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Studies on Durability Properties of Natural Fibre-Reinforced Green Lightweight Foamed Concrete Employing Industrial Hemp Fibres

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ABSTRACT

The utilization of natural fibres for the invention of building materials has increased significantly in recent years in the construction industry. Hemp fibre-reinforced concrete, according to research, can provide low-cost building materials for residential and low-rise buildings while achieving sustainable construction and meeting future environmental targets. The purpose of this research was to improve the durability of lightweight foamed concrete (LFC) reinforced with hemp fibre (HF). Six weight fractions of HF were considered specifically 0.0% (control), 0.1%, 0.2%, 0.3%, 0.4% and 0.5%. Besides, three densities of LFC which were 500, 900 and 1300 kg/m3 were cast and tested. The properties evaluated were drying shrinkage, water absorption, depth of carbonation and porosity. From the durability tests, it was observed that the optimal results for water absorption, depth of carbonation and porosity tests were attained with the addition of 0.5% HF into LFC mixes. For the drying shrinkage test, LFC with the weight fractions of 0.3% (500 kg/m^3), 0.4% (900 kg/m^3) and 0.5% (1300 kg/m^3) reveal the optimal drying shrinkage. This research has provided a foundation for further research into HF-strengthening LFC. There is a huge potential to utilize HF in cement-based materials for durability and mechanical properties enhancement. The use of industrial HF might make it possible to reduce fine aggregate while still producing LFC of higher quality. The inclusion of agricultural fibres in LFC will also promote the expansion of farming operations, which will have rewarding economic benefits.

1. Introduction

Given the scarcity of natural resources, sustainable and green building materials are anticipated to be desired and essential [1]. Sustainable materials and buildings are distinguished by their

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durability and effectiveness over time, in contrast to conventional structures whose primary concern is their initial cost [2]. Using aggregates in concrete for construction causes rapid material depletion and have a devastating effect on the environment and its surroundings [3-6]. This issue has been a major source of concern on a global scale [7-11]. This study focuses on sustainable concrete materials, which can be defined as concrete made with less aggregate or concrete made from recycled concrete [12-15]. It is generally desirable to create a new material with acceptable performance while conserving natural resources. The reduction of coarse aggregates is consistent with some long-term interests, whereas the use of agricultural fibres is consistent with increased agricultural activity and affluence [16].

The necessity to reinforce or retrofit building structures arises for a variety of reasons, including but not limited to changes in the use of buildings, deprivation, alterations of design requirements and codes, and the modification of design and flaws in construction. Additional structural members such as wall, beam and column connecting steel plates to structural elements, exterior post-tensioning, and fibre-fortified shields are the traditional methods of structural strengthening [17]. Due to its superior strength to self-weight proportion, corrosion endurance, and simplicity of managing and installation, externally bonded fibre-reinforced concrete is one of the most popular techniques.

Awwad *et al.*, [18] explored the properties of concrete reinforced with hemp, banana, and palm fibres. Specifically, natural fibre-reinforced concrete were examined for their bending and compressive strengths. The tested flexural beam specimens were found to exhibit ductile behaviour. These preliminary test results showed promise in compression and flexural strength values for concrete mixes that included industrial hemp fibres, and they corroborated the possibility for reduced utilization of aggregate when adding hemp fibres. Additionally, Awwad et al. [19] conducted additional research on industrial hemp, preparing and testing cubes, beam and cylinder specimens. For the sake of verification and comparison, they also included a mix of control and polypropylene fibres. Both synthetic and natural fibre additions were shown to reduce the strength. In contrast to the brittle nature observed in the control concrete sample with no fibres, the existence of hemp fibres in conjunction with a decrease in the aggregate ensued in a flexible bending performance. The cylinder specimen results demonstrated a correlation between fibre content and coarse aggregate reduction, suggesting that the latter creates more room in the concrete matrix for the former to interact with its constituents should the former be present in sufficient quantity.

Although lightweight foamed concrete (LFC) has received a lot of research consideration, some downsides, such as its weak bending, still restrict the scope of its use. The strength of LFC can be affected by a variety of factors, including the cementitious materials used, the cement dosage, the mix proportion, the water-cement ratio, the foam volume, the foaming agent, the curing method, the additive, and the addition of waste by-product [20]. The density of the LFC material has some influence over its strength. Therefore, striking a balance between the two is essential at all times if one wishes to maximize strength while at the same time minimizing density to the greatest extent possible. When this is the goal, it is sometimes possible to achieve it by selecting exceptional quality foaming agents and ultralight fillers or aggregates, as well as by optimizing the cementitious materials in the mix. When the density of the concrete remains the same, the types of filler used and the incorporation of natural fibres will have an effect on the water-solid ratios, and decreasing the size of the sand particles will contribute to an increase in the concrete's strength [21]. The pozzolanic effect of natural fibre causes it to react with the secondary portlandite product of cement hydration, Ca(OH2), to produce more C-S-H gel. This reaction takes place as a result of the natural fibre’s pozzolanic effect (secondary C-S-H). During the pozzolanic reaction, longer silicate chain lengths are produced as the Ca: Si molar ratio of C-S-H decreases. This secondary C-S-H strengthens the interfacial bond between the aggregate particles and the fibre, lowers the porosity of the bulk cement paste, and raises the ion diffusion resistance of the LFC [22].

LFC has recently attracted a significant amount of attention from industrial players and manufacturers of building materials [23]. This can be attributed to the fact that LFC possesses excellent thermal and mechanical characteristics, some of which include high flowability, low self-weight, good thermal performance, and sound insulation properties. In addition, LFC is an environmentally friendly building material because it requires a low quantity of aggregate and has a high potential for the integration of waste materials, such as natural fibres. LFC, also known as self-compacting material, is a mixture of cement paste (slurry) and homogeneous foam that is introduced using a suitable foaming agent [24]. This mixture can be thought of as a self-compacting material. LFC stands out from other highly air-entrained materials because it has a volumetric air content that is greater than 25 percent. The use of LFC in the context of the Malaysian construction industry is still in its infancy [25], despite the increased attention that it has received on a global scale. On the other hand, it has been implemented in a number of construction and void-filling projects. Therefore, this research was done to examine how HF might be used in LFC to enhance its durability properties.

2. Methodology

2.1 Constituent materials

To make LFC, the three main materials employed were Ordinary Portland cement (OPC), fine sand, water and stable foam. Since this research aims to produce LFC in the range of densities between 500-1300 kg/m^3, the protein-based foamed agent was used in order to produce a consistent bubble size. Locally available Ordinary Portland cement (Castle brand) was employed. For general-purpose mortar and concrete applications, this OPC is designed to meet sufficient strength while also providing better workability.

Besides, the fine filler applied in this laboratory investigation was provided by DRN Technologies. The fineness modulus of the sand used was 2.95, and its specific gravity was 2.60. The fine sand sieve analysis was in agreement with the ASTM C33 standard. Next, for various LFC mixes, normal distilled tap water that maintains a pH of 7 and contains no harmful substances was used.

Additionally, the HF employed in this study was obtained from an international supplier. The raw HF was utilized considering this is the preliminary study. Five HF weight fractions were used such as 0.0% (control), 0.1%, 0.2%. 0.3%, 0.4% and 0.5%. Before being used as an additive in LFC, the HF was thoroughly cleaned to remove any unwanted debris and impurities. Figure 1 shows the HF employed in this study. Table 1 shows the physical and mechanical properties of HF while Table 2 reveals the HF chemical composition.

Fig. 1. Raw hemp fibre employed in this study

Table 1
Physical and mechanical properties of hemp fibre

Properties	Values
Fibre dry density	1.38 g/m^3
Average diameter	358 µm
Elongation at break	3.8 %
Tensile strength	654 N/mm^2
Young modulus	85 GPa

Table 2
Chemical composition of hemp fibre

Properties	Values
Lignin	5.8%
Cellulose	72.5%
Hemicellulose	20.8%
Wax	0.9%

2.2 Mix Design

There were three densities of LFC were prepared in this study specifically 500, 900 and 1300 kg/m^3. The cement-to-sand ratio was fixed at 1:1.5 while the water-to-cement ratio was maintained at 0.45. This water-to-cement ratio was found to give desirable workability of LFC for all three densities considered in this study. Table 3 visualized the mix design of LFC with varying weight fractions of HF.

Table 3
LFC mix design with varying weight fractions of MF

Sample	Density (kg/m^3)	Hemp fibre (kg/m^3)	Cement (kg/m^3)	Sand (kg/m^3)	Water (kg/m^3)	Foam (kg/m^3)
Control-500	500	0.00	194.1	291.2	87.4	46.3
0.1% HF500	500	0.62	194.1	291.2	87.4	46.3
0.2% HF500	500	1.24	194.1	291.2	87.4	46.3
0.3% HF500	500	1.86	194.1	291.2	87.4	46.3
0.4% HF500	500	2.48	194.1	291.2	87.4	46.3
0.5% HF500	500	3.09	194.1	291.2	87.4	46.3
Control-900	900	0.00	338.6	507.9	152.4	33.8
0.1% HF900	900	1.03	338.6	507.9	152.4	33.8
0.2% HF900	900	2.07	338.6	507.9	152.4	33.8
0.3% HF900	900	3.10	338.6	507.9	152.4	33.8
0.4% HF900	900	4.13	338.6	507.9	152.4	33.8
0.5% HF900	900	5.16	338.6	507.9	152.4	33.8
Control-1300	1300	0.00	483.0	724.5	217.4	21.3
0.1% HF1300	1300	1.45	483.0	724.5	217.4	21.3
0.2% HF1300	1300	2.89	483.0	724.5	217.4	21.3
0.3% HF1300	1300	4.34	483.0	724.5	217.4	21.3
0.4% HF1300	1300	5.78	483.0	724.5	217.4	21.3
0.5% HF1300	1300	7.23	483.0	724.5	217.4	21.3

2.2 Experimental Setup
2.2.1 Accelerated carbonation test

Carbonation is a significant factor in the pH value reduction of LFC. Calcium hydroxide reacts with atmospheric carbon dioxide to produce carbonate as a result. Carbonic acid is also thought to be a factor in pH value reduction. This accelerated carbonation test apparatus adheres to BS 1881: Part 201 [26]. At exposure ages of 70, 90, and 110 days, the carbonation tests were conducted. Following the flexural test, the newly broken prism was sprayed with phenolphthalein solution, an indicator liquid that has the ability to convert the colour purple to colourless or white.

As a result, the non-carbonated surface would change to a dark purple colour while the carbonated surface maintained its colourless form. To evaluate the response, the approximation of the carbonation expanse inwards was documented on four sides of the LFC specimens, with four readings at each side taken at intervals of two centimetres.

Therefore, there is a chance that corrosion will develop in the marked front area. A good indication of the area of the depassivation front can be obtained by means of the phenolphthalein method, and this area, which is a few millimetres ahead, is where the pH adjustment occurs. Figure 2 depicts a depth of carbonation test example.

Fig. 2. Phenolphthalein solution was sprayed on the LFC specimen

2.2.2 Porosity test

The Vacuum Saturation Apparatus was utilized to determine the porosity value in most cases. After drying the samples for this study, they were placed in a desiccator and subjected to a vacuum for three days; after this time had passed, the desiccator was found to be full of de-aired, distilled water. oven-dry mass was determined by drying the samples in a ventilated oven at 105 degrees Celsius. After 3 days in the oven, the specimens were taken out and chilled at room temperature. While the desiccator was sealed with a lid and protected with vacuum grease, the specimens' weights were measured to determine their oven-dry masses prior to being vacuum saturated. In the meantime, a pressure gauge was attached to the vacuum line connector, and pumping began. This continued for three days. Figure 3 shows the LFC specimens were placed in a vacuum-sealed desiccator.

Fig. 3. LFC specimens in a vacuum-sealed desiccator

2.2.3 Shrinkage test

Drying shrinkage tests are performed to understand more about how LFC shrinks. In addition, this method can gather data on how the LFC samples affect the drying shrinkage. The purpose of this experiment is to provide evidence that HF has the ability to withstand volume changes. This method of testing conforms to ASTM C878 [27] standard. The test specimen should be a prism with a dimension of 75 mm x 250 mm. Three LFC specimens were prepared for each experiment. Figure 4 demonstrates the apparatus employed for the shrinkage test.

Fig. 4. Shrinkage test apparatus

2.2.4 Water absorption test

For the current study, cylinders measuring 75mm in diameter x 100mm in height were prepared and tested in accordance with BS 1881: Part 122 [28]. The immersed surface dry weight, W_{sat}, of the specimen was determined by removing the cylinder samples a day before curing, cleaning the samples, and then measuring their dimensions. After this was done, the samples were dried in an oven at 105°C for 72 and a half hours in order to get an accurate reading of the oven-dried weight. On the other hand, a more thorough calculation was run, and the LFC's water absorption was evaluated using Eq. (1):

$$\mathrm{Wa} = \frac{\mathrm{Wsat\text{-}Wdry}}{\mathrm{Wdry}} \times 100\% \qquad (1)$$

where
W_a = LFC water absorption (%)
W_{sat} = LFC saturated surface dry weight (kg)
W_{dry} = LFC oven-dried weight (kg)

3. Results

This section will present the results obtained from the laboratory investigation of LFC reinforced with varying weight fractions of HF. The properties assessed were water absorption, porosity, drying shrinkage, and depth of carbonation.

3.1 Water absorption

The influence of varying HF weight fractions in FC on water absorption capacity is shown in Figure 5. It is evident that as the weight fraction of HF rises, the percentage of FC water absorption capability drops. This tendency is brought on by an increase in FC density, which demonstrates that FC with a density of 900 and 500 kg/m^3 both have higher water absorption capacities than FC with a density of 1300 kg/m^3. The percentage of water absorption for control FC with densities of 1300, 900, and 500 kg/m^3 were at 11.0%, 16.2%, and 21.0%, respectively. The results, therefore, show that FC with a density of 500 kg/m^3 has a high-water absorption rate because the density necessitates using a large amount of foam, which results in more air voids. According to the research, FC with a density of 500 kg/m^3 was able to form pores of a bigger size.

However, these associations with the matrix had no major impact on the lightweight FC's quality. Because the pores were close to one another, some of the air bubbles combined to form larger pores. Additionally, this led to the formation of loose microstructure and brittleness, which reduced the material's resistance to severe stresses. Since the pores are so numerous and so much larger as the density decreases, it's possible that the results will show that water absorption increases with density. Capillary pores are another crucial factor in water transport. This result can be explained by the fact that FC initially absorbed water at a slower pace, especially when it had a higher weight fraction of HF.

Furthermore, due to the tiny size and volume of the pores, FC with a higher HF content was able to resist water penetration. The drying process caused the HF to lose its moisture and return to its original size. The formation of C-S-H gel in the FC matrix with a higher HF content reduced pore size, which decreased water absorption. Due to the small voids in the FC, water absorption took place. Therefore, it is reasonable to assume that the absorption decreased as the FC matured. Overall, the results indicate that increased HF weight fraction, as compared to the lower density of FC, tends to absorb water at the underlying stage more slowly. This might be explained by the fact that pores with large surface areas have poor connections to the matrix [29]. Increased natural fibre water absorption results in unstable volume and weak matrix-fibre adhesion, which causes the natural fibre to degrade more quickly in the alkaline environment of cement and concrete [30]. The paste phase influences the water absorption of FC more so than entrained pores that are not cohesive.

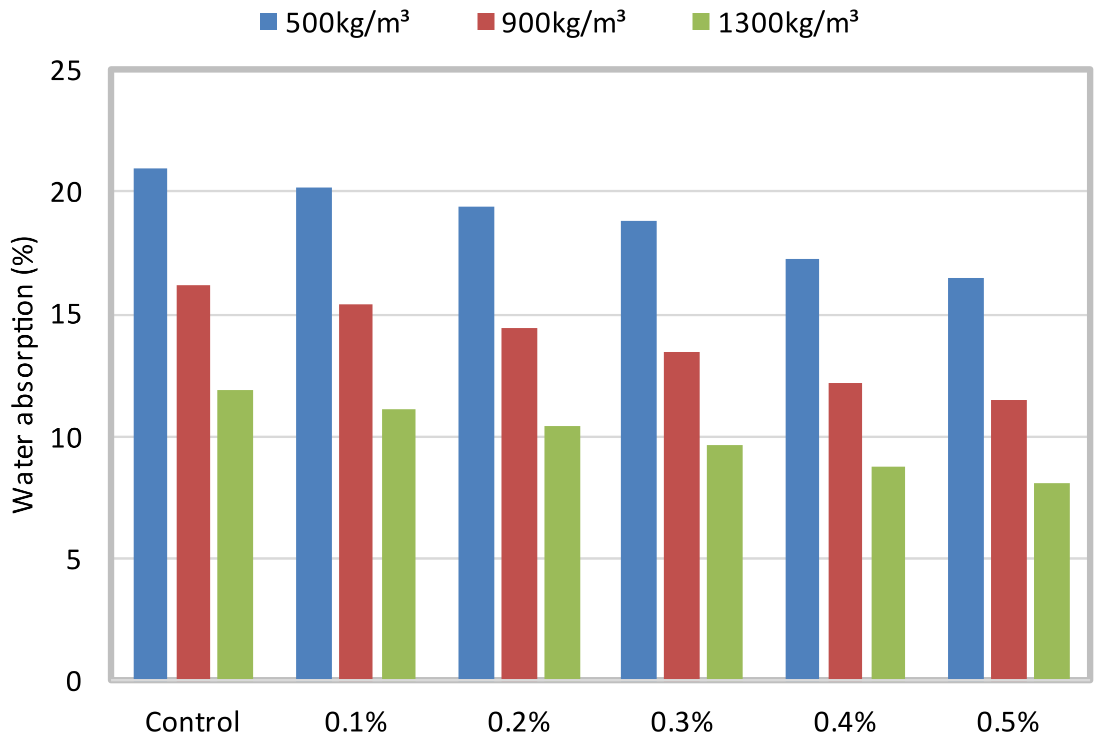

Fig. 5. Water absorption of LFC with varying weight fractions of HF

3.2 Porosity

Obviously, LFC's porosity and pore structure affect its mechanical qualities. The strength of FC will be impacted by its increased porosity percentage. It's also crucial to consider that the air pore within LFC can become entrained. The impact of various HF weight fractions on the porosity of LFC is shown in Figure 6. When the HF weight fraction and FC density rise, the porosity level of the material gradually decreases. In addition, the change in the HF's shape and modification makes LFC less porous. Figure 6 findings demonstrate that FC with densities of 1300, 900, and 500 kg/m^3 with an HF weight fraction of 0.5% gives the lowest porosity values of 25.3%, 46.2%, and 62.9%. The porosity percentages of LFC of 0.1% HF with densities of 1300, 900, and 500 kg/m^3 were greater, at 30.9%, 51.4%, and 67.6%, respectively.

Overall, for all the densities examined in the current research, the porosity of LFC decreases as the HF weight fraction increases. However, compared to 500 kg/m^3 and 900 kg/m^3, a density of 1300 kg/m^3 has the lowest percentage of porosity. The interaction of the cement paste and HF may be one explanation for this. It is important to notice that HF assisted to bridge the matrix while higher-density LFC reduced the amount of porous structure as shown in Figure 7. As a result, changes in the morphology of HF activate lighter LFC's reduced porosity. The foam also makes it possible for air to enter the mix slurry as it is being mixed.

As a result, a lot of foam must be used to let air voids into the mixture to reduce density. In other words, this shows that to attain higher porosity values, low-density LFC needs more foam [31]. Additionally, a high degree of porosity might result in an increase in voids, which can weaken FC's compressive strength. Therefore, given the minimal relationship between the pores and the matrix, this means that there is insufficient surface area that unites them. In addition, the additional foam places restrictions on the binding materials at this density, which delays the LFC's process of setting and becoming hard.

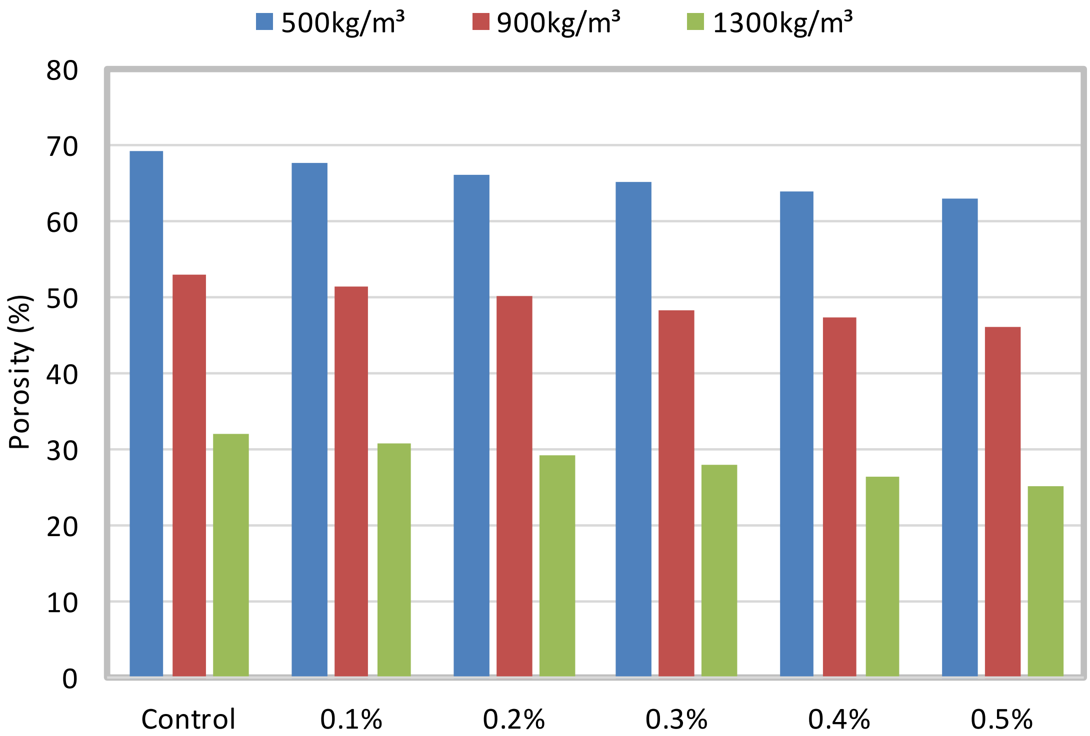

Fig. 6. Porosity of LFC with varying weight fractions of HF

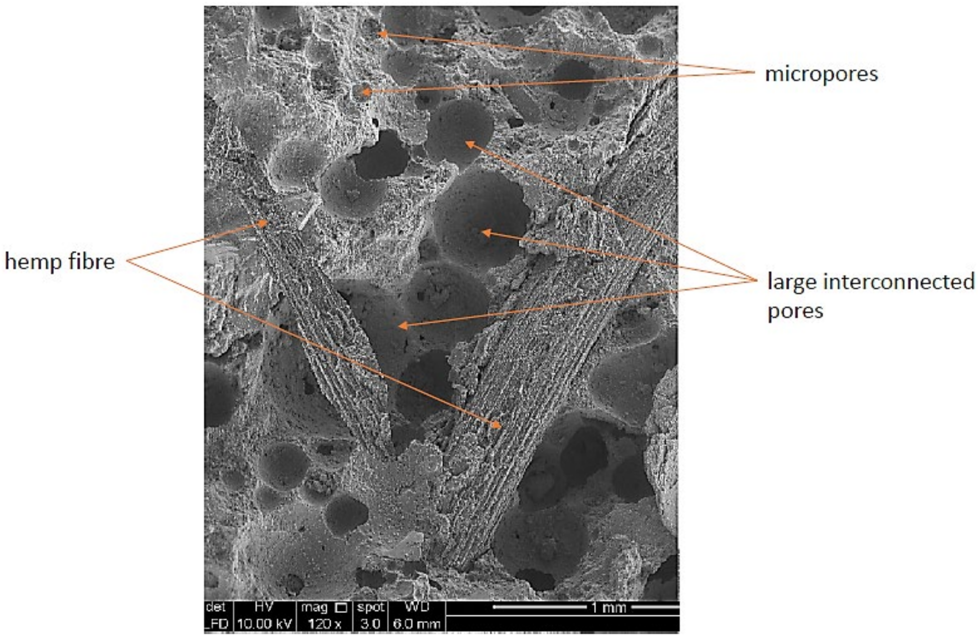

Fig. 7. Morphology of 1300 kg/m^3 density LFC reinforced with 2% weight fraction of HF

3.3 Shrinkage

The expansion of LFC can be measured by doing a drying shrinkage test. In addition, this method can be used to get information on how the specimen affects drying shrinkage. It's also worth noting that the purpose of this experiment is to provide evidence for the effectiveness of fibres in withstanding variations in volume. The drying shrinkage data is displayed in Figure 8-10. All specimens show a substantial increase in drying shrinkage up to day 30. After that point, drying shrinkage increases more slowly. Drying shrinkage was shown to be greater in the control mixtures at densities of 500, 900, and 1300 kg/m^3. When HF is used, the drying shrinkage of LFC specimens is greatly reduced. LFC with the weight fractions of 0.3% (500 kg/m^3) and 0.4% (900 kg/m^3) shows the least drying shrinkage.

Conversely, the optimum performance is shown by a density of 1300 kg/m^3 and a weight fraction of 0.5% HF. Incorporating HF into FC improves its ability to resist shrinking, as a result. By comparing Fig. 8-10, it can be seen that low-density LFC tends to shrink more than its higher-density FC due to the greater quantity of foam and the lesser amount of aggregate content employed in the mix. Moreover, compared to the control mix of LFC, the addition of HF in LFC delivers the best results in reducing shrinkage. The HF works as a filler, creating a more compact microstructure and reducing the pore size and number. Cement paste is the main factor that affects the shrinkage behavior of concrete.

Since LFC shrinkage is a measure of foam volume, it can be traced back to the concentration and characteristics of the paste used to make the foam. Additionally, reduced moisture content generally results in greater shrinking. An increase in the foam content causes a decrease in drying shrinkage. Lower paste substance in the mix causes lower content of pores, which in turn causes less drying shrinkage at larger foam volume. Adding more HF to LFC decreases its drying shrinkage. However, unlike normal strength concrete, LFC does not contain aggregates and hence it shrinks considerably further. Consequently, HF works as an aggregate in LFC mix due to its capacity for void filling, lowering the shrinkage impact in the cement matrix.

Additionally, HF is effective in minimizing shrinkage and can reduce the percentage of cracks in LFC. In addition, once a crack has formed, HF can bridge it, which is especially useful for preventing more cracks from forming. Even large quantities of air trapped within the cement matrix do not significantly alter the tiny pore structure after hardening [32]. The drying shrinkage that is proportional to the amount of LFC paste in each design mix is thus inhibited by the presence of micro-pores in it.

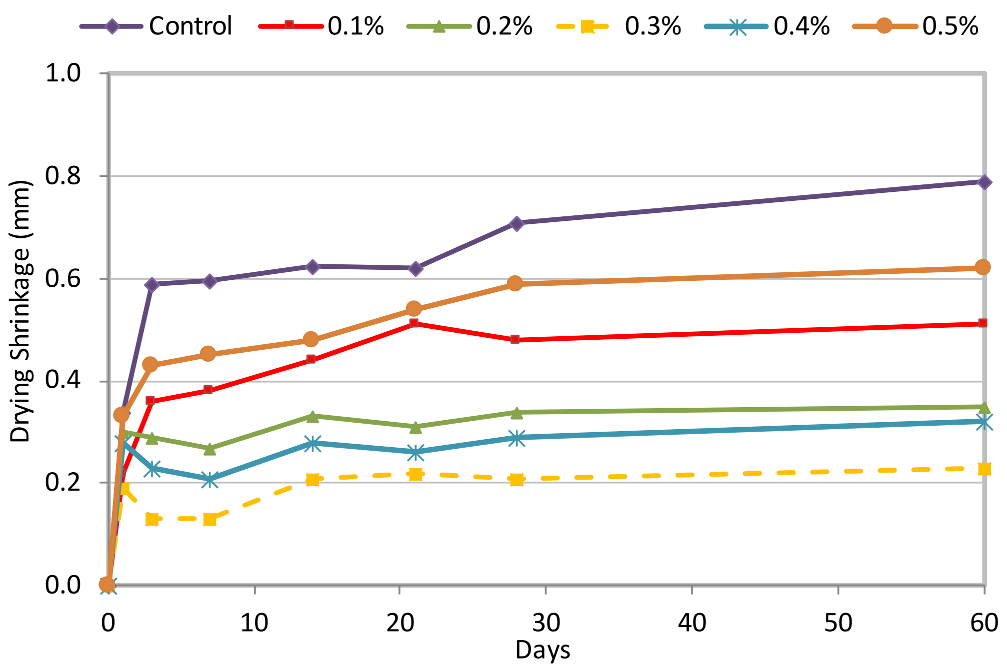

Fig. 8. Drying shrinkage of 500 kg/m^3 density LFC with varying weight fractions of HF

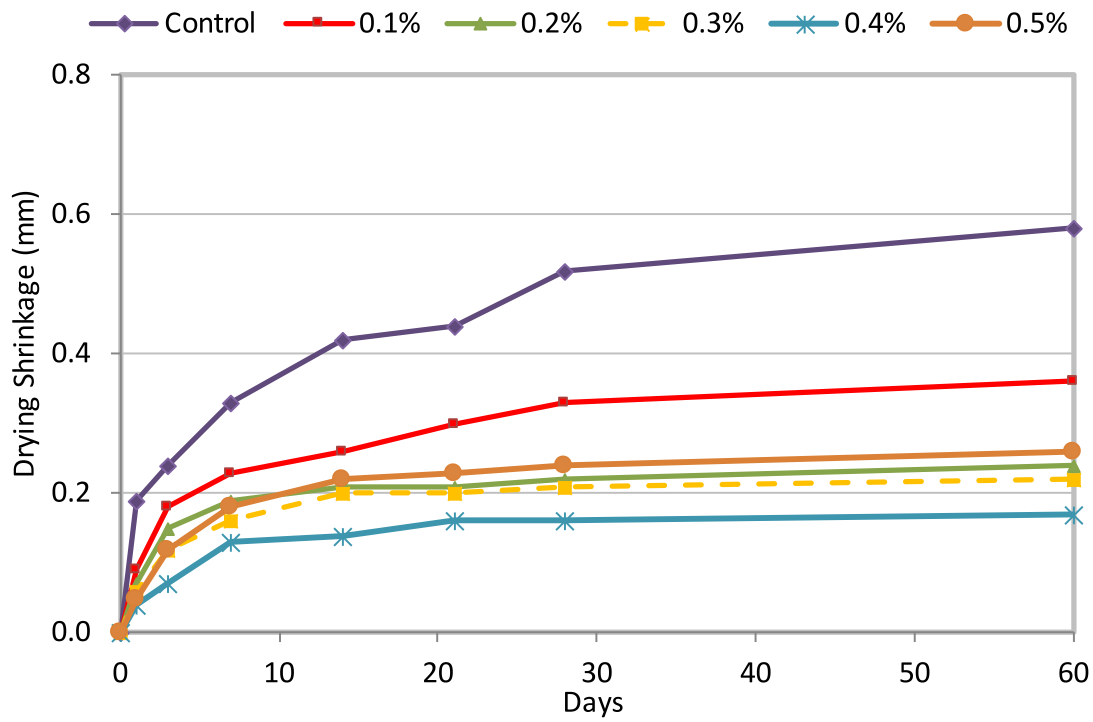

Fig. 9. Drying shrinkage of 900 kg/m^3 density LFC with varying weight fractions of HF

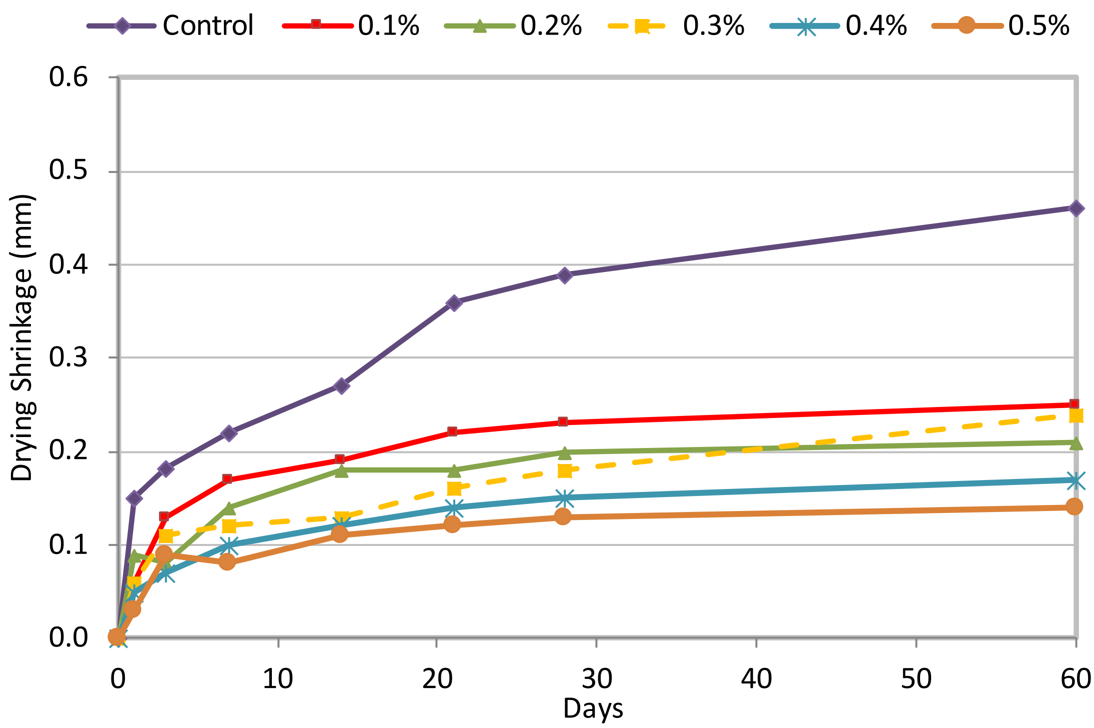

Fig. 10. Drying shrinkage of 1300 kg/m^3 density LFC with varying weight fractions of HF

4.4 Depth of carbonation

Different environmental conditions have a major impact on LFC-based material. LFC's structure deteriorates because of its low durability in certain situations, one of which is the carbonation process, which takes place when carbon dioxide in the air reacts with hydration products in the water.

Further, carbonation can be brought on by several different issues, one of which is the cement paste's intrinsic diffusivity after it has solidified. The rate of carbonation can be managed by regulating the diffusion of CO_2 into the LFC pore structure. Factors such as cement type, the porosity of the material, curing period, and type and quantity of fibre addition can all affect the diffusion rate, and this must be considered.

Carbonation depth data for LFC with densities of 500, 900, and 1300 kg/m^3 at varying weight fractions of HF are depicted in Figure 11-13. The test durations were 70, 90, and 110 days, respectively. According to the data provided, the control specimen at 110 days shows a staggering discovery of carbonation depth, with the maximum at 36.5 mm, followed by 28.8 mm, and 23.1 mm for densities of 500, 900, and 1300 kg/m^3. So, it's clear that the durability attributes of the control samples are subpar. Meanwhile, at 110 days, specimens with 0.5% HF demonstrate reduced carbonation depth results compared to control specimens, with the lowest at 33.5 mm, followed by 25.2 mm, and finally 19.5 mm for densities of 500, 900, and 1300 kg/m^3. Therefore, it may be inferred that 0.5% HF weight fraction specimens exhibit high durability.

As a result, the results demonstrated clearly that the carbonation depth decreased with increasing weight fractions of HF and testing time, hence increasing the carbonation depth of FC. The rate of carbonation also increased because of the higher CO_2 content [33,34]. Since the process in hardened LFC takes place through the pore system, it is especially true for specimens with a greater water-binder ratio, like the control specimens, which have large pore sizes and volumes [35]. Meanwhile, the filling action of the HF decreased the water/binder ratio of the FC, leading to a shallower carbonation depth in the HF-incorporated specimens [36]. Consequently, this resulted in a decrease in both the pore size and volume of LFC, even though the water-binder ratio is still crucial to the FC carbonation process.

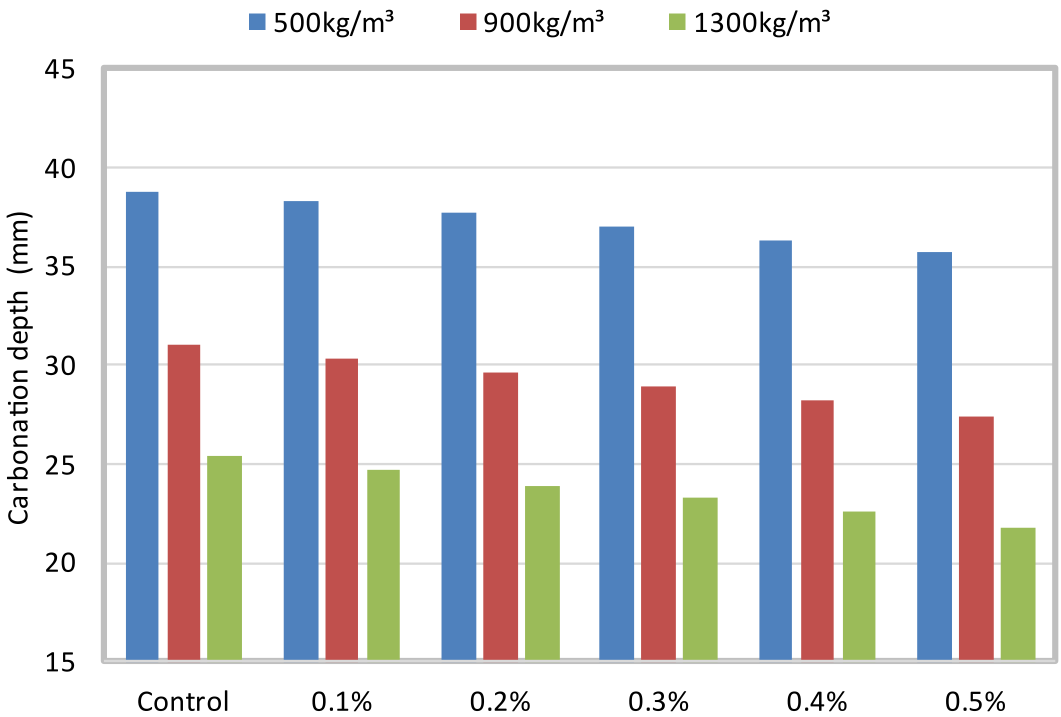

Fig. 11. Depth of carbonation of LFC with varying weight fractions of HF on day-70

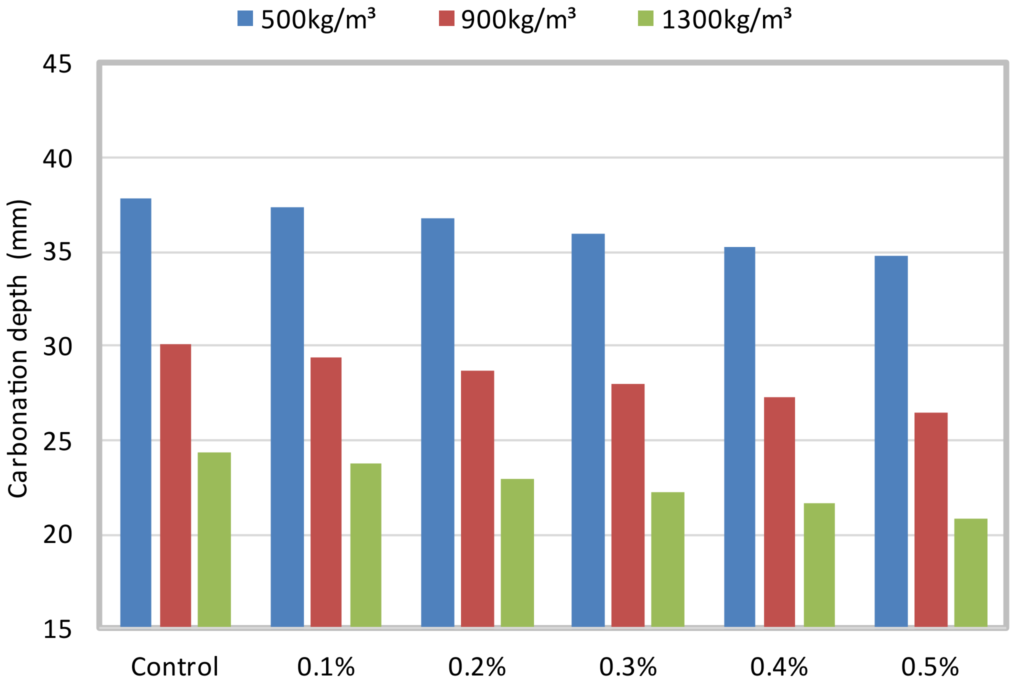

Fig. 12. Depth of carbonation of LFC with varying weight fractions of HF on day-90

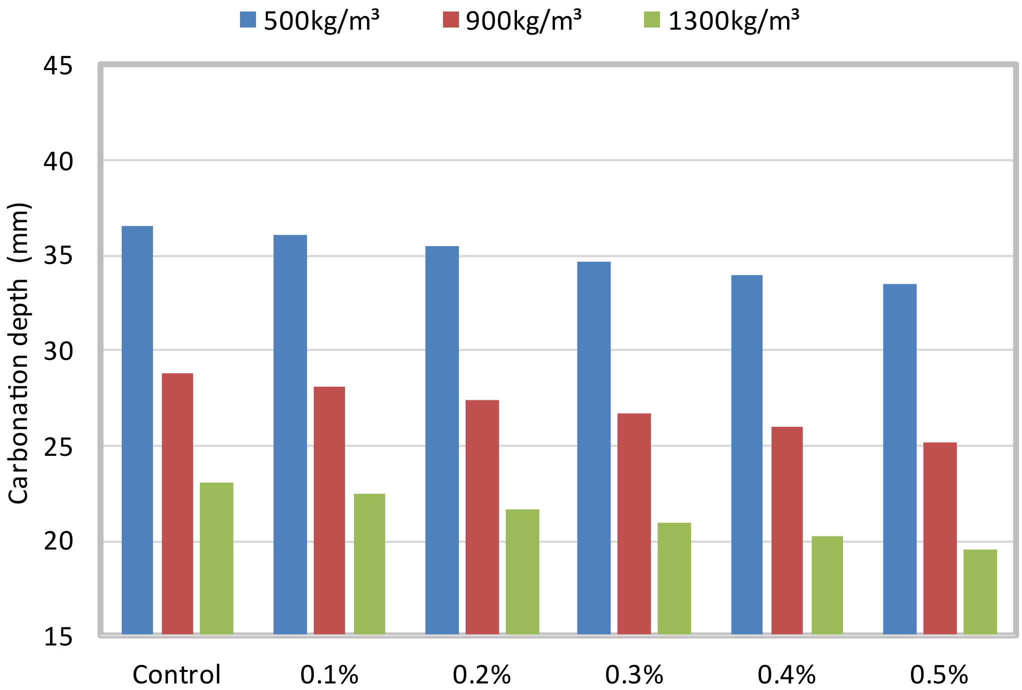

Fig. 13. Depth of carbonation of LFC with varying weight fractions of HF on day-110

4. Conclusions

This study experimentally investigated the effects of incorporating varying weight fractions of raw hemp fibre (HF) into three different densities of LFC (500 kg/m^3, 900 kg/m^3 and 1300 kg/m^3) on its durability properties. The influences of adding HF at six different weight fractions such as 0.0%, 0.1%, 0.2%, 0.3%, 0.4% and 0.5% were evaluated. The experimental results show that incorporating HF into LFC improves the water absorption capacity, porosity, depth of carbonation and drying shrinkage. However, LFC's durability properties varied depending on the percentage of HF added. Overall, 0. 5% HF in LFC gave the optimal result. Boundary bonding in an HF-matrix, which is generally considered to have a coarser surface, has advantages. As a result, it stimulates the mechanical interlocking of HF fibres and the matrix, which improves LFC's durability properties.

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