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Sustainable Lightweight Foamed Concrete using Hemp Fibre for Mechanical Properties Improvement

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ABSTRACT

Fibres have long been used as an additive in the fabrication of building elements and materials. A combination of natural and synthetic fibres has shown promise in preliminary research and testing, with the added benefit of greatly improved strengths of the composites. Compared to traditional reinforcement bars, natural fibre reinforcement's ratio of fibre required is significantly lower, making it more beneficial in terms of energy and economic values. Recent research has focused on the feasibility of using both natural and synthetic fibres as reinforcement in concrete and other construction materials. Thus, the purpose of this research is to investigate the feasibility of using hemp fibre at various percentages (0%, 0.2%, 0.4%, 0.6%, and 0.8%) as an additive in lightweight foamed concrete to enhance mechanical properties. Three LFC densities namely 500, 900 and 1300 kg/m^3 were fabricated and tested. Axial compressive strength, flexural strength, splitting tensile strength, and ultrasonic pulse velocity were the four mechanical parameters that were assessed. The findings demonstrated that adding 0.4-0.6% of HF to LFC produced the best results for ultrasonic pulse velocity, compressive strength, flexural strength, and splitting tensile strength. The HF is essential in assisting to stop the spread of cracks in the plastic state of the cement matrix after the load was applied.

1. Introduction

Aside from the fact that its production requires a lot of energy and results in releases of carbon dioxide that have a negative impact on the environment [1], cement is arguably the material that is used the most in the process of concreting for construction [2]. Conventional concrete contains a large portion of cement quantities in it [3]. As a result, conventional concrete construction is a major contributor to the pollution of the global environment and air [4]. As a result of these problems,

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researchers are looking into alternatives to cement as well as the utilization of materials that are better for the environment in concrete construction [5]. Concrete that is environmentally friendly and sustainable is called green concrete, and it is a composite material where cement and aggregate is replaced with waste and natural materials [6]. Since the beginning of the 21st century, scientists have been toiling away 24 hours a day, seven days a week in an effort to perfect a form of sustainable concrete that is superior in terms of its properties, kind to the environment, and capable of bringing down the cost of production [7]. In an effort to develop environmentally friendly concrete, a number of natural fibres like coir, sugarcane bagasse, hemp bamboo, jute, flax and ramie have been continually tested out in an effort to cut back on the consumption of cement and make better use of resources that are readily available as well as to progress the concrete properties [8].

Building materials have traditionally been made with the assistance of fibres for a very long time. The results of preliminary research and testing have shown that the combination of natural and synthetic fibres in a composite material can produce remarkable results. This is due to the fact that the presence of both types of fibres confers significant advantages on the composite material's mechanical properties. Because the ratio of fibre needed for natural fibre reinforcement is significantly lower than that required for traditional reinforcement, natural fibre reinforcement is significantly more beneficial in terms of energy and economic values than conventional reinforcement bars [9]. Recent research has been organized to explore the possibility of using natural and synthetic fibres as reinforcement in construction materials, specifically concrete.

Significant interest from industrial players and manufacturers of construction materials has been focused on lightweight foamed concrete (LFC) as of late [10-13]. This is because LFC has high workability, variation in densities, decent thermal insulation properties, and sound protection, among other desirable mechanical qualities [14]. Furthermore, LFC is an eco-friendly construction material due to its low aggregate needs and a high potential for the incorporation of waste materials like natural fibres [15]. Using a suitable foaming agent, cement paste and homogeneous foam are combined to create LFC, also known as self-compacting material. It's possible to think of this blend as a self-compacting material [16]. Because its volumetric air content is greater than 25%, LFC stands out from other highly air-entrained materials [17]. Despite growing interest in LFC around the world, its implementation in the Malaysian construction industry is just getting started [18]. Conversely, it has been used in a variety of building and earthfilling initiatives [19]. LFC has some disadvantages such as low flexural and tensile strengths, high shrinkage and porous in nature [20]. Therefore, utilizing natural fibres in LFC would assist to improve these drawbacks.

Several studies on the effects of adding natural fibres to cement-based materials have been conducted over the past few decades for instance hemp, kenaf, and bamboo natural fibres. Wahyuni et al. [21] found that the addition of 0.5% bamboo fibres resulted in a similar increase in splitting tensile strength, tensile strength by 24%, rigidity by 55 to 97%, and elasticity by 16% to 60%. Besides, Kumarasami et al. [22] made a similar finding, determining that 2% is the sweet spot for bamboo fibres due to their demonstrably superior properties. On the other hand, Kavitha and Kala [23] observed that the workability of bamboo decreased gradually as the amount of bamboo fibres increased. Archilla et al. [24] determine that bamboo-reinforced concrete is not a suitable replacement for steel reinforcements in concrete. Treatments applied to the surface to improve adhesion are time-consuming, expensive, and often toxic. That means that in addition to steel reinforcements, bamboo fibres can be used to fortify concrete. Li et al. [25] Incorporating 0.5% alkali-treated bamboo fibres into cement concrete increased toughness and decreased elastic modulus, according to a recent study.

Furthermore, kenaf fibres are highly suitable for use as a reinforcement material due to their high mechanical strength and low density. Sodium hydroxide surface treatment allows for the regulation of hydrophilic properties [26]. In contrast to the brittle failure displayed by control concrete, the kenaf fibre concrete specimens display ductile failure. The concrete with unprocessed kenaf fibres demonstrated superior workability [27]. Elsaid et al. [8] found that the kenaf fibre concrete had lower compressive strength (57.0 N/mm^2, 6.0 N/mm^2, and 3.0 N/mm^2), flexural strength (5.0 N/mm^2), and split tensile strength (4.0 N/mm^2) than the control concrete. At the microstructural level, a strong bond between the concrete matrix and kenaf fibres has been seen, and the toughness index of the kenaf fibre concrete is about three times that of the control concrete. According to Kim et al. [29], gamma-ray irradiation significantly boosts the compressive and flexural strength of cementitious composites containing kenaf grafted with acrylamide. According to the study conducted by Mohsin et al. [30], the addition of kenaf fibre increases flexural strength, enhances ductility, and decreases crack propagation. The addition of 0.25–0.50% kenaf fibres have been shown to significantly reduce autogenous and drying shrinkage cracking [31].

Hemp fibre added to concrete causes a 45-minute delay in the setting time [32]. Researchers Poletanovic et al. [33] found that adding hemp fibres at a concentration of 0.5% to 1.0% lowered the concrete density 5%. The modulus of elasticity was decreased by 7% [34], while the flexural strength decreased by 31%, the splitting tensile strength decreased by 1%, the compressive strength decreased by 19%. The ideal fibre ratio, according to Kaplan and Bayraktar [35], is 2% for fibres that are 1 cm long. According to Li et al. [36], adding 20 mm length fibre in 0.36% by weight increased compression strength by 4%, flexural tensile strength by 9%, toughness index by 214%, and flexural toughness by 144%. Ghosn et al. [37] found that recycled aggregate concrete made with alkali and acetyl-treated hemp fibre performed better. While flexural and splitting tensile strengths remained the same, compressive strength and modulus of elasticity decreased.

There was a noticeable improvement in toughness, energy dissipation, thermal properties, and resistance to freeze-thaw cycles. Some researchers have found that hemp concrete has a low resistance to freeze-thaw cycles [38]. Although hemp fibres did not significantly slow the spread of cracks, they did not help prevent fires either [39]. Ziane et al. [40] found that mechanical properties are degraded when using hemp fibres at concentrations above 0.25% due to the uneven distribution of the fibres. Absorption and dynamic modulus are both improved. To counteract external sulphate attacks, concrete with 0.25% hemp fibres has been shown to have tensile strength on par with polypropylene fibres. Therefore, considering the literature gap, this paper thoroughly investigates the influence of HF addition into LFC on its mechanical properties such as compressive strength, flexural strength, splitting tensile strength and ultrasonic pulse velocity.

2. Methodology

2.1 Materials

2.1.1 Fine sand

Fine river sand that met the requirements of BS EN 12620 [41] was used. A finer sand material for LFC production was obtained by first drying the sand in the lab and then sieving it through a 1.18 mm sieve. Figure 1 displays the findings of a sieve analysis completed on the fine sand to determine its gradation. Based on the sieve analysis outcomes, the sand may qualify as fine sand (size smaller than the 1.18mm sieve).

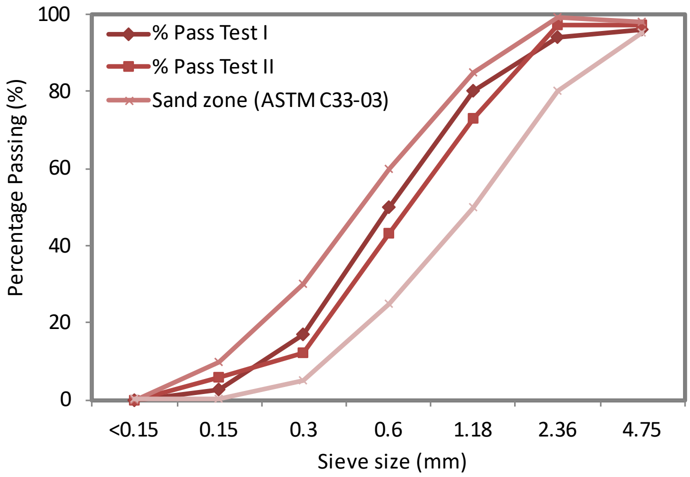


Fig. 1. Sand grading curve with upper and lower limits

2.1.2 Cement

Ordinary Portland Cement (OPC) utilized in this investigation was provided by YTL Cement. The cement chemical compositions are listed in Table 2. The cement meets the requirements set forth in BS EN 197-1 [42], which are the international standards for Portland cement.

Table 1
OPC chemical composition employed in this study

S/No.	Oxides	Composition (%)
1	Calcium Oxide	65.94
2	Ferric Oxide	2.65
3	Aluminium Oxide	5.83
4	Silicon dioxide	16.83
5	Magnesium Oxide	1.50
6	Potassium Oxide	0.86
7	Sulphur Oxide	2.77
8	Phosphorus Oxide	0.07
9	Loss of Ignition	-

2.1.3 Water

The mixture was made using pure, drinkable tap water. As a surfactant, a protein-based foaming agent made in Malaysia was used.

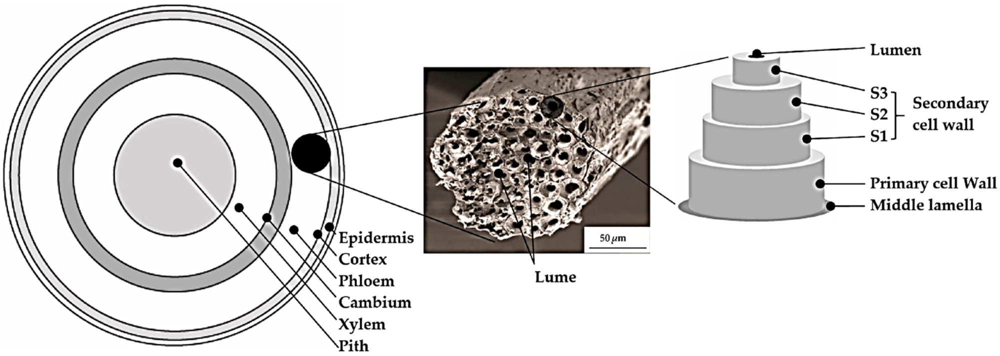
2.1.4 Hemp fibre

There were five different HF weight fractions used: 0.0%, 0.2%, 0.4%, 0.6%, and 0.8%. The HF was meticulously washed to eliminate any undesirable debris and impurities before being used as an additive in LFC. The HF used in this research is depicted in Figure 2. Table 2 displays the chemical composition and mechanical properties of HF employed in this investigation. Figure 3 demonstrates the structure of HF [43].

Fig. 2. Raw hemp fibre employed in this study

Table 2
Chemical composition and properties of single hemp fibre

Properties	Values
Cellulose	72.5%
Hemicellulose	20.8%
Lignin	5.8%
Wax	0.9%
Density	1.38 g/m^3
Diameter	358 µm
Elongation at break	3.8 %
Tensile strength	654 N/mm^2
Young modulus	85 Pa



(a) (b) (c)

Fig. 3. HF structure: (a) a section through the middle of the HF stem [44], (b) the morphology of the HF bundle [45], and (c) a simplified representation of the fundamental HF [6]

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-sand ratio was fixed at 1:1.5 while the water-cement ratio was retained 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

2.3 Experimental Setup
2.3.1 Compression test

The LFC cube sample with dimensions of 100 x 100 x 100 mm was used to test the compressive strength of the hardened concrete specimen. A general testing device with a 3000KN load capacity, the GOTECH GT-7001 BS 300, was used for the test in the concrete laboratory (Figure 4). According to BS EN 12390-Part 3 [47], a compressive strength test was performed with a load speed of 0.6 MPa/sec. For every curing period, three samples were tested.

Fig. 4. Apparatus for compression testing

2.3.2 Splitting tensile test

Test samples that were 100 mm in diameter and 200 mm in height were used for the splitting tensile strength test. The LFC specimens were assessed on a similar testing machine that was utilized to test the compressive strength. Also, the speed was kept at 0.55 MPa/sec. Three LFC specimens were taken and tested at each curing time. The test was done according to the BS EN 12390-Part 6 [48] standard.

Fig. 5. Setup for splitting tensile test

2.3.3 Flexural test

A 100 x 100 x 500 mm prism (beam) was used to test the flexural strength. The size of this beam was chosen because low-density LFC has a very low strength. As with compressive strength, three LFC specimens were assessed, and the average of the three results was recorded as flexural strength. The test was done at a rate of 0.35 KN/sec on an ELE flexural testing machine. In line with BS EN 12390-Part 5 [49], a three-point bending test was done. Figure 6 shows the setup of the three-point flexural test.

Fig. 6. Setup for three-point flexural test via ELE flexural testing machine

2.3.4 Ultrasonic pulse velocity test (UPV)

The UPV is a useful parameter for determining concrete properties using a non-destructive method. This test procedure entails sending wave pulses across LFC of a specific length dimension and in line with ASTM C 597-16 [50] standard. There are two transducers involved. At one surface of the test samples, one transducer transmits an electro-acoustical pulse in a longitudinal direction. The vibrating pulse is converted into an electrical signal by the second transducers on the opposite face, and the transit time T (s) of the pulse is measured by an electronic timing circuit, from which the velocity of the pulse V (m/s) is calculated with respect to the distance between the two transducers. The pulse velocity V is proportional to the elastic modulus and density of the concrete material. The test method is appropriate for determining the uniformity and relative quality of concrete. It also indicates the presence of air voids and cracks. It is used in the field as a non-destructive method of determining the severity of deterioration or cracking in a concrete structure.

3. Results

The findings from the laboratory investigation of LFC reinforced with various HF weight fractions are presented in this section. Axial compression test, flexural test, splitting tensile strength, and ultrasonic pulse velocity tests were used to evaluate the properties.

3.1 Compressive Strength

The axial compression strength values for FC densities of 500, 900, and 1300 kg/m^3 with various volume fractions of HF are depicted in Figure 7 while Figure 8 demonstrates the normalized compressive strength of these three densities. These normalized values (%) can be used to compare the rate of decrease in compressive strength at different weight fractions of HF. According to Figure 7 and Figure 8, LFC with a density of 500 kg/m^3 and 0.4% HF had a superior axial compressive strength of 1.76 N/mm^2 compared to other weight fractions. Besides, LFC with densities of 900 kg/m^3 and 1300 kg/m^3 and 0.6% HF produces ideal axial compressive strength compared to other HF weight fractions at 4.75 N/mm^2 and 7.45 N/mm^2 respectively.

It can be stated that the optimal method for achieving high axial compressive strength is to use HF between 04% to 0.6%. The bond between the cement matrix and the fibre is strengthened by the addition of HF to the base mix at this range. The experimental results show that the compressive strength of LFC is directly related to its density, with a decrease in density having an exponentially negative effect on the property [51]. Furthermore, low-density LFC generates reduced strength, whereas high-density FC generates good axial compressive strength, as seen in Figure 7. Since LFC is porous, its compressive strength is also strongly influenced by its density. The compressive quality was diminished because more foam was used at lower densities than was necessary [52]. This is because more foam agent generally results in the development of air voids.

The presence of pores, air voids, and matrix; all attributes of microstructure; usually has an impact on compressive strength, which is linked to density [53]. Longer testing ages resulted in greater LFC compressive strength, which was another factor that affected the compressive strength. Natural fibre HF can be used as an anti-micro cracking agent and improves the axial compressive quality of LFC. HF has a high failure strain, remarkable compatibility, and a strong particle bonding between the fibres and the matrix. It can also absorb energy [54].

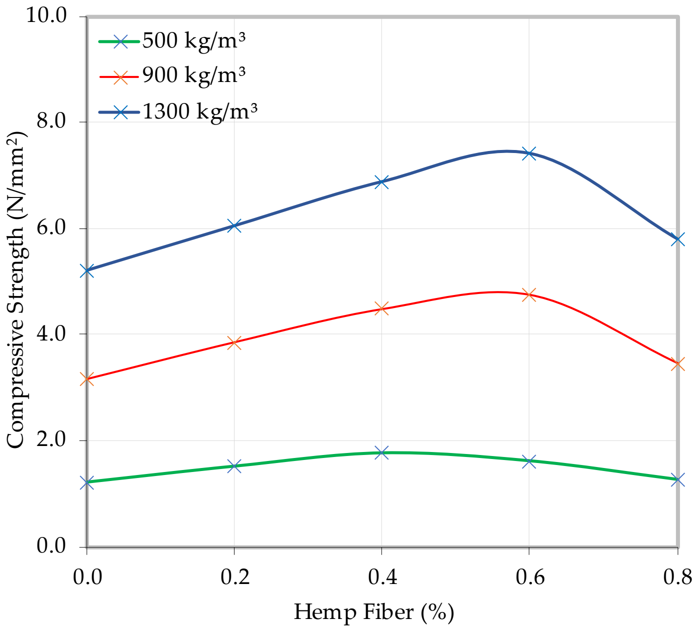


Fig. 7. Influence of HF weight fractions on compressive strength of LFC

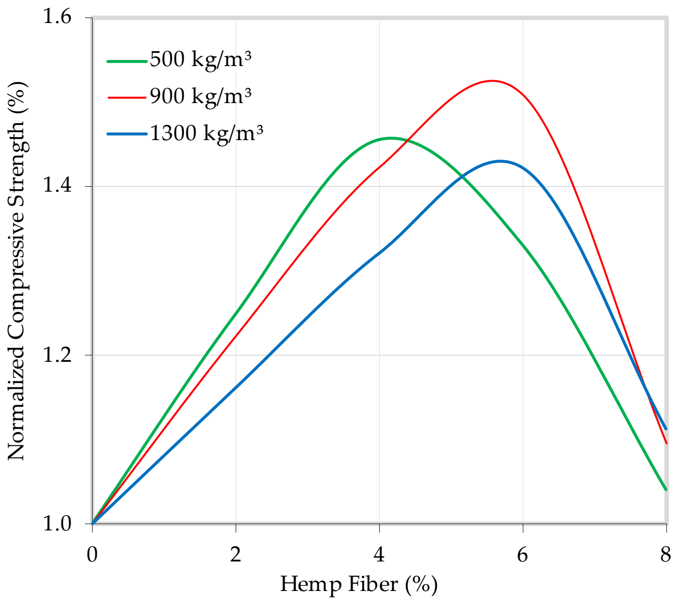


Fig. 8. Influence of HF weight fractions on normalized compressive strength of LFC

As shown in Figure 9, HF is a multi-filament fibre that improves the bonding between the parts of particles and lowers the void ratio to increase compressive strength. In most circumstances, the microstructure characteristics of air spaces, pores, and matrices influence the density-related compressive quality. Testing also showed that as the samples aged, the compressive quality of the LFC improved. The presence of HF would not cause the samples to break; rather, they would act as an anti-micro crack agent to prevent the cracks from spreading. Since HF has a greater modulus, a greater concentration of fibres calls for a greater force to be applied. It's also worth noting that HF, according to its biodegradable properties, can be used as a strengthening agent. In most cases, the high failure strain of HF results in a very compatible combination of fibres and matrix. In addition, an increase in blockages causes an increase in hardness as the fibre content grows. The shorter the fibres, the more securely they can anchor the dust [55]. The results showed that HF could soak up force because of the tight bonds it formed between the fibres and the matrix [56].

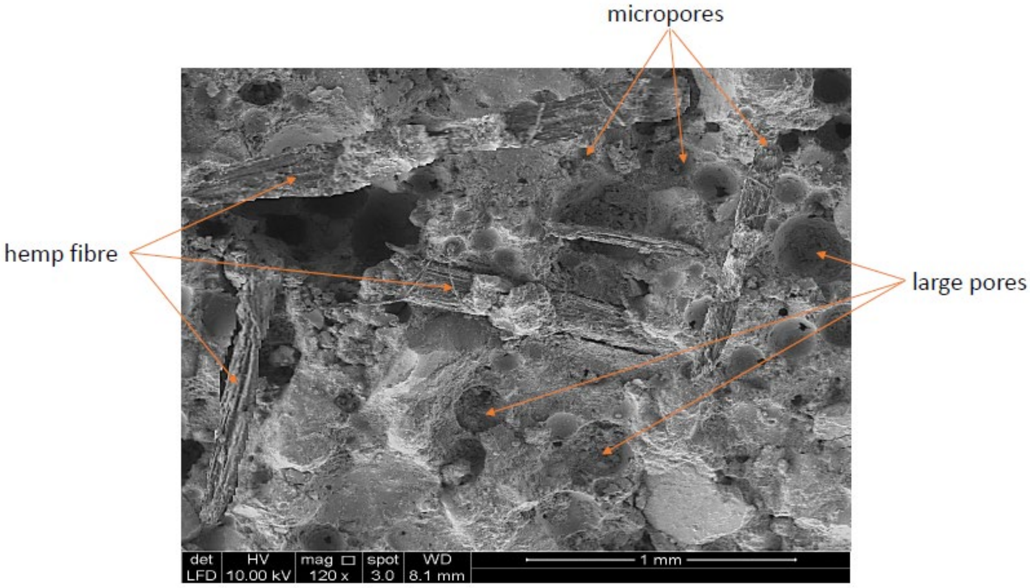


Fig. 9. Morphology of 1300 kg/m^3 LFC reinforced with 0.6% HF

3.2 Flexural Strength

The flexural strength values for LFC densities of 500, 900, and 1300 kg/m^3 with varying weight fractions of HF are shown in Figure 10 and Figure 11 shows its normalized flexural strength. LFC with a density of 500 kg/m^3 and 0.4% HF produces flexural strength of 0.37 N/mm^2, while LFC with a density of 900 kg/m^3 and 1300 kg/m^3 and a HF weight fraction of 0.6% has an optimal flexural strength result, with values of 1.05 N/mm^2 and 1.63 N/mm^2 respectively.

LFC's flexural strength declined dramatically after the HF volume fraction was above a particular threshold; for instance, the strength of 500 kg/m^3 density FC dropped once the HF volume fraction was above 0.4%. In addition, when HF was above 0.6%, the flexural strength of LFC with densities of 900 kg/m^3 and 1300 kg/m^3 dropped. This could be because the surrounding fibres were not completely saturated with matrix, which was a primary contributor to the composite's insufficientness. This tendency of weakening at specific HF volume fractions was therefore also observed in axial compressive strength.

The flexural strength to compressive strength ratio of LFC is higher than that of normal concrete, ranging between 0.20 and 0.40. The current study found that the flexural strength to compressive strength ratio of control LFC (without fibre) was 0.20. As a result, the addition of HF significantly improved the tensile strength to compressive strength ratio of LFC in the range of 0.20 to 0.28. HF's ability to transform the cement matrix from brittle to ductile elastic-plastic is one of its many benefits to the LFC mass reinforcement process [57].

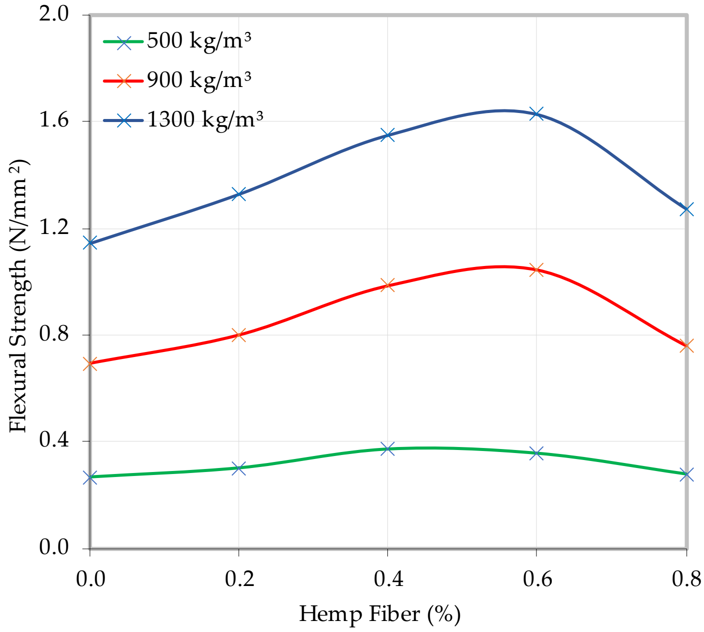


Fig. 10. Influence of HF weight fractions on flexural strength of LFC

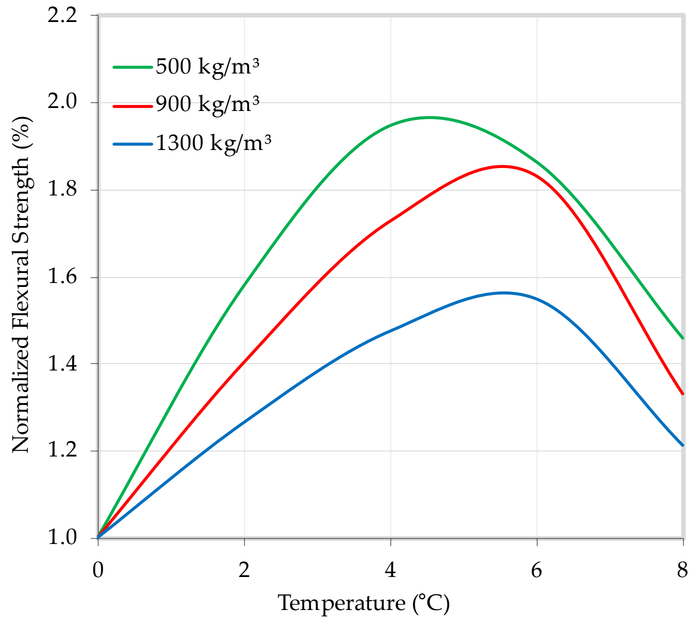


Fig. 11. Influence of HF weight fractions on normalized flexural strength of LFC

3.3 Splitting Tensile Strength

The splitting tensile strength for LFC densities of 500, 900, and 1300 kg/m^3 with various weight fractions of HF is shown in Figure 12 and Figure 13 demonstrates its normalized compressive strength. LFC with a density of 500 kg/m^3 and 0.4% HF had a superior splitting tensile strength of 0.24 N/mm^2 when compared to other weight fractions, as shown in Figures 12 and 13. In addition, LFC with densities of 900 kg/m^3 and 1300 kg/m^3 and inclusion of 0.6% HF produces ideal splitting tensile strength when compared to other HF weight fractions, with respective values of 0.71 N/mm^2 and

1.11 N/mm^2. It is possible to state that the utilisation of HF at concentrations ranging from 0.04% to 0.60% is the method that works best for achieving a high splitting tensile strength. When the weight fraction of HF exceeded the specified percentages, there was a significant decrease in the splitting tensile strength of the material. This was also true for the axial compressive strength and the flexural strength. In this particular scenario, the splitting tensile strength of FC with a density of 500 kg/m^3 decreased as the volume fraction of HF got closer to being greater than 0.4%. In addition, the splitting strength of FC with densities of 900 and 1300 kg/m^3 decreased when the volume fraction of HF was greater than 0.6%. It's possible that the tensile failure in the LFC was caused by the dislocation of molecules and atoms within the material, so this could be explained by that. On the other hand, the fibre that was included acted as a binder, which helped to maintain their cohesiveness [58]. In addition to this, HF makes it easier to bring the load through the shear stress at the interface, which results in an increase in the splitting tensile strength of the LFC. However, in order for these properties to be present, the HF and the matrix need to have strong bonds.

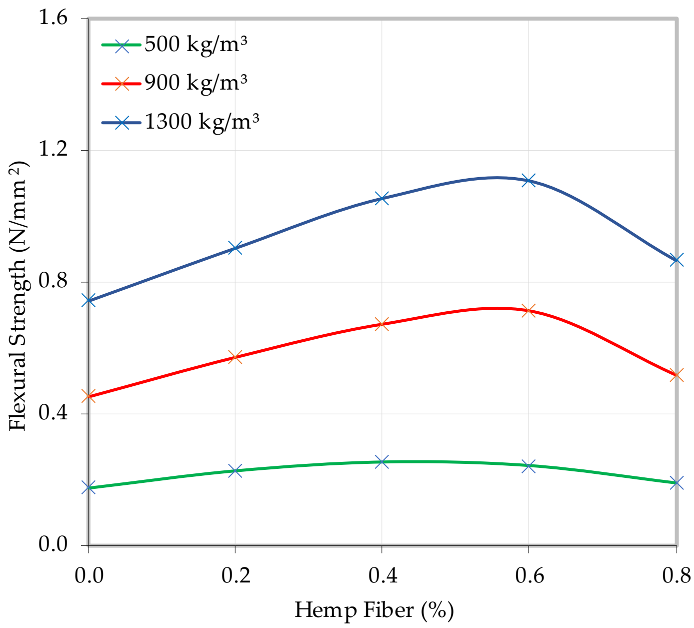


Fig. 12. Influence of HF weight fractions on splitting tensile strength of LFC

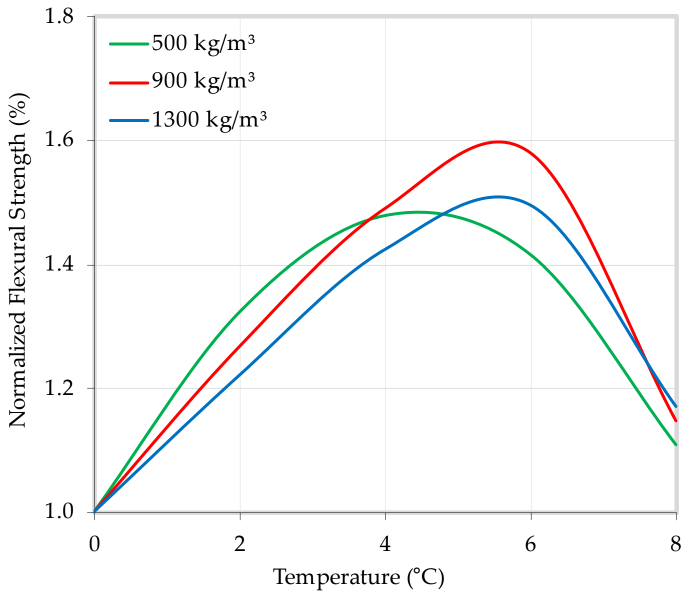


Fig. 13. Influence of HF weight fractions on normalized splitting tensile strength of LFC

3.4 Ultrasonic Pulse Velocity

The ultrasonic pulse velocity (UPV) method is one of the most well-known methods used to identify the properties of concrete's strength. Despite not being a precise instrument for evaluating concrete's pore structure, it can still show an initial forecast of the material's condition. More so, UPV is a non-destructive test that measures the time it takes for a pulse to travel a predetermined distance; therefore, it is safe to use on LFC samples. The purpose of the examination is to ascertain numerous factors, such as the homogeneity of the LFC, the presence of a crack, or the occurrence of any other flaw. High velocities indicate high-quality, uniform concrete, while low velocities may reveal concrete with multiple cracks or voids. The results of the ultrasonic pulse velocity (UPV) measurements are shown for all three densities in Figure 14. The ultrasonic pulse velocity (UPV) is higher in the LFC samples with the HF inclusion in the base mix compared to the control samples. Densities of 900 and 1300 kg/m^3 are more effective than a 500 kg/m^3 density. Ultrasonic pulse velocity (UPV) readings of 2688 m/s for 900kg/m^3 density and 3341 m/s for 1300 kg/m^3 density are significantly increased when 0.5% HF is added. Higher HF rates in the base mix of LFC for fibre may account for this. Also, as HF has a relatively high specific gravity of 0.89, its incorporation into the LFC base mix boosted the cementitious material's ultrasonic pulse velocity value. As a result, it was to be expected that the UPV of the 0% fibre would be lower than that of the 0.2%, 0.4%, 0.6% and 0.8% HF addition into LFC. Ultrasonic pulse velocity testing was greatly affected by the presence of voids and other heterogeneities. In this context, it's important to note that the density of LFC and its pliability influence the speed with which waves can travel. In contrast to fluids and gases, solids allow the pulse wave to go through them much more quickly [59]. On top of that, the pulse wave is extraordinarily nuanced and sensitive to fluctuations in the medium, whether they be downward or upward [60].

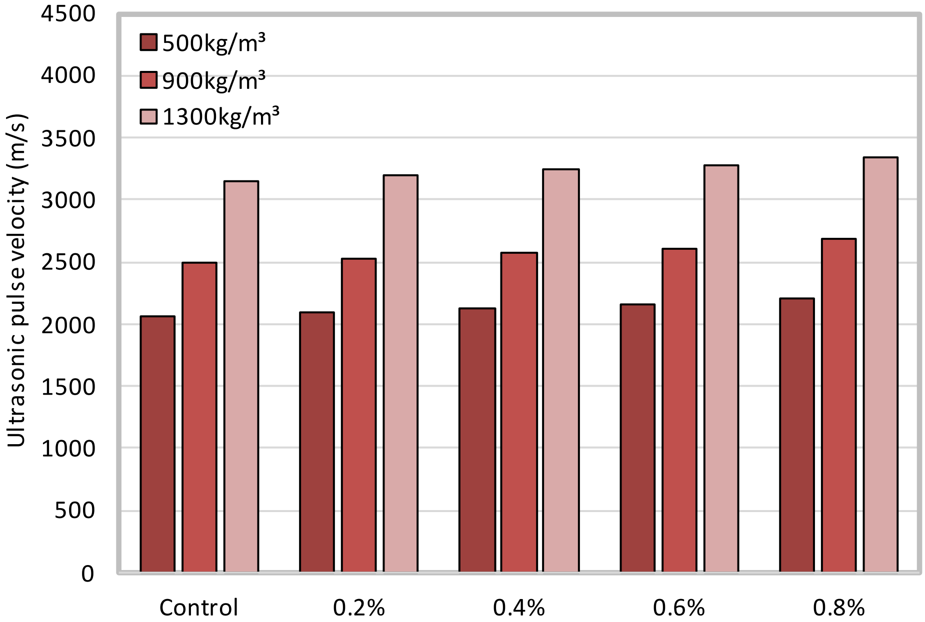


Fig. 14. Influence of HF weight fractions on ultrasonic pulse velocity of LFC

4. Conclusions

The purpose of this study was to conduct an experimental investigation into the effects on the mechanical properties of incorporating different weight fractions of hemp fibre (HF) into three different densities of LFC (500 kg/m^3, 900 kg/m^3, and 1300 kg/m^3). The effects of including HF at five distinct weight fractions, namely 0.0%, 0.2%, 0.4%, 0.6% and 0.8%, were analysed. According to the findings of the experiments, adding HF to LFC enhances the compressive strength, flexural strength, splitting tensile strength and ultrasonic pulse velocity. The mechanical properties of LFC, on the other hand, changed depending on the amount of HF that was added to it. In general, a weight fraction between 0.4% to 0.6% HF in LFC produced the best results. They were bound together by the addition of HF in LFC. The LFC's strength is increased by HF's ability to bring the load through shear stress at the interface. These characteristics must, however, be present for HF and matrix to have a strong bond.

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