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Influence of Bi-directional Fibreglass Grid Reinforcement on Drying Shrinkage and Mechanical Properties of Lightweight Foamed Concrete

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P A P E R I N F O

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A B S T R A C T

This experimental work is about the study of drying shrinkage followed by strength testing of lightweight foamed concrete (LFC) specimens with the confinement of woven fiberglass mesh (FGM) at three different densities. The LFC specimens were wrapped with 1-layer to 3-layer(s) of FGM for cube and cylinder specimens and in beam specimens, it was centrally spread along the longitudinal axis. The specimens were cured under air storage conditions and the drying shrinkage test was carried following ASTM C157/C 157M specification on three prism-shaped '75mmx75mmx285mm' specimens. NORAITE PA-1 foaming agent was used to produce the desired density of LFC. All of 324 specimens were cast and tested for mechanical properties at 7days, 28days and 56days respectively. In compression strength test, cube dimensions of 100mm side following BS EN 12390-3:2009 was adopted. The flexural strength was conducted on '100mmx100mmx500mm' beam specimens following BS ISO 1920-8:2009. The specimens '100mm in diameter and 200mm in height' were tested for split tensile strength considering ASTM C496/ C496M-04e1 specifications. The results showed that confinement with 160g/m^2 (GSM) of FGM significantly restricts the drying shrinkage of LFC specimens compared to control specimens and it decreased with the increases in layer(s) from l-layer to 3-layer(s) and density of LFC. The testing of the mechanical properties of LFC showed a direct proportionality between strength and LFC density and confinement layer(s). The failure pattern observed in all specimens was either by debonding or splitting of fibers of FGM. Thus, LFC at 1600kg/m^3 density confined/reinforced with 3-layers of FGM conquers the good performance in drying shrinkage and strength properties while the poor performance was shown by the unconfined LFC at 600kg/m^3 density.

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1. INTRODUCTION

Lightweight foamed concrete (LFC) is a cellular concrete prepared by combination of foam of desired density in a cement-based slurry. The foam enriches the workability property of slurry due to the thixotropic behaviour of the foam bubbles, allowing it to be easily poured and transported into the desired moulds of any shape. The technical terms used for labelling LFC include reduced self-weight for lower densities [1, 2], which is essential for restoration or to reduce the dead loads on structural elements of buildings, thermal and acoustic insulation [3], partition walls, enhance fire resistance [4], sub-base in highways, insulation of floor and roof screeds, bridge approaches/embankments [5], prefabricated structures and many more.

Choi and Ma [6] engaged LFC to serve in tunnel drainage and it was implemented in a two-lane highway tunnel in South Korea. LFC results in sustainable [7, 8] and economical construction due to use of less labour, easy transportation and low operating costs [2, 6]. In addition to this, the provision of partial replacement of traditional aggregates used in foamed-concrete by fly ash and silica fumes [9, 10] or recycled ingredients like glass and foundry or electric arc furnace slag [11, 12] is possible which can further reduce the cost. In practice, the LFC has found numerous application in the construction field in countries like UK, Turkey, Philippines, Canada, Malaysia, Korea and Thailand [13, 14].

One of the prevalent downsides of LFC is its early age drying shrinkage [15]. The reason being the expulsion of

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water from the capillaries of the concrete mixture [16]. Once the water evaporates, it is impossible to replace it. This problem causes the LFC made elements to shrink and reduce in volume leading to cracking and decreasing overall performance. Kearsley [17] stated that the LFC is noticed to be weak and non-durable due to its characteristic high shrinkage value which can lead to change in dimensions and cracks in the matrix. Besides this, the average percentage of drying shrinkage in LFC is about two to three times greater than conventional concrete. Roslan et al. [18] revealed that the "typical range of drying shrinkage value in LFC is in between 0.1% to 0.35% of the total volume of the hardened concrete matrix". As reported by Fedorov and Mestnikov [19], the highest values of shrinkage deformations lead to low strength characteristics in LFC. The explanation by Rai and Kumar [20] about "high drying shrinkage of LFC due to the absence of coarse aggregates where the result is up to 10 times greater than has been observed in the normal concrete". The examination of the shrinkage behaviour of LFC, moisture content and composition are the basic responsible factors as stated by Nambiar and Ramamurthy [21]. Amran et al. [22] stated that drying shrinkage in LFC can be controlled by the type of material used in matrix design, greater cement, water proportion and admixtures. Namsone et al. [23] also justified that the possible shrinkage problem in LFC is caused by carbonation which leads to cracking and its durability loss. Also, the high volume of voids is the prime cause for increased drying shrinkage proportion in LFC. As reported by Zamzani [24], the drying shrinkage of LFC is radically greater in the beginning till 30 days and then continues to grow gradually. The reason being at the early age of the test, the specimens are not fully hardened, and the lowest percentage of drying shrinkage value is achieved at a higher density of LFC.

Since the drying shrinkage of LFC is higher compared to conventional concrete. Either synthetic or natural fibers like alkali-resistant glass, kenaf, steel, oil palm fiber, and polypropylene fiber [25–27] can be used in LFC to reduce the drying shrinkage and improve its mechanical properties. This paper focuses on the confinement of woven fiberglass mesh (FGM) by 1layer to 3layers(s) in LFC to study the drying shrinkage behaviour followed by basic mechanical property testing of specimens for validation. Three different densities of LFC were chosen based on the application categorized which were 600kg/m^3 for non-structural building material, 1100kg/m^3 for semi-structural while 1600kg/m^3 for structural building material in real practice.

2. MATERIALS AND MIX DESIGN

There are four basic materials utilized in the production of LFC which were cement, fine aggregate (FA), potable-water, and foam. Besides, 160g/m^2 (GSM) of FGM was employed in this research to investigate its functionality to restrict the drying shrinkage and enhance strength aspects of LFC. 53-grade OPC, commercially known by 'Ultra Tech' brand, following the specifications of category 1 portland cement in ASTM C150-04 [28] was used. Table 1 includes the basic chemical configuration of used cement and the reference Type 1 cement as specified.

The FA utilized in this research was restricted to less than 1.18mm diameter with a specific gravity of 2.74 and fineness modulus of 1.35. The grading limits was according to ASTM C778-06 [29]. FA is suitable for producing the LFC as the presence of coarse aggregate creates bigger voids, sinks to the bottom of moulds, affects its flowability resulting in an inconsistent mix and thereby affects the LFC properties.

The presence of water is necessary to mix the cement and FA to form the cement slurry which by a chemical reaction will lead to the hardened mortar paste complied with ASTM C1602-C05 [30]. 'Protein-based foaming agent, NORAITE PA-1' was utilized as a foaming agent that was added into the cement slurry to get the desired density. 1kg of the foaming agent was diluted into 30L of water as shown in Figure 1 before supplied to the foam generator as shown in Figure 2.

Furthermore, the FGM as shown in Figure 3 also known as the textile fabric was used as a confinement/reinforcement. This mesh is categorized as synthetic, lightweight, flexible, eco-friendly and alkali-resistant fiber. Table 2 shows the physical properties of 160 g/m^2 (GSM) woven FGM and Table 3 displays its composition.

TABLE 1. Basic chemical composition of OPC

Chemical compound (%)	OPC	Specification limit as per ASTM C150-04 [10]	
		Max	**Min**
SiO_2	16.00		20.00
Al_2O_3	3.90	6.0	
Fe_2O_3	2.90	6.0	
MgO	1.50	6.0	
SO_3	3.10	3.0	

Figure 1. Foaming agent dilution into the water

Figure 2. Foam generator

Figure 3. 160 GSM woven FGM

TABLE 2. Physical properties of FGM

Properties	160 GSM woven fiberglass mesh
Mesh size	4.0mm x 5.0mm
Colour	White
Coating type	Alkali resistance
Mass (g/m^2)	160±5
Ignition point	759.2ºF/ 404ºC
Melting point	320.0ºF /160ºC
Tensile strength (MPa)	1407
Elongation at break (%)	3.07%
Compliance	ASTM C1116-02

TABLE 3. Composition of FGM

Oxide components (AR-glass)	Percentage by weight (%)
SiO_2	65.4
ZrO_2	17.3
TiO_2	1.2
Al_2O_3	1.6
Fe_2O_3	1.7
CaO	7.2
MgO	0.7
Na_2O	0.6
K_2O	0.4
B_2O_3	2.2
Li_2O	0.3
F_2	0.5
Others	0.9

The mix proportioning of the LFC as shown in Table 4 was prepared at three different densities: 600kg/m^3, 1100kg/m^3 and 1600kg/m^3 with the confinement of 1-layer to 3-layers of FGM. 1L-FGM specifies1-layer, 2L-FGM for 2-layer and 3L-FGM for 3-layers of FGM. The water to cement proportion was fixed to 0.45 as suggested by Talaei et al. [31] and Kearsley and Visagie [32]. Also, the cement to FA ratio was fixed to 1:1.5.

3. EXPERIMENTAL PROGRAMME

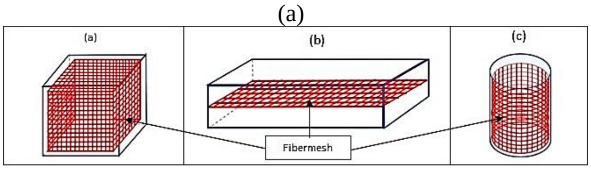
The drying shrinkage test was conducted by using a Mitutoyo brand digital indicator (accuracy up to 0±0.001 mm) with a 298mm reference bar. The test was performed according to ASTM C157/C157M [33] where three prism-shaped '75mmx75mmx285mm' specimens with mesh confinement about the longitudinal lateral surface were installed with a pair of steel screw and cap nut. After demolding, LFC specimens were placed in the length comparator; a setup is shown in Figure 4(a) and rotated anti-clockwise to get the data. The readings were taken and recorded. Then, the steps were repeated for the next age of testing, which was on day 1, 3, 7, 14, 21, 28, and 56.

The strength tests were conducted on 324 specimens, 3 specimens in each category for each test. The different categories were: control,1L-FGM, 2L-FGM and 3L-FGM. The cast specimens were put to test at 7days, 28days and 56days. In compression strength test, cube dimension of 100mm side following BS EN 12390-3:2009 [34] was used. The flexural strength was conducted on '100mmx100mmx500mm' beam specimens following BS ISO 1920-8:2009 [35] and

TABLE 4. Mix design of LFC confined with FGM

Sample	Mix density (kg/m^3)	Cement/ Sand	Water/ Cement	Mix proportion (kg/m^3)		
				Cement	Sand	Water
Control	600	1:1.5	0.45	230.24	345.36	103.61
	1100	1:1.5	0.45	410.79	616.18	184.86
	1600	1:1.5	0.45	591.34	887.01	266.10
1L-FGM	600	1:1.5	0.45	230.24	345.36	103.61
	1100	1:1.5	0.45	410.79	616.18	184.86
	1600	1:1.5	0.45	591.34	887.01	266.10
2L-FGM	600	1:1.5	0.45	230.24	345.36	103.61
	1100	1:1.5	0.45	410.79	616.18	184.86
	1600	1:1.5	0.45	591.34	887.01	266.10
3L-FGM	600	1:1.5	0.45	230.24	345.36	103.61
	1100	1:1.5	0.45	410.79	616.18	184.86
	1600	1:1.5	0.45	591.34	887.01	266.10

(a)



(b)

Figure 4. (a) The instrument for drying shrinkage test; (b) Placement of mesh

lastly, split tensile test was conducted on '100mm diameter and 200mm height' cylindrical specimens considering ASTM C496/C496M-04e1 [36]. The specimens in compressive strength test and split tensile test were confined along the lateral surface and in the flexural test, the mesh was spread in the longitudinal direction at the center of the height of the specimen. Figure 4(b) shows the FGM placement in specimens.

3. RESULTS AND DISCUSSION

3. 1. Drying Shrinkage Figures 5, 6, and 7 depict the graphical development of drying shrinkage results for LFC confined with 160 g/m^2 (GSM) woven FGM. The test results revealed that the control specimens have the uppermost shrinkage strain when compared to the confined LFC specimens for the three respective densities. The drying shrinkage was in indirect relation with LFC density and the layer(s) of FGM. At 600kg/m^3 density of LFC confined with 1-layer FGM, the drying shrinkage was restricted by 48%, while for LFC density of 1100kg/m^3 and 1600 kg/m^3 by 57% and 43% compared to the unconfined specimen at 56days. When the number of layer(s) of FGM was increased by 2-layers and 3-layers, the drying shrinkage behaviour also decreased by 52% to 77% than the unconfined specimens.

At the early stage of the test, all the specimens show inconsistent drying shrinkage measurement as the specimens were not fully hardened. However, on day-30 and above the graph shows only a slight increment in drying shrinkage for the confined LFC while the control specimen shows a noticeable increase. Besides, Karim et al. [37] also clarified that the rapid "increase of drying shrinkage at the early age is due to the rapid loss of moisture from the surface of the specimen while for the later ages, the rate of increase of drying shrinkage is reduced with time depending on the moisture movement of concrete".

The FGM not only prevents the water diffusion from the cement matrix, but it also avoids the loss of existing water in LFC. This also has been proved by Falliano et al. [38] stating that the "unreinforced specimens exhibit a shrinkage that decreases with increasing dry density". Namsone et al. [23, 39] also concluded that the addition of fiber can reduce the risk of shrinkage and stabilize the fresh mix.

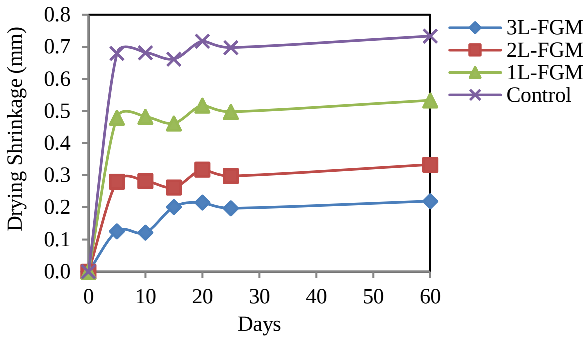


Figure 5. Drying shrinkage results of 600kg/m^3 density LFC confined with a different number of layer(s) of fibreglass mesh

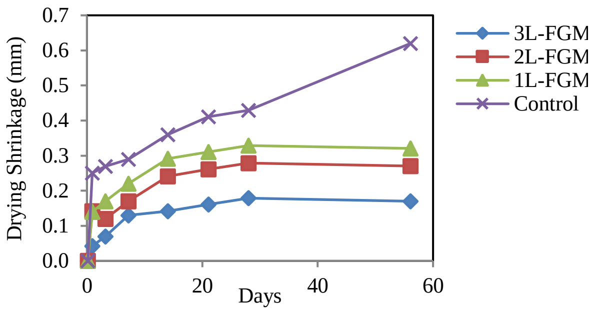


Figure 6. Drying shrinkage results of 1100kg/m^3 density LFC confined with a different number of layer(s) of fibreglass mesh

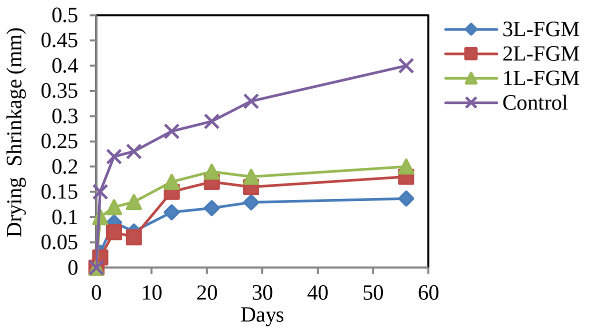


Figure 7. Drying shrinkage results of 1600kg/m^3 density LFC confined with different number of layer(s) of fiberglass mesh

3. 2. Compressive Strength The compressive strength test (CT) results of LFC specimens of density 600kg/m^3, 1100kg/m^3 and 1600kg/m^3 respectively are displayed in Figures (8,9 and 10) indicating the test outcomes at 7days, 28days and 56 days. It was found that the compressive strength in all cases increases with age and is in direct correlation with LFC density and layer(s) of confinement in the specimens as supported by the literature [40]. The 56th day compressive strength of LFC specimens confined with 1L-FGM,2L-FGM and 3L-FGM at 600kg/m^3 density was +58.94%, +137.89% and +168.42% respectively greater than unconfined/control specimens. Similarly, the 56th day compressive strength of 1100kg/m^3 and 1600kg/m^3 LFC specimens was found in a range of +38.42% to +94.65% greater than unconfined specimens.

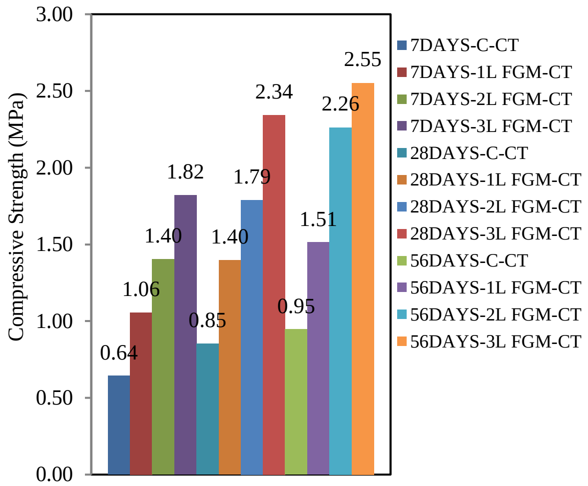


Figure 8. Comparative compressive strength of LFC of 600kg/m^3 density with different layer(s) of FGM

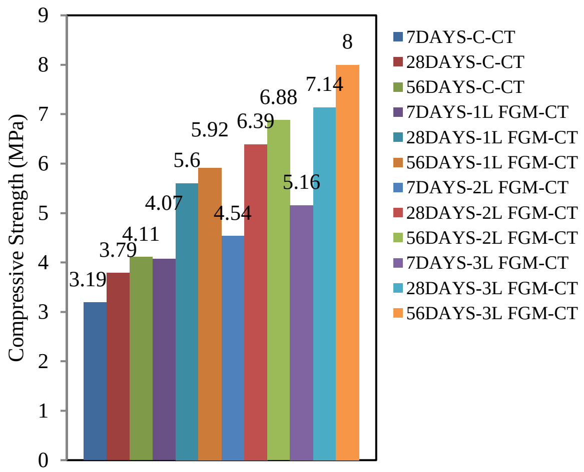


Figure 9. Comparative compressive strength of LFC of 1100kg/m^3 density with different layer(s) of FGM

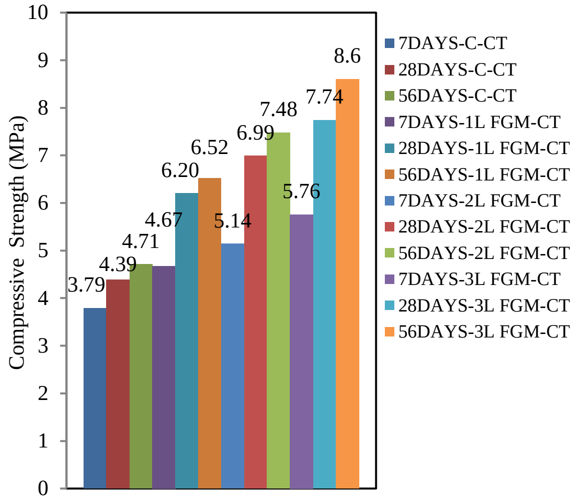


Figure 10. Comparative compressive strength of LFC of 1600kg/m^3 density with different layer(s) of FGM

3. 3. Flexural Strength Figures 11, 12 and 13 present the results of the flexural strength test (FST) at 7days, 28days and 56days. The test results showed a direct correlation between LFC density and the layer(s) of confinement of FGM. Thus flexural strength in LFC can be improved by an appreciable proportion of flexural members of a structure as supported by findings of Musa et al. [41]. The 56th day flexural strength of LFC specimens reinforced with 1L-FGM,2L-FGM and 3L-FGM at 600kg/m^3 was +103.70%, +151.85% and +385.18% respectively greater than control specimens. Similarly, for 1100kg/m^3 and 1600kg/m^3 density LFC specimens, the respective increment in flexural strength after 56days was in a range of +119.54% to +256.32% greater than control specimens.

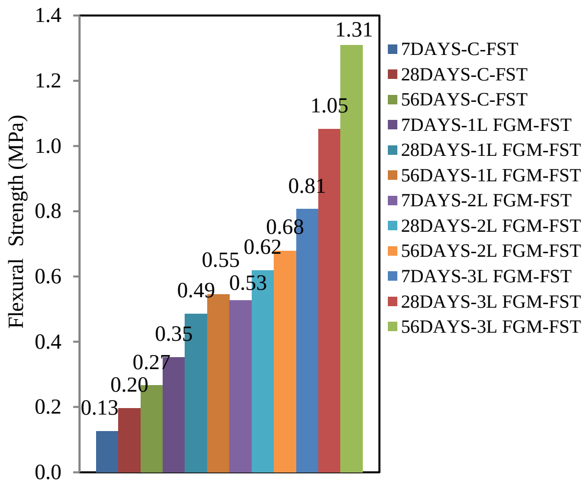


Figure 11. Comparative flexural strength of LFC of 600kg/m^3 density with different layer(s) of FGM

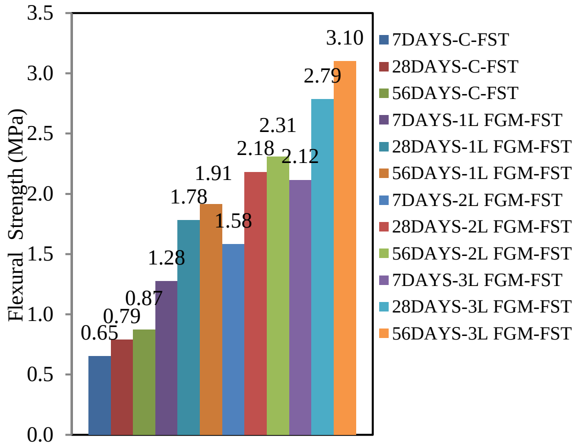


Figure 12. Comparative flexural strength of LFC of 1100kg/m^3 density with different layer(s) of FGM

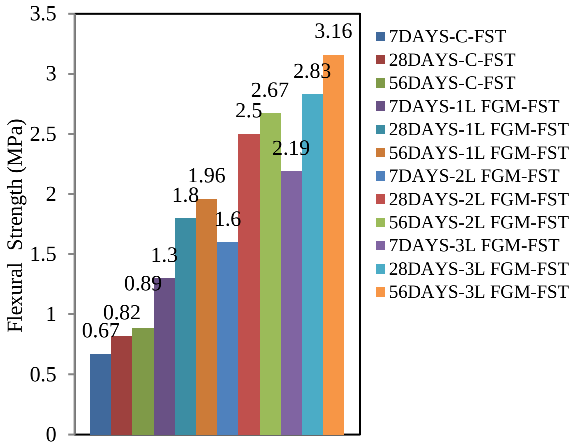


Figure 13. Comparative flexural strength of LFC of 1600kg/m^3 density with different layer(s) of FGM

3. 4. Split Tensile Strength

Figures 14, 15 and 16 present the results of the split tensile strength(STS) test at 7days, 28days and 56days. The 3L-FGM performed outstandingly followed by 2L-FGM and 1L-FGM confinement in all the foam densities. The test results were approved by the finding of [42, 43]. The 56th day split tensile strength test of LFC specimens confined with 1L-FGM,2L-FGM and 3L-FGM at 600kg/m^3 was +157.14%, +242.85% and +471.42% respectively greater than unconfined specimens. Similarly, for 1100kg/m^3 and 1600kg/m^3 density LFC specimens, the corresponding increment in split tensile strength after 56days was in a range of +98.63% to +354.16% greater than unconfined specimens. It was noticed that the appearance of crack was vertical and progress was slow and linear. The failure load of the specimens created a wide crack departing the specimen longitudinally.

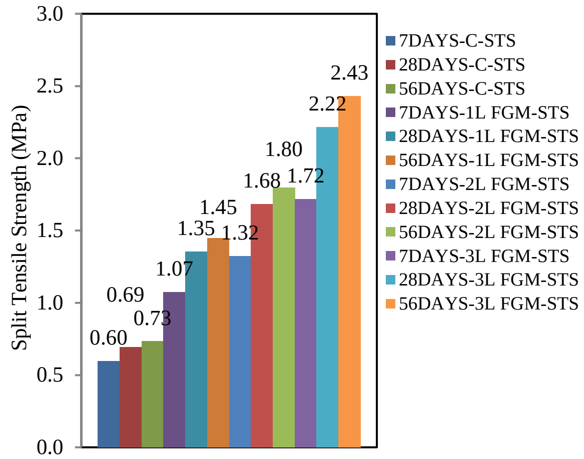


Figure 14. Comparative split tensile strength of LFC of 600kg/m^3 density with different layer(s) of FGM.

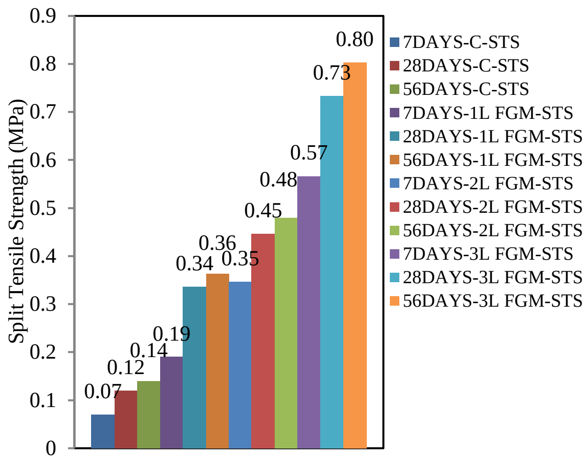


Figure 15. Comparative split tensile strength of LFC of 1100kg/m^3 density with different layer(s) of FGM

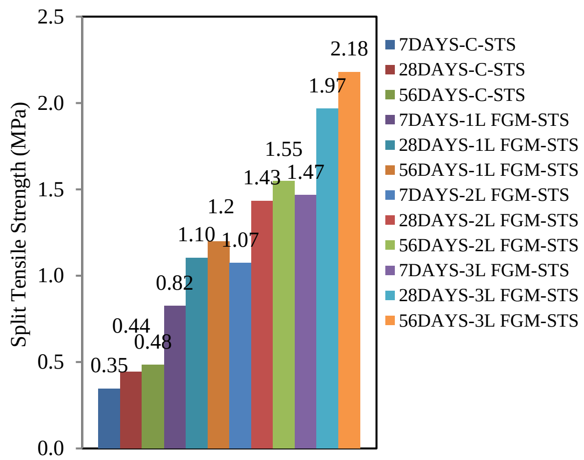


Figure 16. Comparative split tensile strength of LFC of 1600kg/m^3 density with different layer(s) of FGM

After testing the mechanical properties of specimens, the common failure pattern observed in all cases was either by debonding or splitting of fibers of the mesh. Figure 17 shows the scanning electron microscope(SEM) images indicating the typical failure of the specimens.

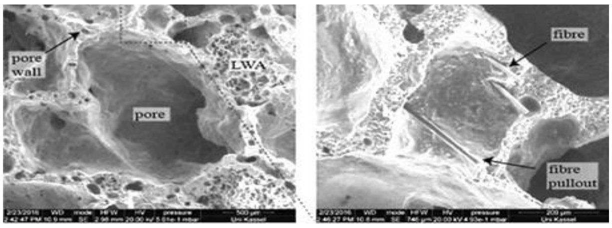


Figure 17. SEM images of failure of specimens

4. CONCLUSIONS

This paper presents the shrinkage behaviour of lightweight foamed concrete (LFC) confined with a different number of layer(s) of woven fiberglass mesh (FGM). Furthermore, to evaluate the strength aspects of LFC specimens, compressive strength, flexural strength and tensile strength tests were conducted. The variables in the study include control specimens, 1layered, 2layered,3 layered FGM specimens with foam density of 600kg/m^3, 1100kg/m^3 and 1600kg/m^3. Thus, based on the interpretation of the data obtained, few conclusions were observed as follows:

1. The higher drying shrinkage was obtained at the low density of LFC and vice versa, which was correlated to the volume of foam added. The utilization of FGM significantly reduces the drying shrinkage issue in LFC.
2. At 600kg/m^3 density of LFC confined with 1-layer FGM, the drying shrinkage was restricted by 48%, while for LFC density of 1100kg/m^3 and 1600 kg/m^3 by 57% and 43% compared to the unconfined specimen at 56th day. When the number of layer(s) of FGM was increased by 2-layers and 3-layers, the drying shrinkage behaviour also decreased by 52% to 77% than the unconfined/control specimens.
3. The early age drying shrinkage results showed inconsistency and on 30th day and after the confined LFC specimens showed a low-rate of drying shrinkage increment while unconfined LFC specimens showed a noticeable high-rate of drying shrinkage growth for the respective densities.
4. Even though many factors can influence the drying shrinkage behaviour in LFC as reported in the previous investigations. However, it can be suggested that the major influences to the drying shrinkage behaviour are: (1) the density of LFC and (2) the number of layer(s) of FGM confinement. Thus, at density 1600kg/m^3 LFC confined with 3-layers FGM conquers the good performance of drying shrinkage while the poor performance was shown by the unconfined LFC at density 600kg/m^3.
5. The testing of mechanical properties like compressive strength, flexural strength and split tensile strength of LFC showed a direct correlation of strength with age, confinement layer(s) and foam density. The type of failure of specimens in all cases was either by debonding or by splitting of fibers.

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Persian Abstract

چکیده

این کار آزمایشی در مورد مطالعه جمع‌شدگی خشک شدن و به دنبال آن آزمایش مقاومت نمونه‌های بتن سبک کف (LFC) با محصور شدن شبکه فایبرگلاس بافته شده (FGM) در سه تراکم متفاوت است. نمونه‌های LFC با نمونه‌های مکعبی و استوانه‌ای با ۱ لایه تا ۳ لایه (FGM) پیچیده شده و در نمونه پرتو، بطور مرکزی در امتداد محور طولی پخش شد. نمونه‌ها تحت شرایط ذخیره‌سازی هوا درمان شده و آزمایش انقباض خشک شدن به دنبال مشخصات ASTM C157 / C 157M بر روی سه نمونه منشوری شکل mmx75mmx285mm۷۵ انجام شد. برای تولید چگالی مطلوب LFC از ماده کف‌کننده NORAITE PA-1 استفاده شد. در مجموع ۳۲۴ نمونه برای خواص مکانیکی LFC مورد آزمایش قرار گرفتند. نمونه‌های بازیگران در ۷ روز، ۲۸ روز و ۵۶ روز مورد آزمایش قرار گرفتند. در آزمون مقاومت فشاری، ابعاد مکعب ضلع ۱۰۰ میلی متر به دنبال BS EN 12390-3: 2009 به تصویب رسید. مقاومت خمشی بر روی نمونه‌های پرتو be 100mmx100mmx500mm به دنبال BS ISO 1920-8: 2009 انجام شد. نمونه‌ها با قطر ۱۰۰ میلی‌متر و ارتفاع ۲۰۰ میلی‌متر با توجه به مشخصات ASTM C496 / C496M-04e1 از نظر مقاومت کششی تقسیم شدند. نتیجه نشان داد که حبس با ۱۶۰ گرم در مترمربع (GSM) از FGM به طور قابل توجهی جمع شدن خشک شدن نمونه‌های LFC را در مقایسه با نمونه‌های کنترل محدود می‌کند و با افزایش لایه (لایه‌ها) از لایه L به ۳ لایه و تراکم کاهش می‌یابد. از LFC. آزمایش خصوصیات مکانیکی LFC تناسب مستقیمی بین قدرت و تراکم LFC و لایه(های) حبس نشان داد. الگوی شکست مشاهده شده در همه نمونه‌ها یا با تجزیه یا تقسیم الیاف FGM بود. بنابراین، LFC با تراکم ۱۶۰۰ کیلوگرم در متر مکعب با ۳ لایه FGM محدود / تقویت‌شده عملکرد خوبی را در خواص انقباض و مقاومت خشک کردن تسخیر می‌کند در حالی که عملکرد ضعیف توسط LFC غیرقابل کنترل در تراکم ۶۰۰ کیلوگرم در متر مکعب نشان داده شد.