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FOAMED CONCRETE DURABILITY PROPERTIES REINFORCED WITH AGAVE CANTALA-BASED FIBRE

The construction industry across the world recognizes the need for green, lightweight, and self-compacting materials that are also ecologically benign. Considering this requirement, a recent discovery has indicated that a novel form of concrete, known as foamed concrete (FC), has the potential to reduce structural self-weight. Natural fibres are an excellent option to be added in FC for durability properties improvement and are viewed as a great way to contribute to sustainability. The purpose of this study is to examine the possible utilization of agave cantala-based fibre (AF) in the fabrication of foamed concrete (FC) with the objective of enhancing their durability properties. Low densities FC are prone to serious durability performance degradation hence in this experiment FC of low density of 650 kg/m^3 was fabricated and evaluated. Varying weight fractions of AF between 0% to 5% were considered as an additive in FC. The durability parameters that were evaluated included apparent porosity, shrinkage, water absorption and UPV. The experimental findings indicate that incorporating a weight fraction of 3% of AF in FC resulted in the optimal durability characteristics across all the durability measures examined in this study. The inclusion of AF in the combination resulted in a significant decrease in the permeability porosity and water absorption of FC. The presence of FC-AF composites with 4% fibre led to the highest drying shrinkage and UPV value and it performed better than the remaining mixtures.

Keywords: Foamed concrete; durability properties; apparent porosity; water absorption; ultrasonic pulse velocity

1. Introduction

In the past several years, there has been a notable surge in the degree of focus and research dedicated to the field of lightweight concretes due to their substantial employment opportunities within the construction industry [1]. Consequently, their utilization has become prevalent on a global scale. The interest in this subject arises primarily from the necessity to augment the environmental sustainability of the construction trade [2]. This can be achieved by employing more sustainable materials instead of conventional ones, while simultaneously pursuing various objectives such as structural lightweight, energy preservation, reduction in the consumption of primary resources, resource efficiency, and minimizing the embodied energy and embodied carbon throughout the product's life cycle [3]. It is crucial to maintain a high level of technical performance throughout this process. When comparing foamed concrete to commonly utilised materials like organic thermal insulation materials, it becomes evident that foamed concrete possesses favourable thermal insulation properties, enhanced fire resistance and durability, as well as reduced economic and environmental costs. Moreover, this can be acquired via commonplace materials that are easily accessible and can be generated using a straightforward production procedure that can be executed on location [4].

Furthermore, it is important to address the urgent need for thorough investigations regarding the environmental effects of the building industry on long-term viability It is also crucial to develop efficient techniques to mitigate possible risks to sustainability. The main goal of these prevention strategies is to protect the purity of natural resources whereas also reducing the creation of waste materials. The analysis of the life cycle assessment regarding buildings has become a noticeable area of study, mainly motivated by the

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concerning natural implications related to the materials used for construction, with concrete getting of particular importance [5].

Foamed concrete (FC) is a commonly employed construction material that enables the fabrication and use of lightweight building components. The removal of larger particles from FC combinations allows for the creation of mixtures that possess a significant degree of versatility. The FC attains its unrestricted fluidity through the amalgamation of a cement-based mortar slurry with pre-formed foam [6]. The incorporation of particular material mixtures can provide significant advantages in construction endeavours situated in regions characterised by difficult soil conditions, wherein the magnitude of load imposed on building foundations is prone to be comparatively small [7]. However, the expansion of FC technological advances may encounter challenges due to the deterioration of the ecosystem caused by the emission of contaminants as well as worries regarding environmental responsibility associated with the extraction of natural aggregates [8]. The incorporation of natural fibres in the augmentation of properties of FC in the process of FC production has yielded a notable array of prospective consequences [9].

The utilisation of FC can exhibit variability based on the optimisation of the FC mixture [10]. The material under consideration exhibits the capacity to serve as a non-load-bearing component, a semi-structural component, or a structural component across many applications. The attributes and properties of the material can be greatly affected by the unit weight of FC. An earlier study has established a density range of 500 to 1800 kg/m^3 for FC [11]. In addition, FC demonstrates fire-resistant characteristics and displays thermal and acoustic insulation performances, making it well-suited for various uses including roofing and flooring insulation [12].

It is crucial to acknowledge that FC has faced a multitude of obstacles in its progression as a feasible material within the construction sector. The concerns involve a range of variables including brittleness, reduced bending, and tensile strengths, increased drying shrinkage, enhanced water absorption capacity, and limited fracture management capabilities. Furthermore, the topic of brittleness has been identified as a significant concern. The use of FC is primarily restricted to non-structural load-bearing uses owing to its inherent limitations in terms of mechanical strength and durability. The issues related to the relatively low fracture toughness of FC can be alleviated by incorporating polymer fibres derived from various sources [13]. Due to this phenomenon, FC demonstrates behaviour that bears resemblance to that of a composite material compared to an unreinforced FC [14].

It is important to note that synthetic fibres are frequently utilized as the preferred option for reinforcing concrete. Nevertheless, there is an increasing inclination towards the utilization of natural fibres [15]. There has been an increasing apprehension about the utilization of materials reinforced with natural fibres. The incorporation of natural fibres is of utmost importance owing to their inherent attributes of long-term viability resiliency, and degradation [16]. Considering the significant environmental ramifications linked to synthetic fibres, it is reasonable to contemplate replacing them with natural fibres. Consistent with prior scholarly investigations on the application of polymer fibres for reinforcement purposes, these investigations have noted that the inclusion of fibre reinforcement results in greater durability in cement-based materials, along with increased mechanical performances. The deterioration of cell walls in natural fibres can take place under highly alkaline conditions, primarily because of the relatively low stability of lignin and hemicellulose. The quantification of the relative proportions of fibres, binder, filler, water, and surfactant within the mixture holds considerable significance. Natural fibres possess several advantages over synthetic fibres in different aspects. These advantages include their inherent ability to undergo natural decomposition, lower density, and enhanced resistance to melting under high temperatures. The utilization of natural fibres in cement-based materials has been observed to improve their mechanical properties [17]. Extensive research has been conducted by numerous scholars to examine the durability characteristics of FC that have been augmented with both natural and synthetic fibres.

Prior research has explored the utilization of natural fibres derived from coconut fibre, bamboo, jute, banana, abaca, and sugarcane bagasse in FC. These studies have demonstrated intriguing outcomes [18]. However, it is imperative to broaden the range of natural fibres utilized by taking into account regional raw materials specific to each region (e.g., agave in India, Philippines and Indonesia) aim to enhance the sustainable energy performance of buildings by integrating environmentally friendly components into the materials used [19-22]. Expanding studies on this field is crucial through including a wider range of plant and cementitious materials. This will enhance knowledge, yield improved outcomes, and open up new avenues for research projects to discover other potential applications.

Agave fibre (AF) is sustainable or recycled materials that have been previously employed in the automotive sector, construction and various other industries [23]. AF are incorporated with polyester, epoxy, biopolymers and concrete matrix. AF provide favourable mechanical characteristics, including exceptional toughness, robust fibre-matrix adhesion, and minimal susceptibility to damage [24]. These traits can be augmented by the appropriate treatment procedure. Several studies in the literature review primarily examine the fibre treatment effects of unprocessed natural fibres. The adhesion between plant fibres and the matrix is a significant difficulty at the interface [25].

AF is extensively cultivated in Southeast Asia and has been the focus of numerous scientific studies because to its notable mechanical and physical qualities. AF exhibits a low density, strong tenacity, and significant extensibility when compared to other textile fibres [26]. Therefore, based on these characteristics, it can be concluded that AF has the potential to be a beneficial strengthening material for cement-based structures. However, it seems that no effort has been made to use AF as a reinforcing component in the manufacturing of FC. It is necessary to investigate the efficient use of this native fibre to address the significant scarcity of affordable, sturdy, and long-lasting build-

ing materials and other applications in numerous nations where these fibres are plentiful [27].

As to the findings of Sathiamurthi et al. [28], the flexural strength was best in the combination containing 20% AF strengthened with epoxy hybrid. Sakuri et al. [29] examined the strength properties of composites composed of AF combined with a polyester binder and microcrystalline cellulose. AF was subjected to treatment using a 6% NaOH solution at various soaking durations. After subjecting AF to NaOH treatment for 360 minutes, researchers found that it exhibited a crystallinity index of 73.65%. The researchers examined the structure of fibres after subjecting them to various alkali treatments using SEM. The laboratory results demonstrate the complete removal of hemicellulose, wax, and other impurities. Huerta-Cardoso et al. [30] conducted a study where AF were subjected to four distinct treatments. The purpose of these treatments was to enhance the morphology of AF and their ability to interact well with polylactic acid as a solvent. The study conducted by Sathiamurthi et al. [28] examines the tensile and flexural characteristics of epoxy-based composites strengthened with AF. AF have a range of lengths from 1 to 4 cm, and their weight fraction proportional to the total weight varies between 10% and 25%. Their findings indicate that the composite made from AF measuring 3 cm in length and with an equivalent loading of 20% had the highest tensile strength and modulus.

Based on the prior investigation, it can be concluded that AF has the potential to be utilized in cement-based materials such as FC to improve their mechanical and durability characteristics. Hence, the primary objective of this work is to investigate the possible application of AF in FC in order to improve their durability properties.

2. Experimental setup

2.1. Basic materials

To produce FC, it was imperative to have five indispensable components. The components included cement, which functioned as the binding agent, fine aggregate, which served as a filler, clean water, and a protein-based foaming agent, which acted as a surfactant. The incorporation of AF as an additive was employed in the FC base mixture. The cement utilized in the research was Portland cement, more specifically Ordinary Portland Cement (OPC). The present study utilized fine river sand as a filler material. The sand in question was obtained from a supplier in close proximity. As per the BS-3148 standard, the procedure for blending and solidifying the FC necessitates the utilization of potable water that is free from any contaminants. The application of Noraite PA-1, a surfactant derived from proteins, was executed. The surfactant and water were prepared in a ratio of 1:30. The foam solutions exhibited the capability to achieve a density of 70 ± 5 kg/m^3 through the process of aeration. The AF utilized in this study (Fig. 1) was supplied by DRN Technologies Sdn Bhd. The raw material that was obtained underwent a comprehensive rinsing and cleaning process in order to efficiently eliminate any impurities and debris. Subsequently, the specimen was subjected to a drying process in which it was exposed to solar radiation for a duration of 48 hours. Following this, the unprocessed AF material underwent a cutting process resulting in a final length of 19 mm. TABLE 1 presents the chemical composition of AF, while TABLE 2 illustrates its physical properties.

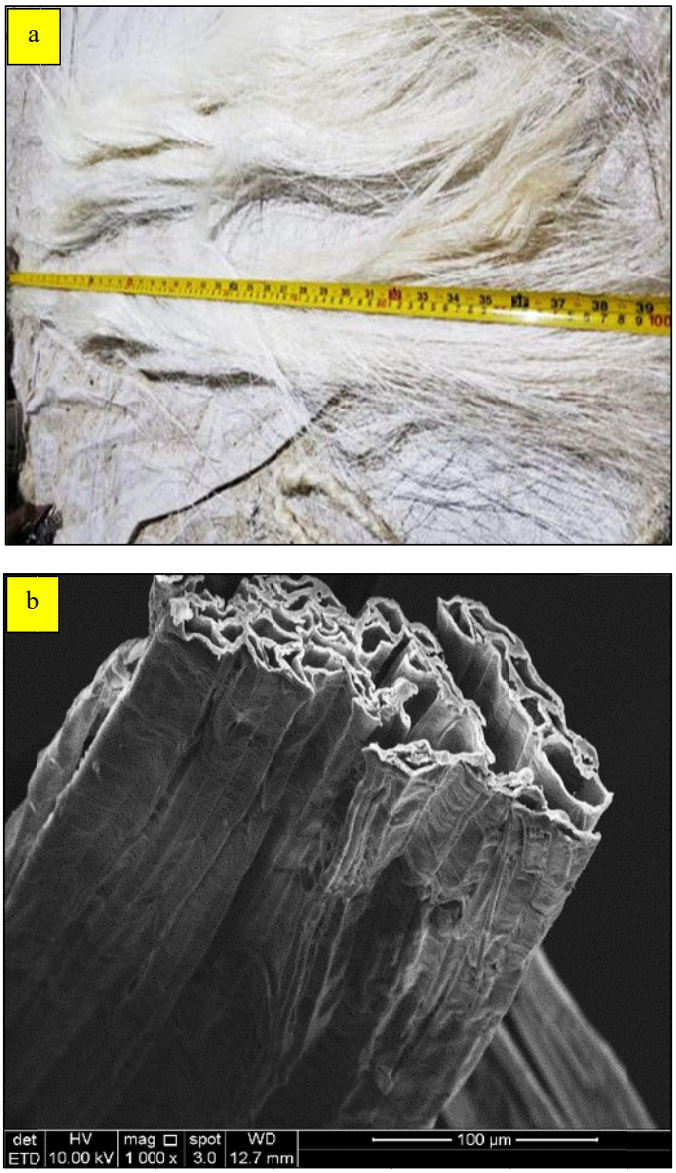


Fig. 1. AF employed in this investigation (a) raw AF; (b) AF cross-section

TABLE 1

Agave cantala-based fibre chemical composition

Elements	Percentage (%)
Cellulose	76.8
Lignin	8.6
Hemi-cellulose	6.1
Wax	0.9
Moisture	7.6

TABLE 2

Agave cantala-based fibre physical properties

Property	Value
Density (g/cm^3)	0.105
Colour	white
Length (mm)	19
Diameter (mm)	0.12-0.14
Aspect ratio (l/d)	136-158
Tensile strength (MPa)	350
Tensile modulus (MPa)	11.5
Specific gravity	0.70
Elongation at break (%)	3.2
Water absorption (%)	38.5

2.2. Mix design

A grand total of six different FC blends were created. It was decided to make an FC with a low density of 650 kg/m^3. The weight fractions of FC mixtures that were mixed with AF ranged from 0% to 5%. In each of the mixes, the ratio of sand to cement was 1:1.5, and the ratio of water to cement was held at a constant value of 0.48 throughout. In the current experiment, the mix design of FC is provided in TABLE 3.

TABLE 3

FC mix design with various agave cantala-based fibre weight fractions

Mix	AF (%)	AF (kg/m^3)	Sand (kg/m^3)	Cement (kg/m^3)	Water (kg/m^3)	Foam (kg/m^3)
FC0	0	0.0	368.7	245.8	118.0	41.6
FC1	1	7.3	368.7	245.8	118.0	41.6
FC2	2	14.6	368.7	245.8	118.0	41.6
FC3	3	22.0	368.7	245.8	118.0	41.6
FC4	4	29.3	368.7	245.8	118.0	41.6
FC5	5	36.6	368.7	245.8	118.0	41.6

2.3. Experimental setup

In order to assess the durability characteristics of FC containing different weight fractions of AF, a series of four tests were performed. These tests specifically focused on evaluating the apparent porosity, ultrasonic pulse velocity (UPV), water absorption, and drying shrinkage properties of the FC specimens.

The water absorption test was performed following the guidelines outlined in the BS1881-122 standard, using a cylindrical specimen measuring 75 mm × 100 mm. The samples were left in the tank until the day of testing as shown in Fig. 2(a).

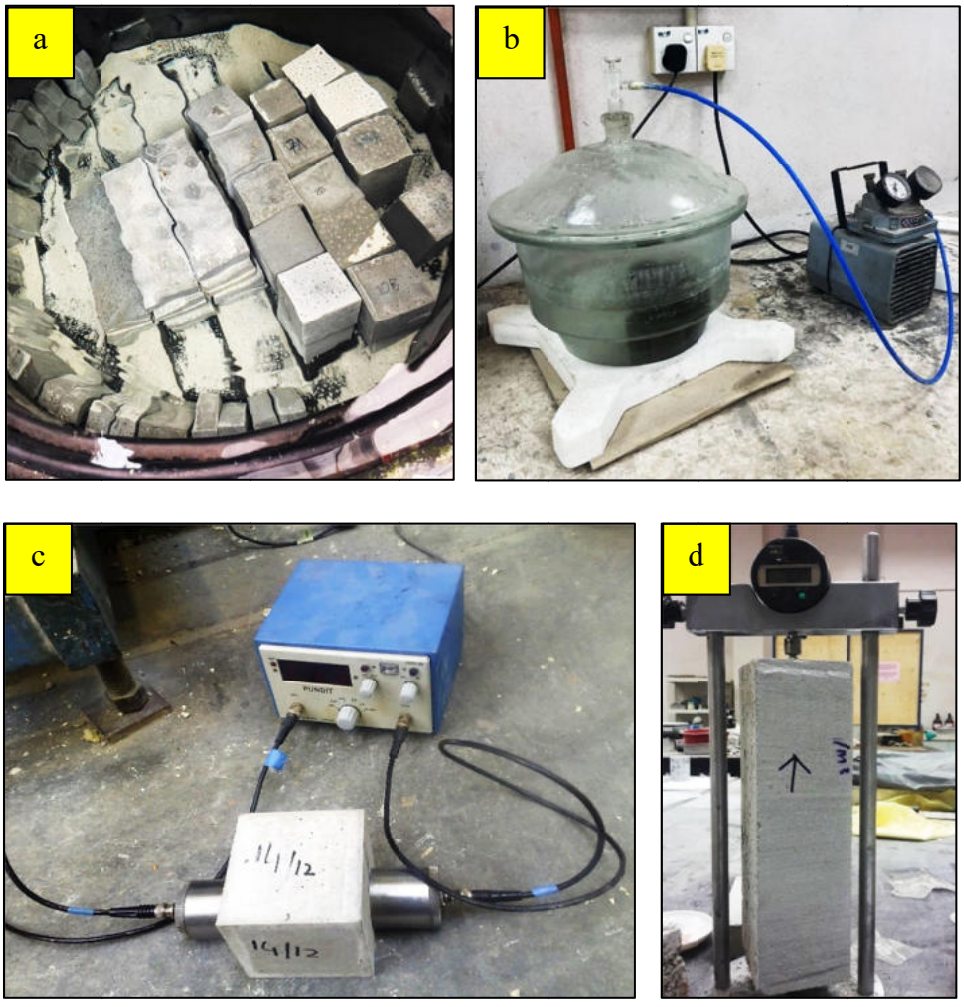


Fig. 2. List of tests executed in this study (a) water absorption; (b) apparent porosity; (c) UPV; (d) drying shrinkage

When the test day arrived, from each batch, three specimens were unwrapped and placed under the oven for 72 h to dry. In the next step, the weight of each cooled, oven-dried specimen was recorded as W_d, and then the specimens were completely immersed in a water tank for almost 30 min. Later, any excess water present on the test specimen was removed via a dry cloth and its weight was recorded as W_s in a saturated condition. The water absorption has been signified as a percentage as W_a, which was calculated by employing Eq. (1). As the final result, the average water absorption pertaining to these three samples was considered.

$$Water\ absorption, (\%) = \left(\frac{W_s - W_d}{W_d} \right) \times 100\% \quad (1)$$

where,

W_s – Saturated surface dry weight,

W_d – Oven-dried weight.

Next, the apparent porosity was assessed using a vacuum saturation technique. The test was conducted on day 28 by subjecting the FC specimens to a vacuum desiccator as shown in Fig. 2(b). The purpose of this test is to determine the air void percentage in relation to the FC specimens, as this can have an immediate effect on the durability performance. Three FC specimens with a 50 mm height and 45 mm diameter were taken from each batch and placed inside an oven to remove moisture for 72 hours or until no weight changes were noted. Each specimen was then allowed to cool, and the weight of each was noted as W_{dry}. The specimens were kept completely submerged in a vacuum chamber until the 72nd hour or until no bubbles were visible. The weights of the specimens were recorded both in the water ($W_{s,a}$) and in the air ($W_{s,w}$). Using Eq. (2), the porosity percentage in relation to the FC was calculated.

$$Total\ porosity, (\%) = \left(\frac{W_{s,a} - W_{dry}}{W_{s,a} - W_{s,w}} \right) \times 100\% \quad (2)$$

were,

$W_{s,a}$ – weight of saturated sample in air,

W_{dry} – weight of oven-dried sample,

$W_{s,w}$ – weight of saturated sample in water.

The UPV test was conducted using a cube sample measuring 100×100×100 mm, as per the guidelines outlined in BS12504-4. Fig. 2(c) shows the setup for UPV test. The shrinkage test was initiated in accordance with the ASTM C878 standard. A prism measuring 75 mm in width and 250 mm in length was utilized and the setup is displayed in Fig. 2(d).

3. Results and discussion

This section will present a summary of the results obtained from the laboratory assessment carried out to determine apparent porosity, UPV, water absorption, and drying shrinkage.

3.1. Water absorption

Fig. 3 presents the outcomes of water absorption tests conducted on FC samples containing varying weight percentages of AF. Fig. 3 illustrates a noticeable decrease in water absorption with a growth in the weight fraction of AF. The observed decline in water absorption can be ascribed to the incorporation of AF. Specifically, the adding up of AF at a weight fraction of 5% resulted in the lowest water absorption rate of 15.1%, while the inclusion of 1% AF led to a water absorption value of 21.1%. The greatest water absorption was found on the control FC. The intrinsic closeness of the pores in FC enables their merging, resulting in the formation of bigger pores. This phenomenon can be explained by the material's toughness and the resulting microstructural breakdown, which leads to an increased ability to absorb water [31]. The increased concentration of AF successfully hindered water infiltration due to the reduced size of the void diameters [32]. The AF matrix experienced reduced moisture levels, causing it to shrink due to the drying process in the cement-based composite material [33]. Moreover, the creation of calcium silicate hydrate gel in a matrix with a greater amount of AF led to a decrease in void size, resulting in a reduction in water absorption.

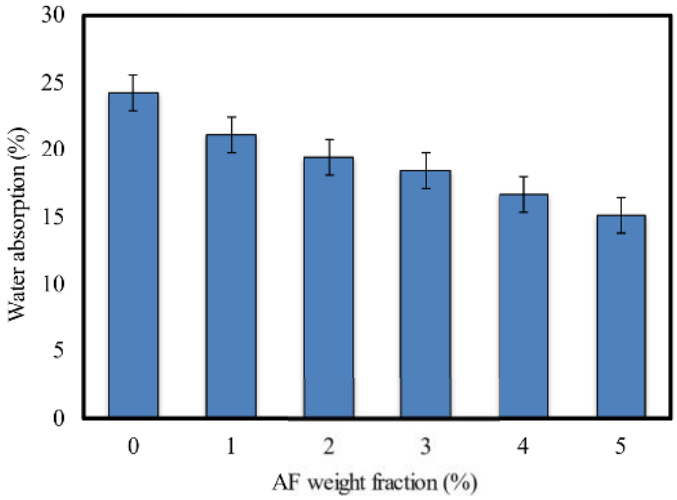


Fig. 3. Influence of various AF weight fractions on water absorption of FC

3.2. Porosity

Fig. 4 illustrates the measured porosity of FC having different weight fractions of AF. The porosity trend exhibits a decrease in conjunction with the rise in the weight fraction of AF in FC. The findings indicate that a porosity level of 56.3% was observed in the sample with a 5% weight fraction of AF in FC. Conversely, the sample with 1% inclusion of AF exhibited the highest porosity level of 61.8%. The porosity of the material is influenced by the incorporation of AF within the FC. The lower density of the FC material will result in a greater degree of porosity in its structure when compared to materials with higher density. A decrease

in the density of FC is associated with an increased quantity of foam, which allows for the presence of a larger number of air pores, resulting in an elevated level of porosity. The extensive presence of foam restricts the adhesion of materials possessing a lower density of FC. However, the presence of AF contributes to the overall improvement of the matrix in the field of study. The decline in the porosity of FC is initiated by the alteration and morphology deviation of AF. The higher weight fraction of AF in cementitious composites facilitates the bonding of the matrix, thereby reducing the porosity of the AF-reinforced cementitious composites.

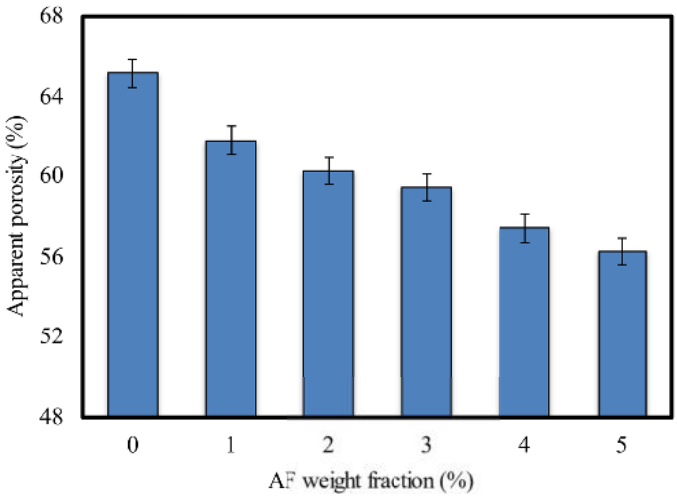


Fig. 4. Influence of various AF weight fractions on apparent porosity of FC

AF facilitated the initiation of pore arrangements, resulting in a reduction in pore diameter and a decrease in the absorptivity of the FC structure. Therefore, it can be deduced that the inclusion of AF significantly contributes to the reduction of the porosity of FC. The natural lignocellulosic fibres exhibit a tendency to undergo swelling when subjected to water absorption [34]. The swelling can cause microcracks to form in the cementitious composite of FC, leading to a brittle matrix. This can increase the movement of water through the fibre matrix boundary and result in a high porosity value [35]. Microcracks develop in the FC matrix in the interface region due to cellulose fibre swelling, leading to an increase in the diffusion of water through them. Furthermore, the activation of the capillary mechanism leads to an increased diffusion of water molecules through the interface of the AF-FC matrix [36].

3.3. Drying shrinkage

Based on the data presented in Fig. 5, it is evident that the drying shrinkage of FC exhibited a significant increase from day-1 to day-28, followed by a period of stable readings from day-28 to day-60. The control group exhibited the highest drying shrinkage in comparison to the specimens containing AF. The drying shrinkage exhibited the lowest value at a concentration of 3% of AF in FC, followed by 2%. 4%, 5%, and 1%. The shrinkage performance was affected by the elevated foam content in the FC. The reduction in cement paste usage is attributed to the increased amount of foam utilized. In addition, the inclusion of AF in the absence of aggregates has been found to enhance the reduction of drying shrinkage [37,38]. Moreover, AF also plays a noteworthy role in enhancing the properties of the cement matrix. Additionally, it also serves to reduce the formation and propagation of cracks [39,40].

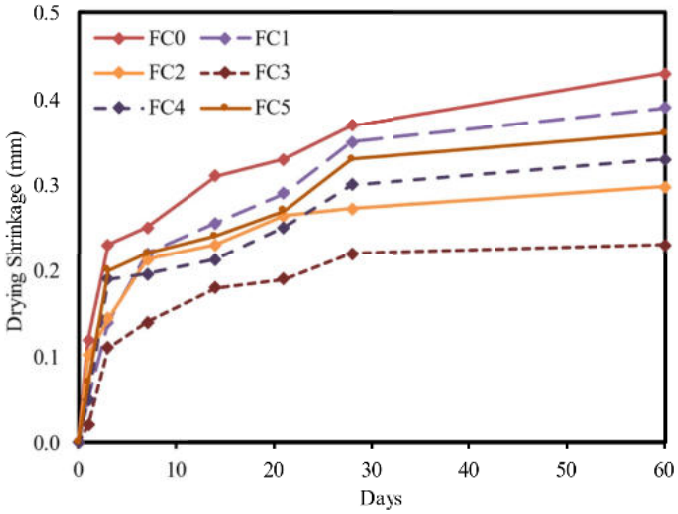


Fig. 5. Influence of various AF weight fractions on drying shrinkage of FC

3.4. Ultrasonic pulse velocity

Fig. 6 illustrates the results obtained from the UPV test. The upward inclination of the UPV is observed to be positively correlated with the growth in AF weight fractions. The data indicate that the incorporation of 4% of AF in the FC led to the utmost recorded UPV value, measuring 1698 m/s. On the other hand, the control mixtures demonstrated the minimum ultrasonic pulse velocity (UPV) measurement of 1404 m/s. The outcomes

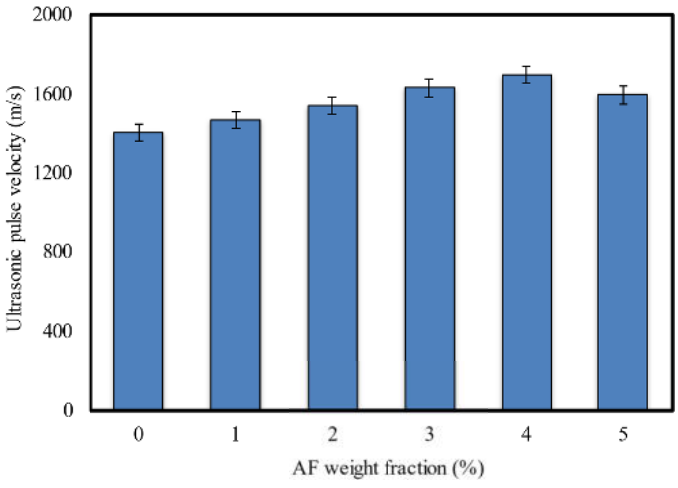
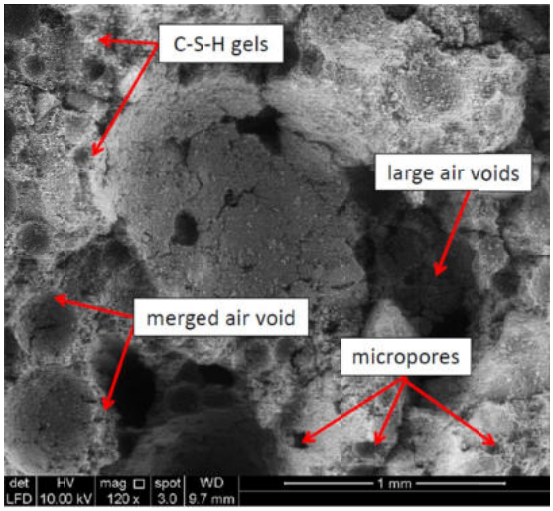


Fig. 6. Influence of various AC weight fractions on ultrasonic pulse velocity of FC

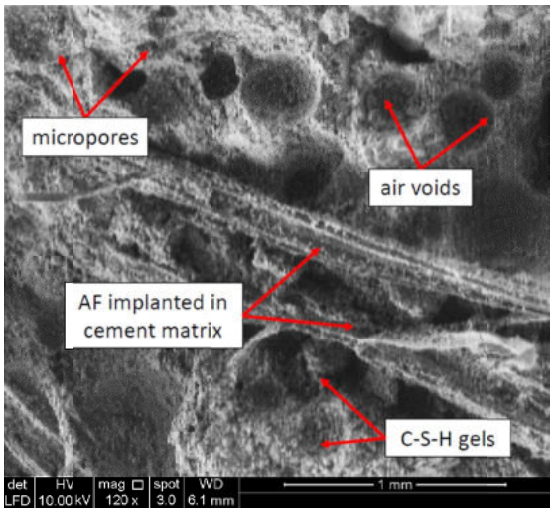
of UPV are affected by the existence of voids and heterogeneity in FC [41,42]. Thus, the velocity of the pulse will increase when the density of the FC is higher. Simultaneously, the time travel duration will be minimized in the event that any indication of deformity in the FC is detected [43-45]. Therefore, it can be inferred that the integration of AF led to more substantial measurements of UPV.

3.5. Microstructural assessment

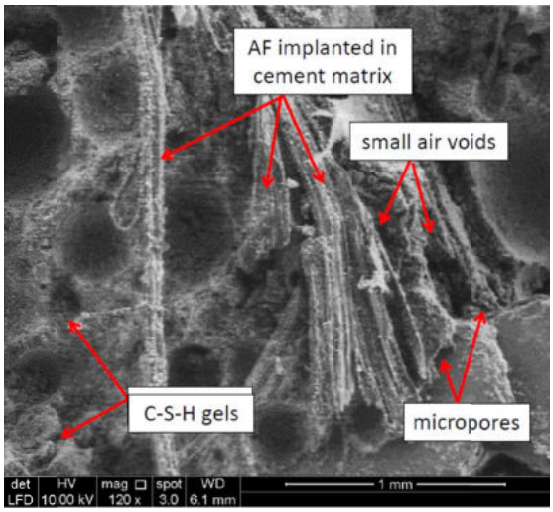
The scanning electron microscopy (SEM) technique was used to analyse the morphology of control FC and FC-AF composites. Fig. 7 illustrates a comparison between the SEM micrographs of the control FC and the sample with an additional 2% and 4% of AF. The presence of greater cavities in the control FC specimen is clearly evident, as depicted in Fig. 7(a). The FC pore structure consists of gel pores, micropores, and air spaces [46]. Due to its self-compacting nature, FC is very difficult to entrap air as it lacks any coarse aggregate. The addition of 2% and 4% AF to FC has clearly resulted in a reduction in the size of voids, as depicted in Figs. 7(b) and 7(c). The cementitious matrix and AF were strongly bound together through interracial bonding, which occurred when the AF was implanted. The presence of fibrillated mechanisms and strong interfacial bonds typically leads to the formation of a compact matrix surrounding the AF. Within the FC structure, the empty spaces generate interfaces that include very small pores, resulting in a decrease in the bonding across interfaces [47]. Consequently, the existence of AF in FC serves to connect and inhibit the formation of microcracks originating from force-crossing fractures. Furthermore, the addition of cellulose natural fibre to cementitious matrixes enhances the density of the mixture and reduces the formation and expansion of cracks. This is due to the fibre's ability to modify the interface attributes and pore structure, as well as its role in transferring stress when fractures happen. Unlike the composite reinforced with 4% AF (as seen in Fig. 7c), the unreinforced composite has a microstructure that has little consolidation, as well as numerous cracks and pores. By incorporating and distributing fibres throughout the base matrix, any empty spaces are filled, resulting in a decrease in the wall impact. The wall impact occurs when the presence of small particles creates additional gaps.



(a) FC0 mix (control)



(b) FC2 mix



(c) FC4 mix

Fig. 7. SEM images of control FC mix in comparison with FC-AF hybrids

4. Conclusions

The durability properties of FC-AF composites were investigated by incorporating different proportions of AF. The FC-AF samples were assessed for their apparent porosity, ultrasonic pulse velocity (UPV), water absorption, and drying shrinkage characteristics. Based on the results of this investigation, the following conclusions can be derived.

1. An evident reduction in water absorption was found as the weight percentage of AF increased. The decrease in water absorption can be attributed to the incorporation of AF. More precisely, the addition of AF at a weight fraction of 5% yielded the lowest water absorption rate of 15.1%, whereas the inclusion of 1% AF resulted in a water absorption value of 21.1%. The control FC exhibited the highest level of water absorption.
2. The porosity trend shows a decrease when the weight percentage of AF in FC increases. The results reveal that the sample containing 5% weight fraction of AF in FC exhibited a porosity level of 56.3%. In contrast, the sample containing 1% AF inclusion displayed the maximum porosity level, measuring 61.8%. The decrease in the porosity of FC is caused by the modification in the morphology of AF. A higher weight percentage of AF in cementitious composites enhances the adhesion between the matrix and reduces the porosity of the cementitious composites.
3. The drying shrinkage of FC saw a notable rise from day-1 to day-28, and then maintained a consistent level from day-28 to day-60. The control specimen demonstrated the highest drying shrinkage as compared to the specimens that included AF. The drying shrinkage was found to be the lowest at a concentration of 3% of AF in FC, with the next lowest value observed at 2%.
4. The increasing trend of the UPV is found to have a favourable correlation with the increase in AF weight fractions. The results suggest that adding 4% of AF to the FC produced the highest recorded UPV value, measuring 1698 m/s. In contrast, the control mixtures exhibited a lowest UPV of 1404 m/s. The results of UPV are influenced by the presence of gaps and irregularities in FC.
5. The control FC specimen exhibits prominent larger voids. The FC pore structure comprises gel pores, micropores, and air voids. The inclusion of AF into FC has evidently led to a decrease in the number of voids. The cementitious matrix and AF exhibited a robust interfacial bond, which was established upon the implantation of the AF.

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REFERENCES

[1] N.M. Sani, M. Taib, N. Mohd Alias, Imperative causes of delays in construction projects from developers' outlook. MATEC Web Conf. **10**, 06005 (2014).
DOI: http://dx.doi.org/10.1051/matecconf/20141006005

[2] M. Nowak, Z. Nowak, R.B. Pęcherski, M. Potoczek, R.E. Śliwa, Assessment of Failure Strength of Real Alumina Foams with Use of the Periodic Structure Model. Arch. Metall. Mater. **63** (4), 1903-1908 (2018).
DOI: http://doi.org/10.24425/amm.2018.125122

[3] A.F. Phius, N.M. Sani, N.M. Tawil, Potential of Green Construction in Malaysia: Industrialised Building System (IBS) vs Traditional Construction Method. E3S Web Conf. **3**, 01009 (2014).
DOI: http://dx.doi.org/10.1051/e3sconf/20140301009

[4] M.N.M. Nawi, W.N. Osman, M.K. Rofie, A. Lee, Supply chain management (SCM): Disintegration team factors in Malaysian Industrialised Building System (IBS) construction projects. Int. J. Supply Chain Manag. **7** (1), 140-143 (2018).

[5] S. Ganesan, A.A.I. Che, N. Sani, Performance of polymer modified mortar with different dosage of polymeric modifier. MATEC Web Conf. **15**, 01039 (2014).
DOI: http://dx.doi.org/10.1051/matecconf/20141501039

[6] H. Awang, A.F. Roslan, Effects of fibre on drying shrinkage, compressive and flexural strength of lightweight foamed concrete. Adv. Mater. Res. **587**, 144-149 (2012).
DOI: http://dx.doi.org/10.4028/www.scientific.net/AMR.587.144

7] E. Serri, M.Z. Suleiman, The influence of mix design on mechanical properties of oil palm shell lightweight concrete. J. Mater. Environ. Sci. **6**, 607-612 (2015).

[8] M.H. Nensok, H. Awang, Fresh state and mechanical properties of ultra-lightweight foamed concrete incorporating alkali treated banana fibre. J. Teknol. **84** (1), 117-128 (2022).
DOI: https://doi.org/10.11113/jurnalteknologi.v84.16892

[9] M.A. Tambichik, A.A. Abdul Samad, N. Mohamad, A.Z. Mohd Ali, M.Z. Mohd Bosro, M.A. Iman, Effect of combining Palm Oil Fuel Ash (POFA) and Rice Husk Ash (RHA) as partial cement replacement to the compressive strength of concrete. Int. J. Integr. Eng. **10** (8), 61-67 (2018).
DOI: http://dx.doi.org/10.30880/ijie.2018.10.08.004

[10] M.A Othuman Mydin, M.F. Mohamed Shajahan, S. Ganesan, N.M. Sani, Laboratory investigation on compressive strength and micro-structural features of foamed concrete with addition of wood ash and silica fume as a cement replacement. MATEC Web Conf. **17**, 01004 (2014).
DOI: http://dx.doi.org/10.1051/matecconf/20141701004

[11] A.I. Çelik, U. Tunç, A. Bahrami, T. Alomayri, Y.O. Özkılıç, Use of waste glass powder toward more sustainable geopolymer concrete. J. Mater. Res. Technol. **24**, 8533-8546 (2023).
DOI: https://doi.org/10.1016/j.jmrt.2023.05.094

[12] L. Yu, Z. Liu, M. Jawaid, E.R. Kenawy, Mechanical properties optimization of fiber reinforced foam concrete. MATEC Web of Conf. **67**, 03022 (2016).
DOI: http://dx.doi.org/10.1051/matecconf/20166703022

[13] J.F. Castillo-Lara, E.A. Flores-Johnson, A. Valadez-Gonzalez, P.J. Herrera-Franco, J.G. Carrillo, P.I. Gonzalez-Chi, Q.M. Li, Mechanical properties of natural fiber reinforced foamed concrete. Materials **13** (14), 3060 (2020). DOI: https://doi.org/10.3390/ma13143060

[14] M.A. Othuman Mydin, N.M. Zamzani, A.N. Abdul Ghani, Experimental data on compressive and flexural strengths of coir fibre reinforced foamed concrete at elevated temperatures. Data in Brief. **25**, 104320 (2019). DOI: https://doi.org/10.1016/j.dib.2019.104320

[15] M.R. Jones, K. Ozlutas, L.i. Zheng, Stability and instability of foamed concrete. Mag. Concr. Res. **68** (11), 542–549 (2016). DOI: https://doi.org/10.1680/macr.15.00097

[16] M.H. Nensok, H. Awang, Investigation of Thermal, Mechanical and Transport Properties of Ultra Lightweight Foamed Concrete (UFC) Strengthened with Alkali Treated Banana Fibre. J. Adv. Res. Fluid Mech. Therm. Sci. **86**, 123-139 (2021). DOI: http://dx.doi.org/10.37934/arfmts.86.1.123139

[17] S.S. Suhaili, M.A. Othuman Mydin, H. Awang, Influence of Mesocarp Fibre Inclusion on Thermal Properties of Foamed Concrete. J. Adv. Res. Fluid Mech. Therm. Sci. **87** (1), 1-11 (2021). DOI: https://doi.org/10.37934/arfmts.87.1.111

[18] H.M. Hamada, J. Shi, M.S. Al Jawahery, A. Majdi, T.Y. Salim, G. Kaplan, Application of natural fibres in cement concrete: A critical review. Mater. Today Commun. **35**, 105833 (2023). DOI: https://doi.org/10.1016/j.mtcomm.2023.105833

[19] A. El Oudiani, Y. Chaâbouni, S. Msahli F. Sakli, Physico-chemical characterisation and tensile mechanical properties of Agave Americana L. fibres. J. Text. Inst. **100** (5), 430-439 (2009). DOI: https://doi.org/10.1016/j.carbpol.2011.06.037

[20] M. Ali, A. Alabdulkarem, A. Nuhait, K. Al-Salem, R. Almuzaiqer, O. Bayaquob, Z. Algafri, Thermal analyses of loose agave, wheat straw fibers and agave/wheat straw as new hybrid thermal insulating materials for buildings. J. Nat. Fibers. **18** (12), 1-16 (2021). DOI: https://doi.org/10.1080/15440478.2020.1724232

[21] A.E.O. Ben Sghaier, Y. Chaabouni, S. Msahli, F. Sakli, Morphological and crystalline characterization of NaOH and NaOcl treated agave americana L. fiber. Ind. Crops. Prod. **36** (1), 257-266 (2012). DOI: https://doi.org/10.1016/j.indcrop.2011.09.012

[22] A. Bezazi, A. Belaadi, M. Bourchak, F. Scarpa, K. Boba, Novel extraction techniques, chemical and mechanical characterisation of agave americana L. natural fibres. Compos. B Eng. **66**, 194-203 (2014). DOI: https://doi.org/10.1016/j.compositesb.2014.05.014

[23] E.O. Cisneros-López, J. Anzaldo, F.J. Fuentes-talavera, R. González-núñez, J.R. Robledo-ortíz, D. Rodrigue, Effect of agave fiber surface treatment on the properties of polyethylene composites produced by dry-blending and compression molding. Polym. Compos. **38** (1), 96-104 (2017). DOI: https://doi.org/10.1002/pc.23564

[24] F.S. Corral, L.A.C. Nava, E.H. Hernández, J.F.H. Gámez, M.G.N. Velázquez, M.I.M. Sierra, R.E.D.D.L. Gómez, Plasma treatment of agave fiber powder and its effect on the mechanical and thermal properties of composites based on polyethylene. Int. J. Polym. Sci. **2016**, 1-7 (2016). DOI: https://doi.org/10.1155/2016/2807915

[25] A. El Oudiani, Y. Chaabouni, S. Msahli, F. Sakli, Crystal transition from cellulose I to cellulose II in NaOH treated Agave americana L. fibre. Carbohydrate Polymers **86** (3), 1221-1229 (2011). DOI: https://doi.org/10.1016/j.carbpol.2011.06.037

[26] S.P. Jani, S. Sajith, C. Rajaganapathy, M. Adam Khan, Mechanical and thermal insulation properties of surface-modified agave Americana/carbon fibre hybrid reinforced epoxy composites. Materials Today: Proceedings **37**, 1648-1653 (2020). DOI: https://doi.org/10.1016/j.matpr.2020.07.180

[27] S. Kumara, L. Prasad, V. K. Patel, V. Kumar Patel, A. Kumar, A. Yadav, Physico-mechanical and Taguchi-designed sliding wear properties of Himalayan agave fiber reinforced polyester composite. J. Nat. Fibers. **8** (4), 3662-3671 (2021). DOI: https://doi.org/10.1080/15440478.2021.1982818

[28] P. Sathiamurthi, K.S. KarthiVinith, T.P. Sathishkumar, S. Arunkumar, A.S. Anaamalaai, Fiber extraction and mechanical properties of Agave Americana/Kenaf fiber reinforced hybrid epoxy composite. Mater. Today: Proc. **46** (17), 8594-601 (2021). DOI: https://doi.org/10.1016/j.matpr.2021.03.571

[29] Sakuri, E. Surojob, D. Ariawanb, A. Rio Prabowo, Investigation of Agave cantala-based composite fibers as prosthetic socket materials accounting for a variety of alkali and microcrystalline cellulose treatments. Theor. App. Mech. **10** (6), 405-11 (2020). DOI: https://doi.org/10.1016/j.taml.2020.01.052

[30] O.H. Cardoso, I.D. Cardenas, V.M. Rodriguez, P. Longhurst, F. Coulon, A. Encinas-Oropesa, Up-cycling of agave tequilana bagasse-fibres: A study on the effect of fibre-surface treatments on interfacial bonding and mechanical properties. Results Mater. **8**, 100158 (2020). DOI: https://doi.org/10.1016/j.rinma.2020.100158

[31] J. Wei, S. Ma, Thomas, G. D'Shawn, Correlation between hydration of cement and durability of natural fiber-reinforced cement composites. Corrosion Science, **106**, 1-15 (2016). DOI: https://doi.org/10.1016/j.corsci.2016.01.020

[32] S. Teng, V. Afroughsabet, C.P. Ostertag, Flexural behavior and durability properties of high performance hybrid-fiber-reinforced concrete. Constr Build Mater. **182**, 504-515 (2018). DOI: https://doi.org/10.1016/j.conbuildmat.2020.118487

[33] B. Raj, D. Sathyan, Mechanical and durability properties of hybrid fiber reinforced foam concrete. Constr. Build. Mater. **245**, 118373 (2020). DOI: https://doi.org/10.1016/j.conbuildmat.2020.118373

[34] B. Sangmesh B. P. Nagraj, K.K. Jaiswal, T.P. Gowrishankar, K. Karthik Selvakumar, M.S. Jyothi, R. Jyothilakshmi, S. Kumar, Development of sustainable alternative materials for the construction of green buildings using agricultural residues: A review. Constr. Build. Mater. **368**, 130457 (2023). DOI: https://doi.org/10.1016/j.conbuildmat.2023.130457

[35] M. Asim, G.M. Uddin, H. Jamshaid, A. Raza, Rehman Tahir Zu, U. Hussain, A.N. Satti, N. Hayat, S.M. Arafat, Comparative experimental investigation of natural fibers reinforced light weight concrete as thermally efficient building materials. J. Build. Eng. **31**, 101411 (2020). DOI: https://doi.org/10.1016/j.jobe.2020.101411

[36] M. Amin, B.A. Tayeh, M.A. Kandil, I.S. Agwa, M.F. Abdelmagied, Effect of rice straw ash and palm leaf ash on the properties of ultrahigh-performance concrete. Case Stud. Constr. Mater. **17**, e01266 (2022).
DOI: https://doi.org/10.1016/j.cscm.2022.e01266

[37] M. Musa, A.N. Abdul Ghani, Influence of oil palm empty fruit bunch (EFB) fibre on drying shrinkage in restrained lightweight foamed mortar. Int. J. Innov. Techol. Exp. Eng. **8** (10), 4533-4538 (2019).

[38] N.M. Zamzani, A.N.A. Ghani, Effectiveness of 'cocos nucifera linn' fibre reinforcement on the drying shrinkage of lightweight foamed concrete. ARPN J. Eng. Appl. Sci. **14** (22), 3932-3937 (2019).

[39] K. Ramamurthy, E.K. Nambiar, G.I.S. Ranjani, A classification of studies on properties of foam concrete. Cem. Concr. Compos. **31** (6), 388-396 (2009).
DOI: https://doi.org/10.1016/j.cemconcomp.2009.04.006

[40] M.R. Jones, A. McCarthy, Preliminary views on the potential of foamed concrete as a structural material. Mag. Concr. Res. **57** (1) 21-31 (2005).
DOI: http://dx.doi.org/10.1680/macr.57.1.21.57866

[41] S.S. Suhaili, M.A. Othuman Mydin, Potential of stalk and spikelets of empty fruit bunch fibres on mechanical properties of lightweight foamed concrete. Int J Sci Technol Res. **9** (3), 3199-3204 (2020).

[42] O. Gencel, M. Nodehi, O.Y. Bayraktar, G. Kaplan, A. Benli, A. Gholampour, T. Ozbakkaloglu, Basalt fiber-reinforced foam concrete containing silica fume: An experimental study. Constr. Build. Mater. **326**, 126861 (2022).
DOI: https://doi.org/10.1016/j.conbuildmat.2022.126861

[43] A.M. Serudin, M.A. Othuman Mydin, A.N.A. Ghani, Effect of lightweight foamed concrete confinement with woven fiberglass mesh on its drying shrinkage. Rev. Ing. de Construccion. **36** (1), 21-28 (2021).
DOI: http://dx.doi.org/10.4067/S0718-50732021000100021

[44] D. Falliano, D. De Domenico, G. Ricciardi, E. Gugliandolo, Compressive and flexural strength of fiber-reinforced foamed concrete: Effect of fiber content, curing conditions and dry density. Constr. Build. Mater. **198**, 479-493 (2019).
DOI: https://doi.org/10.1016/j.conbuildmat.2018.11.197

[45] O. Onuaguluchi, N. Banthia, Plant-based natural fibre reinforced cement composites: A review. Cem. Concr. Compos. **68**, 96-108 (2016).
DOI: https://doi.org/10.1016/j.cemconcomp.2016.02.014

[46] A.M. Maglad, M.A. Othuman Mydin, S. Dip Datta, B.A. Tayeh, Assessing the mechanical, durability, thermal and microstructural properties of sea shell ash based lightweight foamed concrete. Constr. Build. Mater. **402**, 133018 (2023).
DOI: https://doi.org/10.1016/j.conbuildmat.2023.133018

[47] A.M. Maglad, M.A. Othuman Mydin, S.S. Majeed, B.A. Tayeh, S.A., Mostafa, Development of eco-friendly foamed concrete with waste glass sheet powder for mechanical, thermal, and durability properties enhancement. J. Build. Eng. **80**, 107974 (2023).
DOI: https://doi.org/10.1016/j.jobe.2023.107974