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Thermal conductivity, microstructure and hardened characteristics of foamed concrete composite reinforced with raffia fiber

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ABSTRACT

Researchers have become enthralled with using natural fiber, which is a waste product from industrial processes, as an additive in cement-based materials. This is due to the fact that natural fiber is inexpensive, has principal carbon neutrality, and is obtainable in large quantities. Additionally, this fiber is made from a renewable resource. Hence it has a low density and is amenable to undergoing chemical alteration. The idea of this investigation is to discover the reactivity of raffia (*raphia vinifera*) fiber (RF) in low-density foamed concrete (FC). FC density of 950 kg/m^3 was utilized. Workability, density, thermal conductivity, SEM analysis, compressive, bending, and tensile strengths were the parameters that were quantified and assessed. Based on the outcomes, it has been determined that the mechanical properties and thermal conductivity of FC-RF composites may be enhanced by using RF with an ideal reinforcing fraction content of 6%. Slump flow gradually decreased from 2% to 8% RF fraction content. The lowest slump flow was achieved by adding RF to the FC mixture at a fraction content of 8%. The density of FC-RF composites shows a developing tendency, likely because of the RF's comparatively high specific gravity and increasing fraction content. The addition of RF to FC considerably enhances the material's compressive, bending, and tensile strength. The optimal strength characteristics emerged

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when 6% RF was added to FC. Besides, the FC thermal conductivity improves as the weight percent of RF increases because the porous structure of FC with RF allows it to absorb heat.

1. Introduction

Foamed concrete (FC) is an eminent building material that facilitates the design and construction of lightweight constructions [1]. As a result of the elimination of coarse material from FC combinations, it is possible to create highly workable mixtures [2,3]. FC possesses a great extent of fluidity, which is achieved by combining a mortar slurry, including cement with a prefabricated foam [4,5]. Such concrete combinations can be advantageous for construction in places with difficult soil, where the stress on building foundations is often minimal [6–10]. However, environmental deterioration caused by the emission of toxic compounds and sustainability concerns related to the discovery of natural aggregates might impede the growth of FC technology [11–14]. Utilizing natural fibers to improve the characteristics of low-fluorinated compounds in concrete manufacturing has yielded many possibilities [15].

Depending on the optimization of the mixture, FC can be utilized as a non-load-bearing component, a semi-structural component, or a structural component in applications such as wall panels, partitions, and lightweight blocks [16–19]. The unit weight of FC can substantially influence the material's attributes [20]. FC has density differs from 350 to 1850 kg/m^3 [21,22]. In addition to being fire-resistant, FC is thermally and acoustically insulating, making it ideal for floor and roof insulation and void filling. Additionally, it can be used to reinstate trenches. Besides, FC is also suitable for pipeline annular filling, precast blocks, prefabricated panels, cast-in-place walling, insulation roof screeds, insulation boards and hollow blocks [23,24].

It is important to note that FC has encountered several impediments in its development as a material for building construction, the most notable of which are brittleness, lower bending and tensile strengths, high drying shrinkage, high water absorption capacity and a poor capacity to control fractures. In addition, brittleness has been a major issue [25–28]. A lack of mechanical strength and durability limits the use of FC to applications not involving structural load-bearing construction [29]. Concerns related to FC's low fracture toughness are alleviated when the material is strengthened with polymer fibers derived from various sources [30–34]. As a result of evenly distributing natural and synthetic fibers throughout a fiber composite, a weak matrix can be significantly strengthened [35–38]. Due to this, FC behaves more like a composite material than an unreinforced FC [39,40].

It should be pointed out that synthetic fibers are the most often used forms of fiber to strengthen concrete. Nevertheless, natural plant fibers are becoming increasingly popular [41]. There has been a growing concern regarding materials reinforced with natural plant fibers. Natural plant fibers are essential since they are sustainable, renewable, and biodegradable [42–45]. Due to the larger environmental impact of synthetic fibers, these natural plant fibers could be used in their place. Cement-based composites reinforced with natural fibers like coconut, jute, flax, hemp, sisal, and leaf fibers have been the subject of several scientific investigations. Consistent with the findings when polymer fibers are employed as reinforcement, these investigations have found that fiber reinforcement increases the durability of cement-based compounds and enhances the tensile, bending, impact, and compressive strengths [46–49]. Due to the alkalinity of the cementitious matrix, natural fibers degrade, and their elasticity and deformation ability is reduced. When exposed to extremely alkaline conditions, natural fiber cell walls can degrade due to minimal lignin and hemicellulose stability [50]. It is of the utmost importance to determine the fraction contents of fibers, binder, filler, water, and surfactant that are included inside the mixture. Natural fibers are superior to synthetic fibres in several respects, including their ability to decompose naturally, low density, and their resistance to melting at high temperatures [51]. Cementitious materials may be strengthened with the presence of natural fibers, which are especially useful in the production and development of construction materials. Several researchers put considerable effort into determining the FC durability properties that were strengthened with natural and synthetic fibers. Othuman Mydin et al. [52] executed research on the application of coir fiber in FC. They found that inserting coir fiber in FC diminishes diffusivity and conductivity while increasing the compounds' heat capacity.

Awang and Ahmad [53] started investigating the differences between natural and synthetic fibers when the fraction content was 0.25% and 0.40%. They used steel, glass, kenaf, oil palm, and polypropylene fibers. In terms of thermal qualities, they discovered that polypropylene fiber performed the best, followed by kenaf fiber, oil palm fiber, glass fiber, and finally, steel fiber in that order. According to the research findings, there was a correlation between an increase in the fiber volume percentage and an enhancement in the thermal attributes of FC. According to Raj et al. [54], FC reconstituted with coir fibers and polyvinyl alcohol fibers could improve the effectiveness of FC. It has been observed that coir fiber-reinforced FC outperformed coir fiber-reinforced FC reinforced with polyvinyl alcohol fiber, which outperformed FC reinforced with a hybrid composite of coir and polyvinyl alcohol fibers.

A limited number of research were done to establish the effects of adding RF to concrete. Akpokodje et al. [55] explored the impact of RF inclusion on the strength properties of concrete. According to the investigation findings, RF volume fraction added to concrete significantly impacted the concrete strength properties. The flexural strength of the concrete reduced from 5.6 MPa in the control sample to 2.2 MPa when reinforced with a 3% volume fraction of RF (30 mm in length). Additionally, the flexural modulus diminished from 920 MPa in the control sample to 153 MPa in the reinforced specimen. Concrete absorbs more water as the RF volume fraction and RF length increase. The water absorption rate was 8% for the control specimen (unreinforced) but rocketed to 13% when RF was increased to 3%. In light of the study's findings, RF could be used as low-volume reinforcement in construction components without significant moisture exposure. The material's ductility will increase, despite the decrease in flexural strength.

Similarly, In their study of mortar strength, Aho and Ndububa [56] assessed its compressive and flexural strengths reinforced with 2%, 4%, 6%, and 8% RF volume fractions. The specimens' flexural strength increased as the RF volume fraction increased, whereas their compressive strength decreased. The average flexural strengths were 4.2 MPa and 4.3 MPa for both mix ratios and curing durations. There was a decrease in density when there was a greater proportion of RF in the mortar. The results are similar to those of other studies conducted on concrete reinforced with rice husk, coconut fiber and sawdust. Esegbuyota et al. [57] also researched the influence of numerous RF volume fractions on solid concrete block compressive strength. The blocks were 120 mm wide, 120 mm high, and 100 mm in size, with RF, added in volume fractions of 1%, 2%, and 3%. According to the results of this study, block compressive strength and sorptivity were not significantly affected by RF fraction content.

Hence, this research was driven by a dearth of knowledge regarding FC reinforced with natural fiber. FC might be employed as a lightweight construction material for low-rise construction. Furthermore, no single research has been performed on the employment of RF to reinforce cement-based materials, notably FC, compared to studies on other types of natural plant fibers. RF is an appealing alternative for value-added applications in concrete. As a cement composite reinforcement, RF has economic potential. The utilization of RF in cement composites will offer several advantages, some related to mechanical and thermal properties. Another advantage of the material is its low cost [58]. RF is an excellent example of readily available natural fiber.

1.1. *Research significance*

So far, little research has been conducted on the influence of natural fiber on FC properties. In particular, RF utilization in FC has not been studied yet. Some studies have been conducted on the addition of other natural fibers to FC. However, there are still some uncertainties regarding the mechanism by which natural fibers might change FC properties. It is important to clarify this ambiguity. In light of this, it is essential to investigate the effects of RF modification on the properties of FC. Enhanced mechanical properties of the material are verified by the microstructure analysis of the material using a Scanning Electron Microscope (SEM).

1.2. *Research objectives*

This investigation aims to address this need by conducting a planned inquiry to determine how RF affects FC properties. This study is intended to determine the strength, thermal and durability properties of FC influenced by the addition of RF. The SEM study has confirmed that the FC properties have been enhanced. Workability, bulk density, thermal conductivity, SEM analysis, compressive, bending, and tensile strength of the material were the parameters evaluated. The study is further extended to investigate the relationship between FC mechanical properties. Establishing relationships is necessary for several reasons, including a reduction in research and development costs and a reduction of time required to complete projects.

2. Materials and methods

2.1. *Materials*

Five main ingredients were required to produce FC specimens, including ordinary Portland cement as a binder, fine aggregate as a filler, water and a protein foaming agent as a surfactant. RF was employed as an additive in the FC base mix.

2.1.1. *Binder*

The mixtures were prepared using Portland cement (OPC) according to the specifications of BS197-1 [59]. The strength grade of ordinary Portland cement is 53.4 MPa, the setting time is 45 min, and the soundness is 10 mm. In Table 1, OPC's physicochemical properties are summarized.

2.1.2. *Filler*

The local distributor supplied Fine river sand as a filler in this study. Fine river sand was chosen because its cohesiveness, large surface area, and gradation properties contribute significantly to the workability of FC. Depending on the specific surface area, particles of decreasing size should gradually reduce their workability. Additionally, fine filler assists in compacting FC mixtures. A physical property of sand can be found in Table 2.

2.1.3. *Water*

As per BS-3148 [60], potable water is employed to mix and cure the FC, which is free of impurities. The pH ranges from 6.5 to 8.0. The pH ranges from 6.5 to 8.0.

Table 1 – OPC physicochemical properties.

Elements	Percentage (%)
Calcium oxide	64.63
Silicon dioxide	16.02
Aluminium oxide	4.51
Magnesium oxide	1.19
Sulfur trioxide	3.88
Ferric oxide	6.91
Sodium oxide	0.52
Unsolvable excess	1.06
LOI	1.28
Initial and final setting time	175/220
Surface area (cm^2/g)	3320
Specific gravity	3.11
Compressive Strength (MPa)	53.4

Table 2 – Physical properties of sand.

Elements	Percentage (%)
Oven dry specific gravity	2.53
Saturated surface dry specific gravity	2.59
Cu	4.24
Cc	1.46
D_{60} (mm)	0.85
D_{30} (mm)	0.50
D_{10} (mm)	0.20
Absorption (%)	2.24

Table 3 – Properties of Noraite PA-1 foaming agent.

Components	Properties
Density (g/cm^3)	1.21
pH	6.1
Presence	Brown
Specific gravity	1.07
Molar mass	262 g/mol
Concentration proportion	1:34

2.1.4. *Surfactant*

Protein-based surfactant known as Noraite PA-1 was implemented. The surfactant was mixed up with water at a ratio of one part foaming agent to thirty-four parts water. Foam solutions were capable of achieving a density of 63.0 ± 10.0 kg/m^3 after being aerated. It should be brought to your attention that the pre-foaming process was utilized to produce the foam by using a foam generator TM-1. Table 3 summarizes the properties of Noraite PA-1 surfactant.

2.1.5. *Raffia fiber (RF)*

The RF was supplied by Shantou Co. Ltd., China. Fig. 1 shows the RF used in this research as an additive in FC. The length of the chopped RF was approximately 15–18 mm. The raffia fiber was cleaned correctly in distilled water and dried under the sun. Tables 4 and 5 display the mechanical properties and chemical compositions of RF. From Table 4, we can see that RF has an excellent elongation at break and tensile modulus.

2.2. *Mix design*

In this investigation, five FC mixtures were fabricated: RF0%, RF2%, RF4%, RF6% and RF8% mixtures. The mix design for FC containing 2–8% of treated SBF was denoted by the notation RF2%-RF8%. In addition, a control FC (RF0%) was also produced so that the results could be compared. The ratio of cement to sand used was 1:1.5 across the board for all the mixtures. The proportion of water to cement was predetermined to be 0.45. By keeping the fresh density at around 1084 ± 20 kg/m^3, it was possible to control the density of the FC such that it fell within the range of 950 ± 20 kg/m^3. The FC mix design is shown in Table 6, which includes various fraction contents of RF.

2.3. *Tests methods*

2.3.1. *Compressive strength test*

A 100 mm cube was evaluated for its compressive strength. The specimens were evaluated based on BS 12390-3 [61] standards. Fig. 2 visualized the setup for the compression test. The force applied to the two sides of the FC specimen, and the maximum compression it can sustain prior to failure are recorded. For each curing period, three cubes were examined. A calculation was then made to ascertain the average strength of the three cubes.

2.3.2. *Bending strength test*

Tests were conducted on 100 × 100 × 500 mm FC prisms to determine their bending strength. The BS 12390-5 [62] specifications were adhered to when conducting the tests on the FC prisms. The loading assembly used to determine the bending strength of the sample is displayed in Fig. 3. The bending test setup is indicated in Fig. 4. The bending strength of each FC mix and curing period (7, 28 and 56 days) was evaluated using three different prisms.

2.3.3. *Tensile test*

This experiment was conducted per BS 12390-6 [63] standard. For each mix, three identical samples were made into cylinders with a 100 mm diameter and a 200 mm height. Fig. 5 demonstrates the setup for the tensile strength test. These were used to test the samples at 7, 28, and 56 days.

2.3.4. *Thermal properties test*

To determine the FC thermal properties with varying fraction contents of SBF, guarded-hot-plate apparatus was implemented in line with ASTM C177 [64]. As shown in Fig. 6, the hot disk thermal analyzer measured thermal conductivity, heat capacity, and diffusivity. The 30 mm × 30 mm x 10 mm FC sample size was evaluated. Two composite discs were layered above the sensor, and two more were stacked underneath it, doubling the sample's thickness. The Hot Guarded Plate apparatus is used to measure steady-state heat flow through the foamed concrete specimens. The hot plate is sandwiched between two foamed concrete samples, with the samples' thicknesses, areas, and densities as identical as possible. The hot plate is embedded in the guard. The electric heater generates a fixed rate of heat flow. Because the hot plate and the guard are always at the same temperature, no heat transfer occurs between them. The heat source nor the sample dissipates heat to the surrounding area. The heat produced by the plate is only transferred through the sample. Thus, unidirectional heat flow is generated. After reaching a steady state, the heating and cooling plates have stable temperatures. Then, the thermocouples measure the resulting temperature difference over the sample. The thermal conductivity was calculated by using the heat input, the thickness of the sample, the area of the heating plate, and the temperature difference through the sample.

The Fourier heat flow equation is used to calculate the specimen's average thermal conductivity, k:

$$\textit{Thermal conductivity}, k = \frac{W}{A}\left[1 \times \frac{d}{\Delta T}\right] \quad (1)$$

Where W is the main heater's electrical power input, A is the surface area, T is the temperature difference, and d is the depth of the FC specimen.

Fig. 1 – RF employed in this study (a) raw RF, (b) cleaned and dried RF.

3. Results and discussion

3.1. Workability

Fig. 7 reveals the slump flow results of FC-RF different mixtures. The FC-RF composite slump flow diameter mixtures ranged from 215 to 240 mm. The control FC (RF0%) attained the highest slump flow readings. The control mix recorded a slump flow of 248 mm. As the fiber was attached to the FC base mix, the slump flow gradually decreased when the RF fraction content increased from 2% to 8%. The smallest slump flow was achieved for the FC mix by inserting an 8% fraction content of RF. The value logged was 219 mm. The addition of RF increases the flow resistance and decreases flowability by expanding the intertwining and resistance between the RF and filler, which results in a significant reduction in slump flow diameter [65]. It was discovered that as the RF fraction content increased, the workability of the mixture decreased. This is probably because there was a more fraction content of RF, and they have a higher internal resistance in fresh FC mixtures [66]. Fig. 8 illustrates the measurement of the workability of FC-RF varying mixes. A higher restriction effect is brought about by stiffer mixtures, as shown in Fig. 8(c), which have a higher fraction of RF. The random distribution of the RF in the FC caused a collective filler barrier to build, which decreased the workability. The rise in RF in FC reduced the mixture's capacity to deform. The RF was placed around the mortar slurry in the freshly formed concrete, and they had a tendency to produce an RF-filler interlock, which prevented the filler (fine sand) from shifting [67]. Since the RF distribution was not homogenous, the FC either spread in a manner that was not homogenous or failed to correctly form a circular pattern, as presented in Fig. 8(b) and (c). It had a less circular form on the FC spread, which resulted in a smaller spread diameter. A greater RF fraction content caused a greater restriction on the FC flow, leading to a higher spread diameter loss.

Table 4 – RF engineering properties.

Component	Value
Tensile strength (MPa)	101–145
Elongation at break (%)	5.8–6.1
Specific gravity	0.89–0.91
Young's modulus (MPa)	12,125–12755
Average Diameter (mm)	1.05
Average length (mm)	18
Aspect ratio (L/D)	17.14
Thickness (um)	35–38

3.2. Dry density

The FC dry density is illustrated in Fig. 9 for numerous RF fraction contents. Generally, it can be observed from Fig. 9 that there was a slight trend of increased density with RF fraction content increment. However, the difference was not significant. In that order, the control FC mixture recorded the lowest density value of 951, 955 and 959 kg/m3 on days 7, 28 and 56. While the highest recorded density was accomplished with the inclusion of an 8% RF. The values were 968, 972 and 977 kg/m^3 on days 7, 28 and 56, respectively. When FC was combined with higher fraction contents of RF, self-compaction was more difficult to be achieved, leading to a decreased density of the composite sample when matched to the control sample due to the porous nature of FC. Overall, the densities attained for entire FC-RF mixtures fall within the permitted range of ± 50 kg/m^3. On day 28, the deviations in final dry densities from the desired density were ± 5, ± 9, ± 14, ± 18 and $\pm$ 22 kg/m^3 for fraction contents of RF0%, RF2%, RF4%, RF6% and RF8%, correspondingly. The final density will have a significant impact on FC's attributes. Therefore, it is crucial to achieve the

Table 5 – RF chemical composition.

Constituents	Value
Lignin (%)	26.31
Cellulose (%)	56.49
Hemicellulose (%)	15.77
Extractives (%)	1.43

desired FC density accurately and ensure it is within the previously indicated permitted range.

3.3. *Compressive strength*

Compressive strength results with various RF fraction contents are depicted in Fig. 10. The compressive strength of FC was investigated on days 7, 28 and 56. Due to the hydration process, the FC compressive strength progressively increased with curing age. When the curing period was lengthened from 7 to 28 days, the development rate of compressive strength increased significantly with the addition of RF. On day 28, the control specimen achieved compressive strengths of 3.17 MPa. Adding 6% RF to FC resulted in the highest compressive strength. On day 28, the measured compressive strength was 4.86 MPa. The percentage of strength enhancement was about 53.3% compared to the control specimen. The FC compressive strengths increased by an average of 15.7% and 30.5% on days 28 and 56, respectively, compared to day 7. According to Serri et al. [68], the use of fibers has been proven to enhance the compressive strength of cementitious fiber cement by preventing crack propagation within the cementitious fiber cement. Compared to the control FC with the same density, the FC containing coir fiber increased its compressive strength by 46%. Mahzabin et al. [69] concluded that the perfect bond between the natural fibers (kenaf) and the FC cement matrix was important in compressive strength development. RF's high water retention capacity can be attributed to this improvement in mechanical performance because it absorbs water during FC mixing and releases it gradually in the surrounding area. It aids in hydrating the particles of cement that aren't hydrated [70,71]. A dispersion of RF within the matrix is necessary for this internal curing agent to function effectively [72]. As a result of the high interface between the FC and RF-based matrix, the fiber may also help improve the transfer of stress.

At an 8% fraction content of RF in FC, the compressive strength dropped dramatically to 3.00 MPa on day 28, which was lower than the control sample. This may be because balls are easily formed when the RF fraction content exceeds the crucial fiber fraction content. Since hydrated cement products have higher surface energy, they tend to cluster closer to RF when uniformly distributed in FC at the correct proportion. RF properties help reduce specified tensile stress and improve fracture resistance by enticing tensile energy at the RF-FC matrix interface in response to FC contractions [73]. After achieving their optimal compressive strength with a 6% fraction content of RF, FC-RF composites could not resist the increasing stresses applied to the specimen reinforced with a higher fraction content of RF. The micro-spaces between the fiber increase when the RF fraction content exceeds 6%, resulting in RF agglomeration that results in inadequate load distribution and failure. In turn, this results in a reduction in the bond strength between the FC cementitious matrix and fibers, reducing the compressive strength of FC-RF composites. Furthermore, the agglomeration resulted in defects and voids between fibers and the matrix. For instance, at an RF fraction content of 8%, there was insufficient interfacial interaction between the RF and matrix material. Agglomeration also disrupted the concentration of stress.

3.4. *Bending strength*

The bending strength findings of FC-RF composites at various RF fraction contents are shown in Fig. 11. The bending test was executed for each mixture on days 7, 28, and 56. The findings revealed that FC bending strength gradually increased with age. At 7 and 28 days, the bending strength achieved roughly 31.9% and 13.1% of the 56 days strength, respectively. At 56 days, the bending strength was between 0.7 and 1.4 N/mm^3. When the FC curing period was increased from 7 to 28 days, there was a discernible improvement in the bending strength of 16.6% on average. On the other hand, there was a moderate rise of 13.1% on average between the ages of 28 and 56 days. FC-RF composite mixtures with 6% RF inclusion exhibited optimal bending strength. Bending strengths measured on day 28 with 6% of RF was 1.26 MPa. In contrast to the control FC specimens, which obtained a bending strength of 0.61 MPa, the observed result was 107% greater. The results obtained in this study are in line with the findings by Odera et al. [74]. They found that reinforcing cement mortar with RF increases its flexural strength by more than twice. Additionally, they found that RF-reinforced fiber-mortar roof tiles performed reasonably well. RF was recommended as an ideal ceiling and roofing material for low-cost homes as a cost-effective alternative to more expensive fibrous materials. Aho & Ndububa [56] investigated the flexural strength of cement mortar stabilized with RF. Their study revealed that flexural strength significantly improved with increased RF proportion. As a result of their findings, mortar stabilized with RF is suitable for use in civil engineering work as a light load-bearing member. The bending strength of FC significantly decreased at an 8%

Table 6 – Mix design of FC.

Specimen	Density (kg/m^3)	RF (%)	RF (kg/m^3)	Binder (kg/m^3)	Filler (kg/m^3)	Water (kg/m^3)	Foam (kg/m^3)
RF0%	950	0	–	357	535	161	32
RF2%	950	2	21.7	357	535	161	32
RF4%	950	4	43.4	357	535	161	32
RF6%	950	6	65.1	357	535	161	32
RF8%	950	8	86.7	357	535	161	32

Fig. 2 – Compression test was achieved on a 100 × 100 × 100 mm sample.

Fig. 4 – The bending test was executed on a 100 × 100 × 500 mm prism.

fraction content of RF, as was seen in the compressive strength result. An interfacial transition zone is often formed between RF and foam cement slurry [75]. When RF is added in excess, it will cause an increase in the ITZ zone of FC, resulting in a decrease in bending strength. It will also be difficult to scatter the RF uniformly because of the high fraction content of RF in the cementitious matrix, which would produce fiber agglomeration. The presence of RF fully reverses the bonding intensity inside the FC matrix, resulting in the progressive expulsion of the RF [76]. Even if the matrix collapses, the basic structure may remain intact.

3.5. *Tensile strength*

FC-RF composite mixture tensile strength test findings on 7, 28, and 56 days for various fraction contents of RF are shown in Fig. 12. The results indicated that the tensile strength steadily rose with an increase in the curing age and had a trend that was comparable to that of the compressive and flexural strengths. Tensile strength at 7 and 28 days was approximately 30.9% and 12.9% of the strength at 56 days, respectively. Tensile strength ranged between 0.43 and 0.98 N/mm^3 at 56 days. When the FC curing period was extended from 7 to 28 days, there was an average 15.9% improvement in bending strength. Between the ages of 28 and 56 days, however, there was a moderate rise of 13.0% on average. The tensile findings strongly suggest that adding RF to FC mixes improves the overall tensile strength improvement. On day 28, the control FC specimen's tensile strength was 0.38 MPa. The FC mixture's greatest tensile strength was accomplished with the insertion of 6% RF. On day 28, the tensile strength was 0.88 MPa. In comparison to the control FC sample, there was an approximate 132% improvement in tensile strength. When RF is added to FC mixes, it assures that it will act as a fastener when the FC develops microcracks. Therefore, when the direct boundary strain is attained, the matrix elastic modulus does not instantly decrease to zero. When fractures first appear, the RF will absorb all strain before gradually transmitting it to the binder matrix. At 8% fraction content of RF, however, the tensile strength of FC decreased substantially. If a substantial proportion of RF is in FC, the composites will exhibit an uneven fiber distribution [77]. The loose fibrils on the rugged surface augment the surface area required for

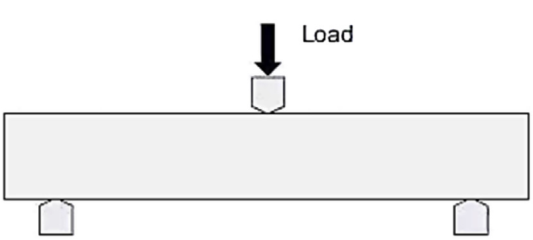


Fig. 3 – Diagram of the three-point bending test arrangement.

Fig. 5 – The tensile test was accomplished on a 100 mm in diameter x 200 mm in height prism.

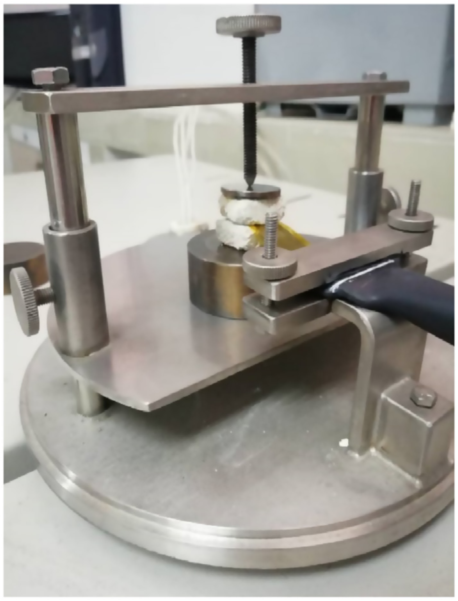


Fig. 6 – Setup for a thermal conductivity test.

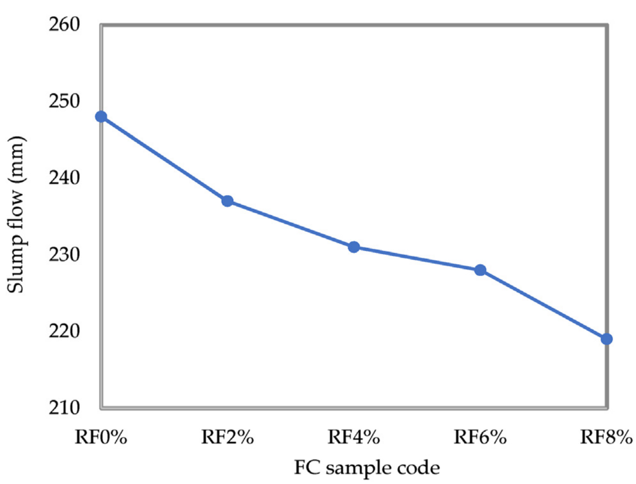


Fig. 7 – Slump flow of FC-RF composites.

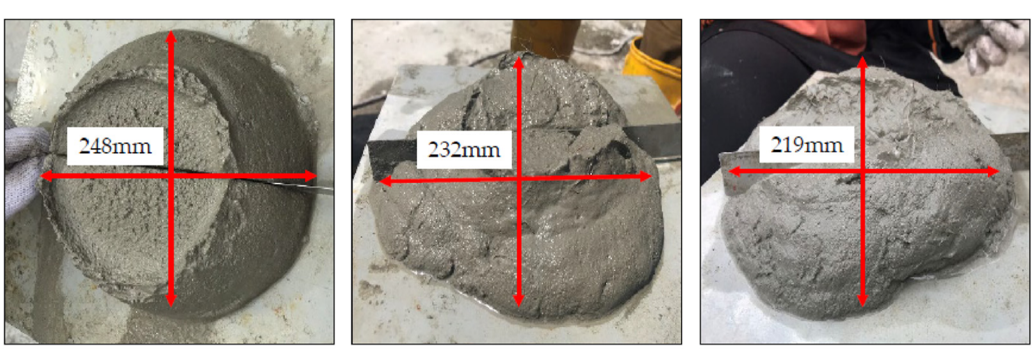
effective interfacial bonding between the RF surface and binder matrix, as well as mechanical intertwining and bonding response.

3.6. *Microstructure analysis*

The microstructures of control FC and FC-RF composites were investigated via scanning electron microscopy (SEM). Fig. 13 compares the SEM micrographs of 950 kg/m^3 densities control FC with the specimen with the addition of a 6% fraction content of RF. It is obvious that the control FC specimen has larger voids, as shown in Fig. 13(a). The FC pore structure includes gel pores, micropores, and air voids. As FC is self-flowing and self-compacting, it is unlikely to trap air since it contains no coarse material. The size of voids has been reduced by adding 6% RF to FC, as seen in Fig. 13(b). The binder matrix and RF were interracially bonded when the RF was embedded in the cementitious matrix. Fibrillated processes and interfacial adhesion usually result in a dense matrix around RF. In FC, the voids in the matrix produce microporous surfaces, which reduce interfacial bonding. Due to this, the presence of RF in FC helps bridge force-crossing cracks and prevent microcracks resulting from these cracks from forming. Moreover, incorporating natural cellulose fiber into cementitious matrixes increases the composite compaction density and diminishes the growth and development of cracks owing to their alteration of composite interface characteristics and pore arrangement [78] and their function as stress transference bridges when cracking occurs [79]. In contrast to the composite reinforced with 6% RF (Fig. 13(b)), the unreinforced composite exhibits a low-compaction microstructure and many cracks and pores. By introducing and dispersing fibers into the base matrix, voids are filled. Therefore, the wall effect is reduced when the presence of fine particles (sand) establishes further cavities. Cementitious composites that are reinforced with cellulose fiber have been reported to exhibit similar behaviour [42].

3.7. *Relationships between the strength's properties*

Figs. 14–16 illustrate the relationships between compressive-bending strengths, tensile-compressive strengths, and bending-tensile strengths. These three figures demonstrate a



(a) FC-RF0% (b) FC-RF4% (c) FC-RF8%

Fig. 8 – Workability of FC with varying fraction contents of RF.

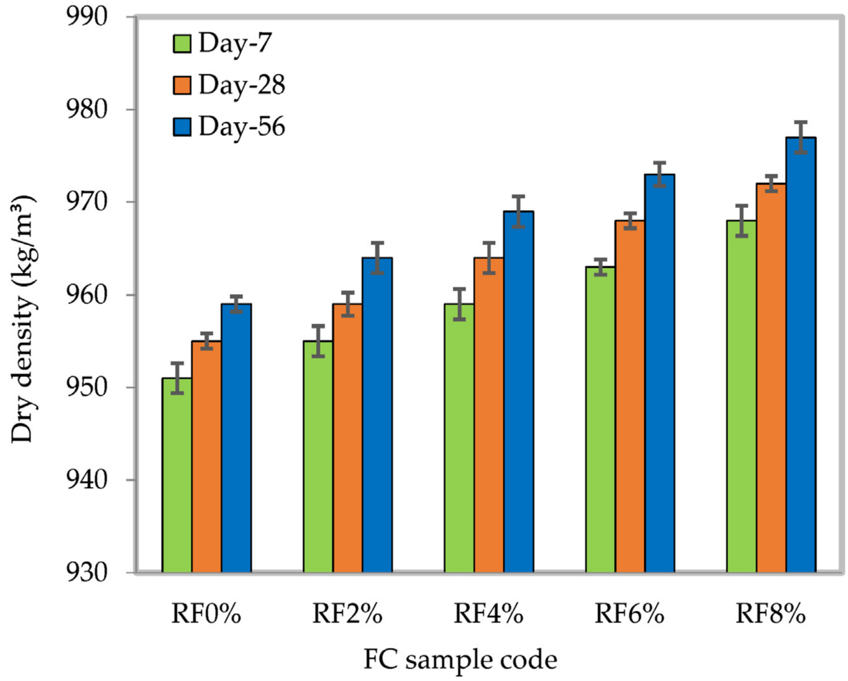


Fig. 9 – Dry density of FC-RF composites.

remarkable correlation between the strength characteristics of FC reinforced with RF based on the data distribution. R-squared values of 0.94 for compressive-bending strengths, 0.95 for compressive-tensile strengths, and 0.99 for tensile-bending strengths indicate a significant linear relationship. The finding of the correlation between the results is very important to find the formula for a strong relationship with high R^2. A quantitative characterization relationship between the strength parameters of the material can be obtained, which further enriches the development of FC theory. On the other hand, most building codes present formulas for finding concrete strengths theoretically, such as ACI. As well as, there were many researchers focused on using theoretical formulations to find the strengths and compare the outcomes from the practical and theoretical formulations [80].

3.8. *Thermal conductivity*

FC thermal conductivity with several weight percentages of RF is depicted in Fig. 17. With the addition of RF to FC, it is possible

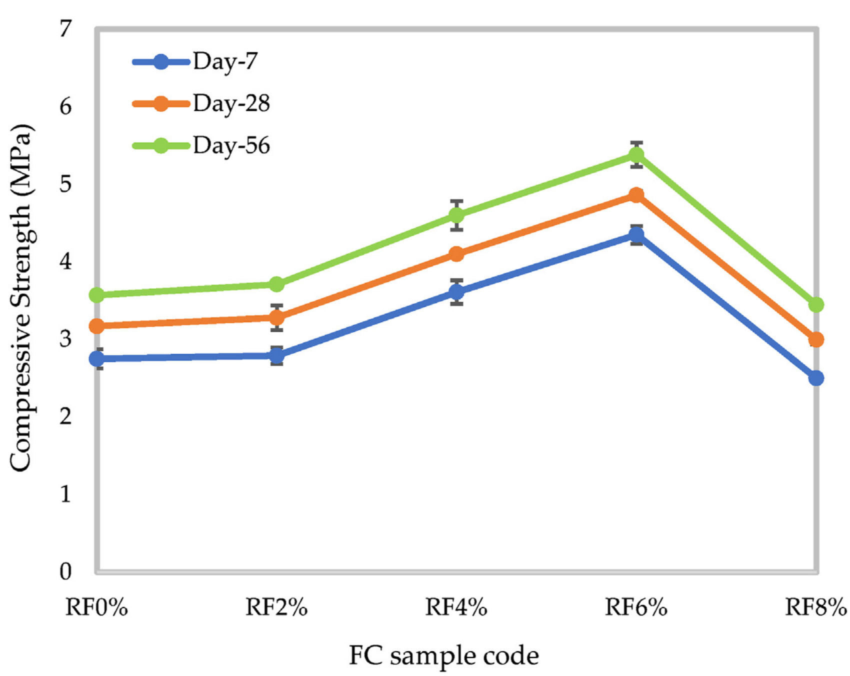


Fig. 10 – Compressive strength of FC-RF composites.

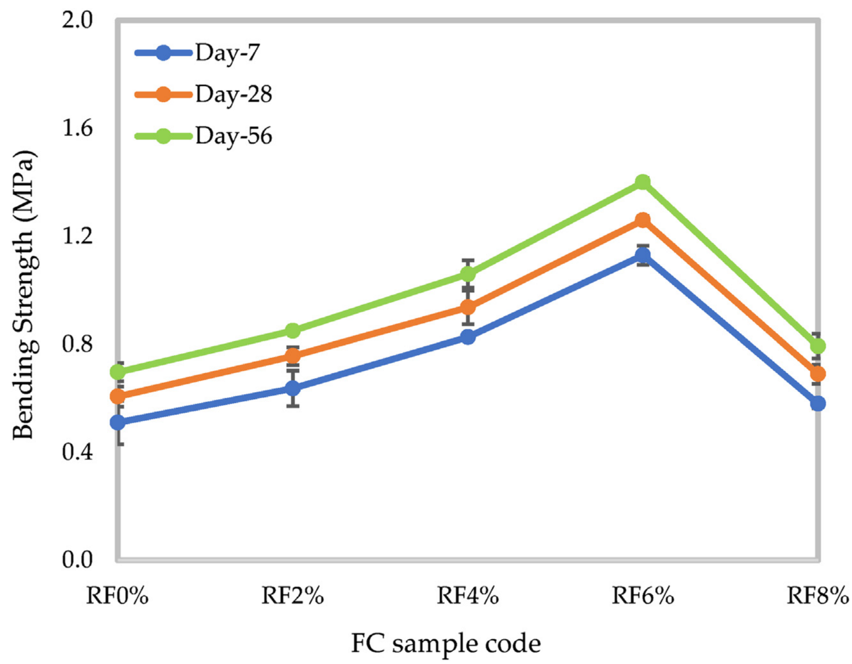


Fig. 11 – Bending strength of FC-RF composites.

to reduce its thermal conductivity. The optimal thermal conductivity result was achieved with an RF fraction content of 6%. Control specimen thermal conductivities were 0.2362 W/mK. In the presence of 6% RF, the thermal conductivity of FC was drastically lowered to 0.1857 W/mK by adding 6% RF. Due to the porous structure of FC with RF, which enables it to absorb heat, the material conductivity reduces as the weight percent of RF increases [81,82]. The incorporation of RF also adds to the reallocation and creation of smaller consistent void sizes, both of which contribute to FC's extremely low thermal conductivity. Additional explanations for improving the thermal conductivity of FC-RF composites with the increase in RF fraction contents include the redistribution and development of a smaller uniform pore void due to the addition of the RF. Because of this effect, more isolated pores were produced in the FC cementitious matrix compared to the control, which contains no fiber

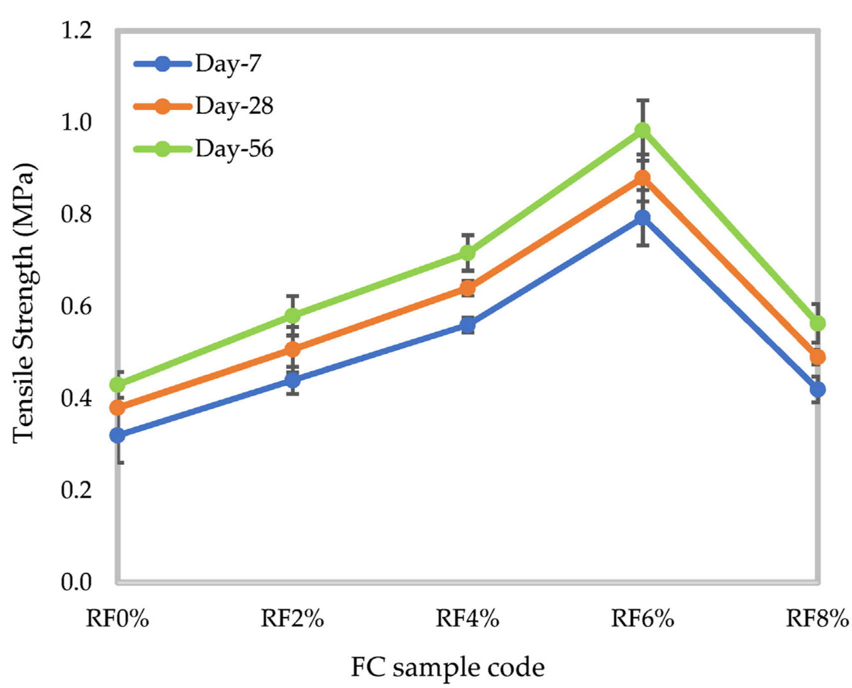
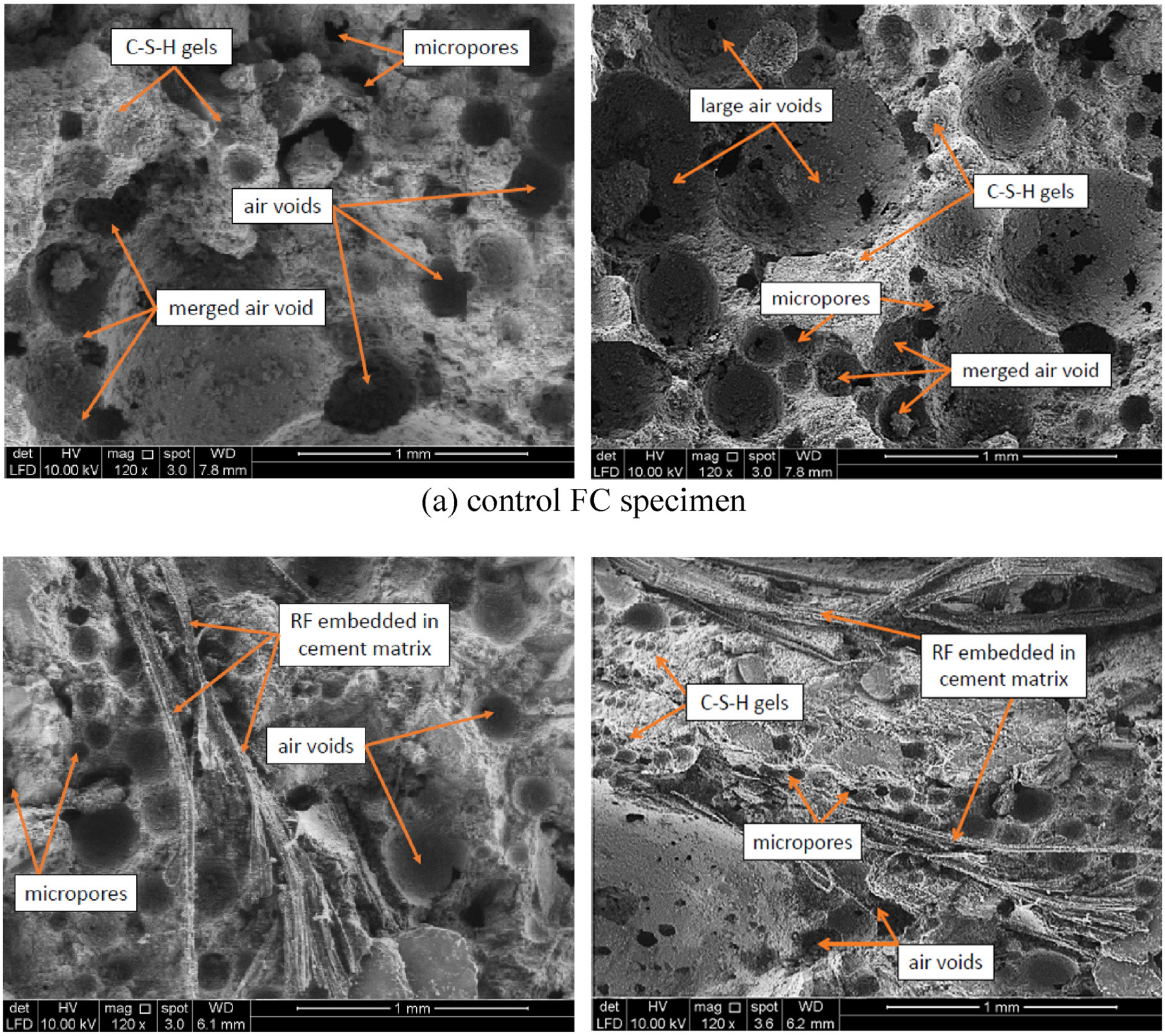


Fig. 12 – Tensile strength of FC-RF composites.



(a) control FC specimen

(b) FC composites with 6% RF

Fig. 13 — SEM micrograph of 950 kg/m^3 density FC.

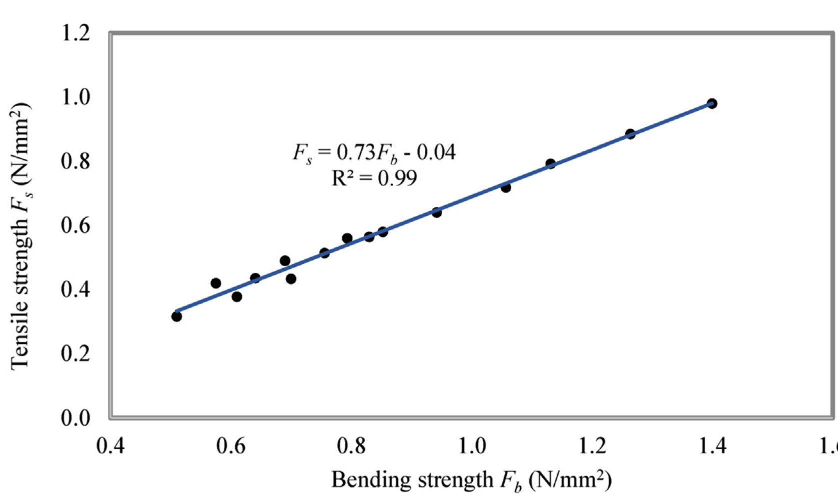


Fig. 14 — Relationship between FC-RF composites' bending-compressive strengths.

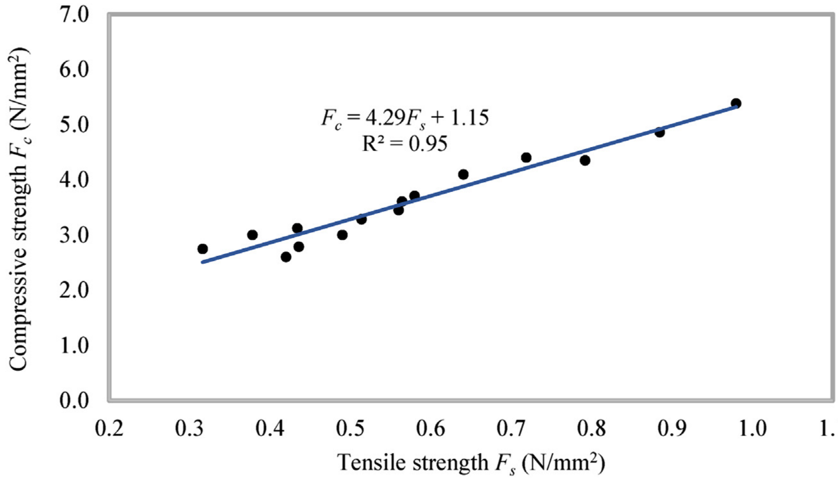


Fig. 15 – Relationship between FC-RF composites' tensile-compressive strengths.

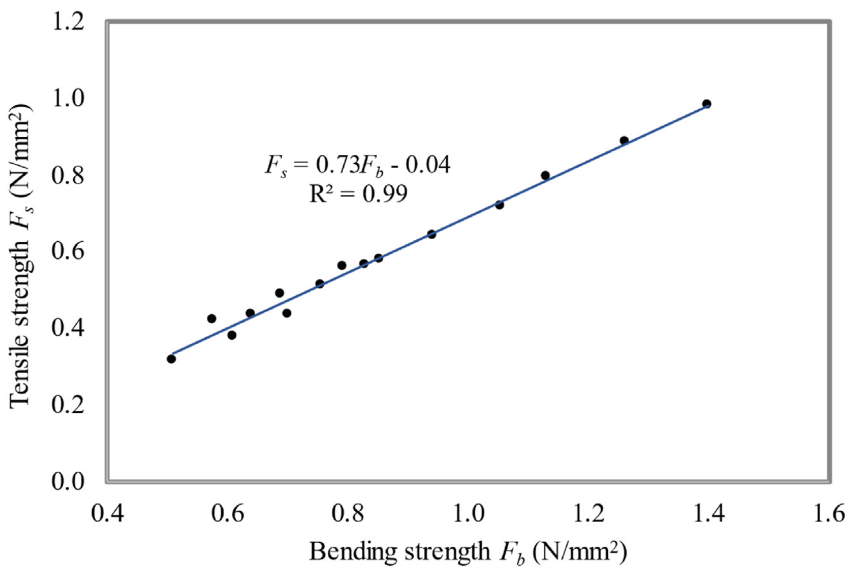


Fig. 16 – Relationship between FC-RF composites' bending-tensile strengths.

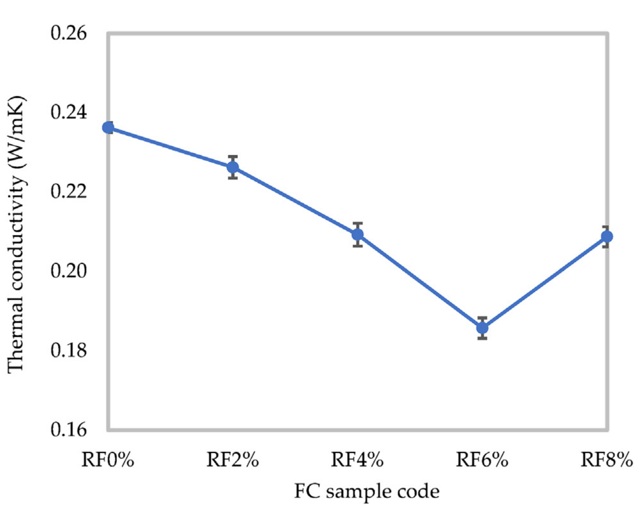


Fig. 17 – Thermal conductivity of FC-RF composites.

addition [83]. Additionally, the studies showed that RF could be employed in cement-based materials, where it could reduce or enhance the thermal conductivity of concrete. Furthermore, FC produced from RF can save considerable energy when used in sustainable construction. However, the FC sample with a fraction of 8% of RF showed higher thermal conductivity than the sample with a fraction of 6% of RF. Once FC reaches its optimum fraction content, SF may be distributed non-uniformly in FC-RF composites. Thermal conductivity may also be affected by the location and relative orientation of the FC pores at 8% weight fraction of RF, which may also contribute to the increase in thermal conductivity [84]. RF presence in the FC sample above the optimum weight fraction tended to create pores at right angles to the direction of heat flow. Due to this, more heat could pass through the pores, thereby increasing thermal conductivity. Xie et al. [85] also observed a higher thermal conductivity when pores were parallel to the heat flow direction.

4. Conclusions

The mechanical properties of FC-RF composites were examined by adding varying fraction contents of RF. According to the findings from this study, the subsequent conclusions can be drawn:

1. The slump flow reduced steadily as the RF fraction content rose from 2% to 8%. The lowest slump flow was attained by incorporating an 8% fraction of RF into the FC mixture. By boosting the intertwining and resistance between the RF and filler, the inclusion of RF increases flow resistance and diminishes flowability, resulting in a considerable reduction in slump flow diameter.
2. Due to the RF's relatively high specific gravity and rising weight percentage, the FC-RF composite density exhibits a growing trend; nonetheless, the difference was not statistically significant.
3. Adding RF to the FC mixture increases its tensile, compressive and bending strength. The highest strength properties resulted from adding 6% RF to FC. Adding RF to FC mixtures ensures that the FC will act as a fastener once microcracks appear. As a result, the matrix modulus doesn't instantly drop when the direct margin strain is met. When fractures initially appear, the RF will completely absorb all strain before gradually transferring it to the cementitious matrix.
4. Significant linear relationships exist between compressive and bending strengths (R2 = 0.94), compressive and tensile strengths (R2 = 0.95) and tensile and bending strengths (R2 = 0.99). It implies a correlation between the predictors' differences and the response variable's variations.
5. FC's thermal conductivity was decreased when RF was included. The porous structure of FC with RF allows it to absorb heat, so its thermal conductivity improves with the increased fraction content of RF in FC. It was largely due to the distribution and growth of smaller, consistent pores in FC that resulted in its low thermal conductivity. Optimal results were obtained with a fraction content of RF of 6% in FC.

Declaration of competing interest

The authors declare that they do not have any conflict of interest.

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