and retard the widening of cracks on exposure to a higher applied load. Improved resistance and ductility are governed mainly by the fibers, which delay cracks in the matrix. The good bonding between the micro synthetic fibers and cement matrix is one of the reasons for the improvement in the strengths of LFC.

References

[1] M.A.O. Mydin, M. Musa, A.N.A. Ghani, "Fiber glass strip laminates strengthened lightweight foamed concrete: Performance index, failure modes and microscopy analysis", *AIP Conference Proceedings*, 2018, vol. 2016, no. 1, art. ID 020111, DOI: 10.1063/1.5055513.

[2] V. Deijik, "Foam concrete", *Concrete*, 1991, pp. 49–54.

[3] E.K.K. Nambiar, K. Ramamurthy, "Air-void characterisation of foam concrete", *Cement and Concrete Research*, 2007, vol. 37, no. 2, pp. 221–230, DOI: 10.1016/j.cemconres.2006.10.009.

[4] M.D. Jalal, A. Tanveer, K. Jagdeesh, F. Ahmed, "Foam concrete", *International Journal of Civil Engineering Research*, 2017, vol. 8, no. 1, pp. 1–14.

[5] E. Serri, M.A.O. Mydin, M.Z. Suleiman, "Thermal properties of Oil Palm Shell lightweight concrete with different mix designs", *Jurnal Teknologi*, 2014, vol. 70, no. 1, pp. 155–159, DOI: 10.11113/jt.v70.2507.

[6] N.A. Ahmad, "A study on the lightweight foamed concrete with artificial lightweight aggregate at 1250kg/m^3 of density", Universiti Sains Malaysia, 2015, pp. 69–75.

[7] M.A. Othuman Mydin, N.S. Sahidun, M.Y. Mohd Yusof, N.M. Noordin, "Compressive, flexural and splitting tensile strengths of lightweight foamed concrete with inclusion of steel fibre", *Jurnal Teknologi*, 2015, vol. 75, no. 5, pp. 45–50, DOI: 10.11113/jt.v75.4962.

[8] R. Shabbar, P. Nedwell, Z. Wu, "Porosity and Water Absorption of Aerated Concrete with Varying Aluminium Powder Content", *International Journal of Engineering and Technology*, 2015, vol. 10, no. 3, pp. 234–238, DOI: 10.7763/IJET.2018.V10.1065.

[9] E.P. Kearsley, P. J. Wainwright, "Porosity and permeability of foamed concrete", *Cement and Concrete Research*, vol. 201, pp. 805–812, DOI: 10.1016/S0008-8846(01)00490-2.

[10] N. Narayanan, K. Ramamurthy, "Structure and properties of aerated concrete: A review", *Cement and Concrete Composites*, 2000, vol. 22, no. 5, pp. 321–329, DOI: 10.1016/S0958-9465(00)00016-0.

[11] M. Visagie, E.P. Kearsley, "Properties of Foamed Concrete as Influenced by Air-Void Parameters", *Concrete Beton*, 2002, vol. 101, pp. 9–13.

[12] T. Luping, "A study of the quantitative relationship between strength and pore-size distribution of porous materials", *Cement & Concrete Research*, 1986, vol. 16, pp. 87–96, DOI: 10.1016/0008-8846(86)90072-4.

[13] A.A. Hilal, N.H. Thom, A.R. Dawson, "Pore structure and permeation characteristics of foamed concrete", *Journal of Advanced Concrete Technology*, 2014, vol. 12, no. 12, pp. 535–544, DOI: 10.3151/jact.12.535.

[14] M.A.O. Mydin, "Preliminary studies on the development of lime-based mortar with added egg white", *International Journal of Technology*, 2017, vol. 8, no. 5, pp. 800–810, DOI: 10.14716/ijtech.v8i5.442.

[15] J. Norgaard, M.A.O. Mydin, "Drywall thermal properties exposed to high temperatures and fire condition", *Jurnal Teknologi*, 2013, vol. 62, no. 1, pp. 63–68, DOI: 10.11113/jt.v62.1369.

[16] M.H. Thakrele, "Experimental study on foam concrete", *International Journal of Civil, Structural, Environmental and Infrastructure Eng. Research and Development*, 2014, vol. 4, no. 1, pp. 145–158.

[17] M.A.O. Mydin, N.M. Noordin, N. Utaberta, M.Y.M. Yunos, S. Segeranazan, "Physical properties of foamed concrete incorporating coconut fibre", *Jurnal Teknologi*, 2016, vol. 78, no. 5, pp. 99–105, DOI: 10.11113/jt.v78.8250.

[18] M.Y. Hunaiti, "Strength of composite sections with foamed and lightweight aggregate concrete", *Journal of Materials in Civil Engineering*, 1997, vol. 9, no. 2, pp. 58–61, DOI: 10.1061/(ASCE)0899-1561(1997)9:2(58).

[19] Z. Zhu, "New biaxial failure criterion for brittle materials in compression", *Journal of Engineering Mechanics*, 1999, vol. 125, no. 11, pp. 1251–1258, DOI: 10.1061/(ASCE)0733-9399(1999)125:11(1251).

[20] Y.H.M. Amran, N. Farzadnia, A.A.A. Ali, "Properties and applications of foamed concrete; A review", *Construction and Building Materials*, 2015, vol. 10, pp. 990–1005, DOI: 10.1016/j.conbuildmat.2015.10.112.

[21] M.H. Thakrele "Experimental study on foam concrete", *International Journal of Civil, Structural, Environmental and Infrastructure Eng. Research and Development*, 2014, vol. 4, no. 1, pp. 145-158.

[22] E.T. Dawood, A.J. Hamad, "Toughness behaviour of high-performance lightweight foamed concrete reinforced with hybrid fibres", *Structure Concrete*, 2015, vol. 16, no. 4, pp. 496–507, DOI: 10.1002/suco.201400087.

[23] M. R. Jones, A. McCarthy, "Preliminary views on the potential of foamed concrete as a structural material", *Magazine of Concrete Research*, 2005, vol. 57, no. 1, pp. 21–31, DOI: 10.1680/macr.57.1.21.57866.

[24] N. Narayanan, K. Ramamurthy, "Structure and properties of aerated concrete: A review", *Cement and Concrete Composites*, 2000, vol. 22, no. 5, pp. 321–329, DOI: 10.1016/S0958-9465(00)00016-0.

[25] M. Kozłowski, M. Kadela, "Mechanical Characterization of Lightweight Foamed Concrete", *Advances in Materials Science and Engineering*, 2018, vol. 2018, pp. 1–8, DOI: 10.1155/2018/6801258.

[26] J.G. Cabrera, C.J. Lynsdale, "A new gas permeameter for measuring the permeability of mortar and concrete", *Magazine of Concrete Research*, 1988, vol. 40, pp. 177–182, DOI: 10.1680/macr.1988.40.144.177.

[27] *BS 1881-12 Testing Concrete Part 122 Method for determination of water absorption*. British Standard Institution, 2011, pp. 3–15.

[28] *ASTM C157/C157M-08 Standard Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete*. ASTM International, 2008, pp. 6–9.

[29] *BS 12390-3 Testing hardened concrete. Compressive strength of test specimens*. British Standard Institution, 2011, pp. 5–7.

[30] *ASTM C293 / C293M Standard Test Method for Flexural Strength of Concrete Using Simple Beam with Centre-Point Loading*. ASTM International, 2016, pp. 4–11.

[31] *ASTM C496 / C496M-17 Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens*. ASTM International, 2017, pp. 1–18.

[32] J. Jiang, Z. Lu, Y. Niu, J. Li, "Investigation of the properties of high porosity cement foams containing epoxy resin", *Construction and Building Materials*, 2017, vol. 154, pp. 115–122, DOI: 10.1016/j.conbuildmat.2017.06.178.

[33] N.M. Zamzani, "Characterization of durability and engineering properties of cocos nucifera linn fibre reinforced foamcrete and its performance at elevated temperatures", Universiti Sains Malaysia, 2019.

[34] H.H. Karim, H.A. Khalid, S.A. Sahii, "Behavior of Light Weight Concrete Using Polymer Materials" in *The 2nd International Conference on Building, Construction and Environmental Engineering*, 2015, pp. 79–84.

[35] D. Falliano, D. De Domenico, G. Ricciardi, E. Gugliandolo, "Experimental investigation on the compressive strength of foamed concrete: Effect of curing conditions, cement type, foaming agent and dry density", *Construction and Building Materials*, 2018, vol. 165, pp. 735–749, DOI: 10.1016/j.conbuildmat.2017.12.241.

[36] P. Shawnim, F. Mohammad, "Porosity, permeability and microstructure of foamed concrete through SEM images", *Journal of Civil Engineering, Science and Technology*, 2019, vol. 10, no. 1, pp. 22–33, DOI: 10.33736/jcest.1434.2019.

[37] S.K. Lim, C.S. Tan, O.Y. Lim, Y.L. Lee, "Fresh and hardened properties of foamed concrete with palm oil fuel ash as filler", *Construction and Building Materials*, 2013, vol. 46, pp. 39–47, DOI: 10.1016/j.conbuildmat.2013.04.015.

[38] L. Huang, X. Yang, L. Yan, K. He, H. Li, Y. Du, "Experimental study of polyester fiber-reinforced polymer confined concrete cylinders", *Textile Research Journal*, 2016, vol. 86, no. 15, pp. 1606–1615, DOI: 10.1177/0040517515596932.

[39] A.E. Naaman, "Textile Reinforced Cement Composites: Competitive status and research directions", *International RILEM Conference on Material Science*, 2010, vol. 1, pp. 3–22.

[40] M. Gencoglu, B. Mobasher, "Static and Impact Behaviour of Fabric Reinforced Composites in Flexure, in *Fifth International RILEM Workshop on High-Performance Fiber Reinforced Cement Composites*, H.W. Reinhardt, A.E. Naaman, Eds. 2007, pp. 463–470.

[41] F. Vogel, O. Holcapek, P. Konvalinka, "Response of high-performance fibre reinforced concrete by textile reinforcement to impact loading", *Acta Polytechnica*, 2016, vol. 56, no. 4, pp. 328–335, DOI: 10.14311/AP.2016.56.0328.

[42] G.V. Reddy, S.V. Naidu, T.S. Rani, "Kapok/glass polyester hybrid composites: Tensile and hardness properties", *Journal of Reinforced Plastics and Composites*, 2008, vol. 27, no. 16-17, pp. 1775–1787, DOI: 10.1177/0731684407087620.

[43] K.J. Wong, U. Nirmal, B.K. Lim, "Impact behavior of short and continuous fiber-reinforced polyester composites", *Journal of Reinforced Plastics and Composites*, 2010, vol. 29, no. 23, pp. 3463–3474, DOI: 10.1177/0731684410375639.

[44] P. Jangra, A. Sharma, "Structural behaviour of fibrous concrete using polypropylene fibres", *International Journal of Modern Engineering Research*, 2013, vol. 3, no. 3, pp. 1279–1282.

Received: 04.01.2022, Revised: 22.03.2022