Influence of elevated temperatures on compressive and flexural strengths of *Cocos nucifera* Linn. fiber strengthened lightweight foamcrete

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Abstract
The call for lightweight foamcrete technology is impelled by the amplified rules and guidelines with the aim of minimizing greenhouse gas emission and reducing carbon footprint. The use of natural fibers in foamcrete is considered as a useful option in making concrete a sustainable material. Therefore, the aim of the present study was to determine the compressive and flexural strengths of foamcrete reinforced with *Cocos nucifera* Linn. fiber (CNF) exposed to elevated temperatures. CNF refers to agricultural waste or by-products obtained from the distribution of coconut oil and accumulated in a large amount in Malaysia. This study aimed to identify the response of CNF towards six different contents (0.1%, 0.2%, 0.3%, 0.4%, 0.5%, and 0.6%) by mix volume. Three different densities of 650, 1050 and 1450 kg/m^3 were tested in this study. The proportion of foamcrete constituted cement, sand, and water which were represented by the ratio of 1:1.5:0.45. Results showed that, CNF-strengthened foamcrete offered progressively ductile structure contrasted with plain foamcrete at elevated temperatures. The incorporation of CNF enhanced the mechanical properties at each predetermined temperature for all densities investigated. This demonstrates that CNF has strong bonding and good quality of chemical properties that are unique to it. The optimum volume fractions of CNF that gave the best improvement in mechanical and high temperature properties were 0.3% for 650 kg/m^3, 0.4% for 1050 kg/m^3 and 0.5% for 1450 kg/m^3.

Keywords: Foamed concrete, elevated temperatures, compressive strength, flexural strength, coconut fiber, coir.

Introduction

Despite the fact that foamcrete mechanical properties are lower compared to normal weight concrete, foamcrete has the potential to be used as in-fill material, partition and light load bearing panel in low rise residential construction (Othuman Mydin et al., 2015). The first stage to realize the potential of foamcrete for application as a load-bearing material in building construction is to obtain reliable mechanical properties at ambient and elevated temperatures (Hilal et al., 2015).

Nowadays, it is widely agreed that construction needs materials that are durable, light, and simple to be used but are more naturally sustainable. Additionally, natural fibers have the potential to perform equally as synthetic fibers (Othuman Mydin et al., 2016). Moreover, this alternative does not need a high amount of energy and is considered as ultimate green product because it utilizes some agricultural wastes as construction materials (Norgaard & Othuman Mydin, 2013). However, there is a minimum potential for the plain concrete to prevent cracking. The issue of cracks is significant as suggested by Gowri & Anand (2018) as it will lead to negative impression of quality and serviceability. Nevertheless in most cases, they are only regarded as aesthetic problems.

Cocos nucifera Linn. fiber (CNF) has always been disposed as wastes instead of utilized as construction materials. The use of foamcrete with CNF is able to reduce the weaknesses of foamcrete which include low tensile strength, shrinkage problem, and serious crack propagation, especially in low densities foamcrete. Furthermore, the addition of CNF is a practical way to improve the bending performance as well as tensile cracking considering that foamcrete is generally weak in tension compared to its capacity in compression (Yalley & Kwan, 2012).

Moreover, the capability of fibers is dependent on the amount of fibers used in the mixture. According to Rai & Joshi (2014), higher percentage of fiber will lead to segregation and roughness of concrete and mortar. However, fibers that are lengthy in the mixture will create workability problems that can be discovered using the flow table test and during the pouring of the concrete into the mold. Therefore, the aim of the present study was to perform experimental studies in order to characterize the engineering properties of foamcrete reinforced with CNF as well as its performance at elevated temperatures (Serri et al., 2014).

Foamcrete is a heterogeneous multi-phase material that is held together by the hydrated Portland cement paste. Non-linearities in material properties, the disparity of physical properties with temperature, tensile cracking, and creep effects affect the buildup of thermal forces, the load-carrying capacity, and the deformation capability (i.e., ductility) of the structural members will take place. The property variations result principally because of the changes in the moisture condition of the concrete constituents and the progressive deterioration of the cement paste-aggregate bond, which is especially critical where thermal expansion values for the cement paste and fillers diverge significantly (Othuman Mydin et al., 2018).

Rafi et al. (2017) detailed the aftereffects of a test and numerical examination to explore and set up the thermal properties of lightweight foamcrete high temperatures. The findings of the study revealed that when lightweight foamcrete is presented with high temperature, the water in the pores essentially decreases and some synthetically bonded water in the hydrated cement paste are discharged.

Othuman Mydin & Wang (2012) carried out compression and bending strength test on the lightweight foamcrete samples at different temperatures up to 600°C. The results of the study showed that compressive quality at raised temperatures, the well accepted Eurocode (2004) and Li & Purkiss (2005) model might be utilized to foresee the compressive modulus of versatility at lifted temperatures. For lightweight foamcrete, the total strain at peak stress is around 1.78 times the elastic train at peak stress.

Bazant et al. (1996) predicted that when the span of the heating procedure is over 60 minutes, the solid will greatly lose its quality and the loss of most noteworthy quality will occur when the exposure is between 1 to 2 hours. This is on the grounds that it will influence the porosity and water dissipates from the total of the samples when the dehydration of hardened cement paste occurs. However, Bingöl & Gül (2009) discovered that lightweight concrete qualities tend to decline at 150°C, and the sample started to lose a portion of their underlying qualities at this temperature. Although the qualities were not lost between 150°C to 300°C, a wide range of concrete mixture kept on losing their compressive quality after 300°C. In addition, the study extensively discovered that the heating span does not significantly impact the quality loss. Falade et al. (2010) mentioned that lightweight concrete containing periwinkle shells is reasonable for structures that will be presented to temperature under 300°C.

A considerable amount of research investigated cement mortar cubes with the inclusion of different percentages of steel fiber. The results revealed that compressive strength of fiber reinforced mortar initially increases up to 200°C temperature, followed by a drop due to further increase of temperature. The impact of high temperature on thermal of concrete with different sorts of pozzolans and total was researched. The outcome demonstrated that thermal conductivity of concrete with siliceous was observed to be somewhat higher than the concrete made with calcareous, aside from the series with granulated blast furnace slag at room temperature(Al-Chaar, 2013).

Sindhu Nachiar et al. (2018) investigated the behavior of foam concrete at high temperature; 200, 400, and 600°C. In their research, a comparative study was performed between conventional and foam concrete for compressive strength, flexural strength, and weight loss. The results suggested that lightweight foamcrete yields better strength at high temperature up to 600°C. Apart from that, it was also mentioned that the flexural strength of conventional concrete loses its strength when the temperature rises. However, the strength of concrete rises simultaneously with temperature in the case of lightweight foamcrete. Hence, this research attempted to determine the compressive and flexural strengths of foamcrete reinforced with CNF exposed to elevated temperatures.

Methodology

Mixture Design Proportion

A total of 21 mixes were prepared to conduct the high temperature test. Three densities were considered in this study which were 650, 1050, and 1450 kg/m^3. The mixture design proportion is shown in Table 1. CNF was used as additives at 0.1, 0.2, 0.3, 0.4, 0.5, and 0.6% by volume fraction of the total mixture. The proportion of mortar comprised the cement, sand, and water which were represented by the ratio of 1:1.5:0.45. Water to cement ratio used for the current research was 0:45, thus indicating that it managed to achieve good workability.

Table 1. Mixture design proportion. Self-elaboration.

Density (kg/m^3)	Sample	CNF (kg/m^3)	Cement (kg/m^3)	Sand (kg/m^3)	Water (kg/m^3)
650	no fiber	-	248.29	372.44	111.73
	0.1% fiber	0.72			
	0.2% fiber	1.44			
	0.3% fiber	2.22			
	0.4% fiber	2.94			
	0.5% fiber	3.67			
	0.6% fiber	4.44			
1050	no fiber	-	392.73	589.10	176.73
	0.1% fiber	1.11			
	0.2% fiber	2.28			
	0.3% fiber	3.44			
	0.4% fiber	4.61			
	0.5% fiber	5.78			
	0.6% fiber	6.94			
1450	no fiber	-	537.18	805.76	241.73
	0.1% fiber	1.56			
	0.2% fiber	3.17			
	0.3% fiber	4.72			
	0.4% fiber	6.33			
	0.5% fiber	7.94			
	0.6% fiber	9.56			

Materials

The Ordinary Portland cement (OPC) used in this research was supplied by Aalborg Portland Malaysia Sdn Bhd. The fine aggregate used was natural sand obtained from a local distributor. Uncrushed fine aggregate in mortar mix is a constituent material with a fineness modulus of 1.35 as well as a specific gravity of 2.74. Essentially, the water to cement ratio employed for the current research was 0.45 because it is able to achieve the desired workability. Apart from that, it is important to note that the water used in the current research has a good and acceptable quality with suitable pH ranging from 6.5 to 8.0. Noraite PA-1 foaming agent which is protein-based was selected for this experimental program due to its characteristics of good quality, potent and dense cell bubble structure. It is important to understand that foam is produced using foam generator (Portafoam PA-1). The foaming generator equipped with a digital timer that can set the flow rate acts a medium that transforms the liquid chemical into stable foam. This study focused on different volume fractions of CNF (0.1, 0.2, 0.3, 0.4, 0.5, and 0.6%) which acted as an admixture in foamed concrete mix with the aim of investigating the effect of the foamed concrete, particularly in terms of engineering properties and its performance at elevated temperatures. CNF was extracted from the outer shell of a young coconut which was randomly oriented. Figure 1 displays the CNFused for the present study, while Table 2 shows its physical properties. The fiber was supplied by DRN Technologies Sdn Bhd. Before the fiber was added into the foamcrete mix, it was thoroughly cleaned using tap water to eliminate any impurities. After the washing process, it was left dried for 24-48 hours before the mixing process.

Figure1.*Cocos nucifera* Linn. fiber. Source: https://www.wellgrowseeds.com

Table 2 Physical properties of CNF used for this study (DRN Technologies Sdn Bhd.).

Component	Value
Length (mm)	17-19
Density (g/cm^3)	1.17
Elongation at break (%)	28.2%
Tensile strength (N/mm^2)	154
Young modulus (GPa)	5.37
Diameter (mm)	0.125-1.31
Water absorption (%)	134

The specimens were stripped from the moulds 24 hours after casting and cured in plastic containers with water for moisture curing. At the age of 28 days, the specimen's substrate was taken out from the plastic containers and put into an oven for oven drying at 105 °C + 2 °C ±24 hours before high temperature testing. Then, the samples were left to cool for 2 hours on average before the test. The purpose of cooling the samples is to get the dried density value. Curing plays an important role on the strength development of concrete. Figure 2 shows the foamcrete samples which were sealed cured with plastic sheets (PSC).

Figure 2. Lightweight foamcrete specimens were properly sealed cured with plastic sheets (PSC). Source: Self-elaboration.

Experimental Setup

High temperature is described as one of the most critical physical deterioration procedures that affect the quality and sturdiness of concrete structures. Moreover, high temperature may cause permanent damage in the structures, especially building that are exposed to high temperature which may become out of service (Khoury et al., 2004). In the present study, the elevated temperatures performance of foamcrete reinforced with CNF were investigated at different heating temperatures of 105, 200, 300, 400, 500, 600, 700, and 800°C. Three samples (compressive strength test and splitting tensile test) for each mixture were prepared for the experimental studies. The samples were directly collected from the furnace for strength test after two hours of heating process at specific temperatures without having to conduct the cooling process. Figure 3 shows that the specimens were placed in the electric furnace until the set temperature was reached and then left for a period of 120 ± 5 minutes. It should be noted that the temperature was set to start from the lowest until it reached the predetermined temperature. Finally, the samples were withdrawn from the furnace and instantly continued with compression, flexural, and splitting tensile tests.

Figure 3. Foamcrete samples were exposed to high temperature. Source: Self-elaboration.

Generally, high temperature extremely harms the microstructure which affects the mechanical properties decay of foamcrete incorporated with fiber even though foamcrete is distinguished for a high degree of fire resistance. As a result, the widespread data of mechanical properties of fiber reinforced foamcrete that are exposed to elevated temperature appeared to be significant for a broader use of this material. Hence, this section presents the experimental results obtained from elevated temperature tests on foamcrete reinforced with CNF. The test was conducted for 28 days on all three densities (650, 1050, and 1450 kg/m^3) and six different CNF percentages by volume (0.1, 0.2, 0.3, 0.4, 0.5, and 0.6%). The specimens were exposed to different heating temperatures of 20°C (control specimen), 105, 200, 400, 600, and 800°C. However, it should be noted that only compression test and flexural test were conducted to observe the influence of elevated temperatures on compressive and flexural strengths of foamcrete.

Influence of High Temperature on Compressive Strength

A rise in temperature leads to the alterations in the foamcrete matrix. Foamcrete with the inclusion of natural fibers can offer more ductile structure compared to plain foamcrete matrix. In addition, foamcrete with natural fiber is expected to improve the compressive strength. Figure 4, 6, and 8 present the compressive strength of 650, 1050, and 1450 kg/m^3 densities foamcrete as a component of temperature, while Figure 5, 7, and 9 demonstrate the normalized compressive strength of 650, 1050, and 1450 kg/m^3 densities foamcrete exposed at different temperatures. On the other hand, Table 3, 4, and 5 respectively visualize the percentage of compressive strength retained at predetermined temperatures for 650, 1050, and 1450 kg/m^3 densities foamcrete. The foamcrete samples were exposed to different temperatures at 100, 200, 400, 600, and 800°C for the purpose of determining the influence of elevated temperatures on compressive strength of the foamcrete samples.

As expected, the compressive strength of foamcrete incorporated with CNF reduced with the increase in temperature. For all the densities tested, the inclusion of CNF exceptionally improved the compressive strength at each predetermined temperature. From Figure 4, 6, and 8, it can be seen that there are two foamcrete behavior zones. In the primary zone that changed from room temperature to 400°C, there is a reduction in compressive strength but in all instances of small magnitude. Meanwhile, in the second zone starting from 400°C until 900°C, there is a consistent decrease in the compressive strength without the influence of the type of foamcrete. At preliminary heating stage, foamcrete lost its free or evaporable water, followed by the synthetically bound water. The loss of water further led to micro cracking that resulted in the decrease of compressive strength. Between 100°C to 200°C, the compressive strength of foamcrete gradually reduced due to the release of free water and a portion of the artificially bound water. According to Georgali & Tsakiridis (2005), the reduction in compressive strength is due to the increase in the chemical energy of water, which, by expanding the quantity of layers retained on the outside of the solids, upsurges the incongruity power between the different calcium silicate hydrate stratums. At this point, the decrease in foamcrete strength is not noteworthy and the compressive strength of the foamcrete samples with CNF at 200°C still remained on average of 95% of the original unheated value for all densities. In this temperature range, the control foamcrete (no fiber) samples were retained on average 90% of its original strength. The post peak compressive strength clearly highlighted the role of CNF in which the stress distribution between the faces of the cracks by CNF was significant and able to improve the ductility compared to the control foamcrete.

In the range of 200°C to 400°C, calcium silicate hydrate gel decomposed and the sulfoaluminate phases instigated cracks in the samples (Arioz, 2007). These cracks formation led to substantial impacts on the compressive strength of foamcrete. At 400°C, the control foamcrete strength remained only about 73% of its initial value for all three densities. Nevertheless, the compressive strength retained on 81% on average of its room temperature strength for all three densities for foamcrete incorporated with CNF. This showed that CNF has uncracking effect which allows the dissipation of fluid over pressure in the cementitious matrix of foamcrete, thus leading to higher compressive strength that can be retained at 400°C compared to the control samples. Moreover, foamcrete incorporated with CNF retained on average between 52%-61% of its initial value for all three densities when the temperature reached 600°C. However, the compressive strength for control specimen retained only an average of 42% for 650, 1050, and 1450 kg/m^3 densities. Therefore, it should be pointed out that within the temperature range of 400°C -600°C, dehydration of calcium hydroxide takes place, thus causing the shrinkage and strength loss of foamcrete (Dwaikat & Kodur, 2009). The exposure of heating temperature from 600°C to 800°C had caused further compressive strength degradation of foamcrete. At 800°C, foamcrete incorporated with CNF retained on average between 14%-29% of its initial value for all three densities. However, the compressive strength for control specimen retained only an average of 7% for 1050 and 1450 kg/m^3 densities. Nevertheless, the sample completely lost it flexural strength for CNF with 650 kg/m^3 density. Moreover, the compositions of all the three densities of foamcrete are indistinguishable, with the exception of expanded pores in the lower density foamcrete, it is expected that there is a relationship of foamcrete for that the standardized compressive strength-temperature of 650, 1050, and 1450 kg/m^3 densities are almost the same.

Figure 4. Compressive strength of 650 kg/m^3 density foamcrete as a function of temperature. Source: Self-elaboration.

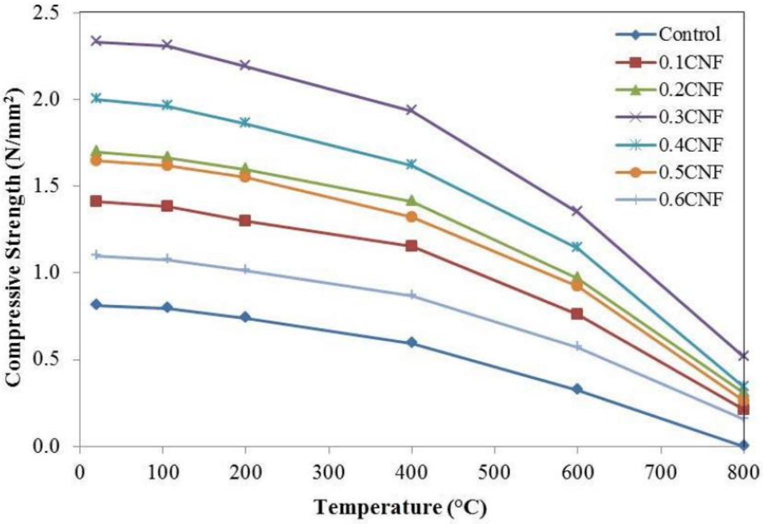


Figure 5. Normalized compressive strength of 650 kg/m^3 density lightweight foamcrete as a function of temperature. Source: Self-elaboration.

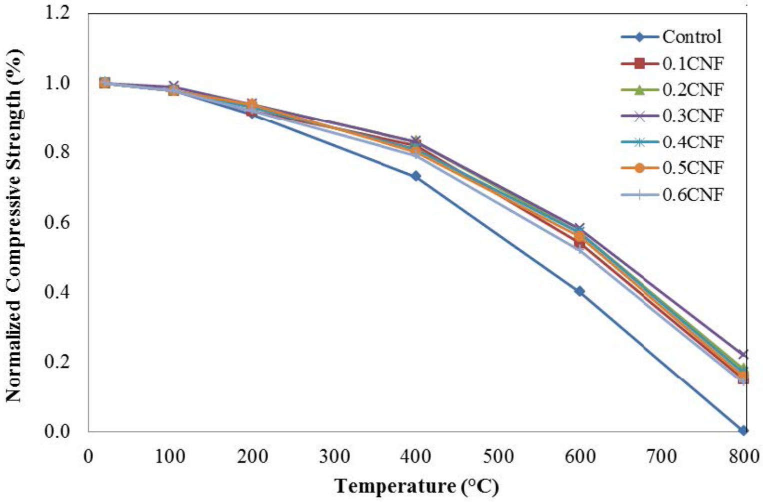


Table 3. Percentage of 650 kg/m^3 density lightweight foamcrete compressive strength retained at predetermined exposed temperature. Source: Self-elaboration.

	Exposed temperature (°C)					
Specimen	20	105	200	400	600	800
Control	100	98	91	73	40	0
0.1CNF	100	98	92	82	54	15
0.2CNF	100	98	94	83	57	18
0.3CNF	100	99	94	83	58	22
0.4CNF	100	98	93	81	57	17
0.5CNF	100	98	94	80	56	16
0.6CNF	100	98	92	79	52	14

Figure 6. Compressive strength of 1050 kg/m^3 density foamcrete as a function of temperature. Source: Self-elaboration.

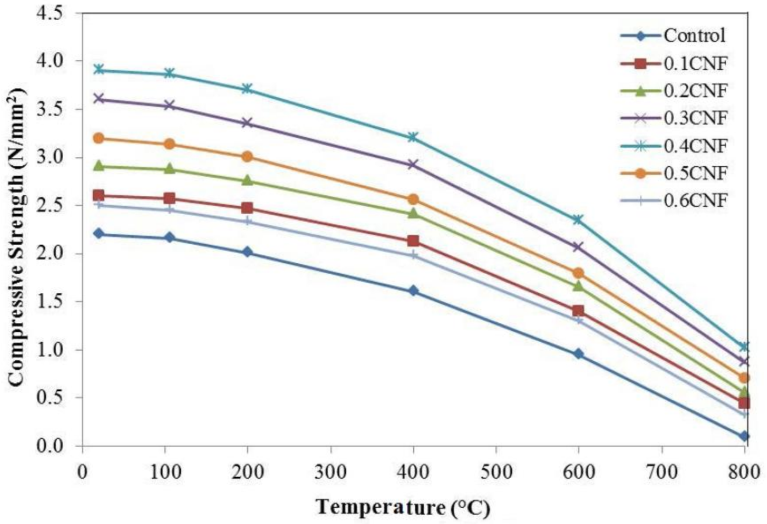


Figure 7. Normalized compressive strength of 1050 kg/m^3 density lightweight foamcrete as a function of temperature. Source: Self-elaboration.

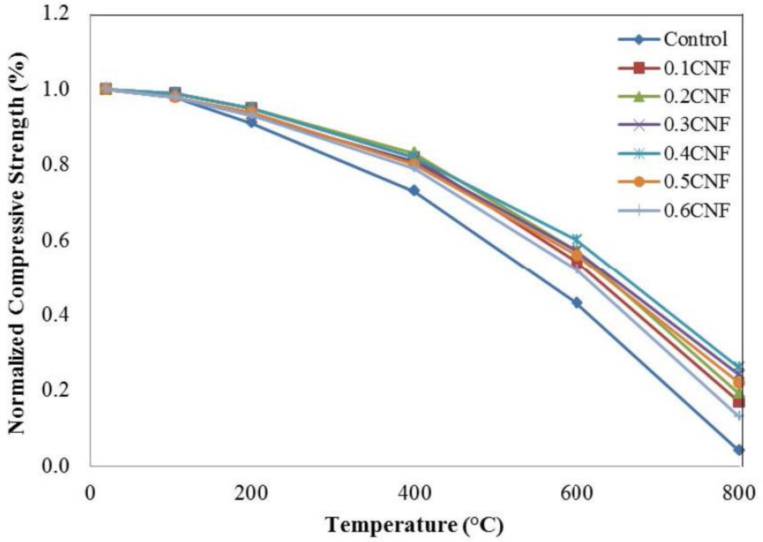


Table 4. Percentage of 1050 kg/m^3 density lightweight foamcrete compressive strength retained at predetermined exposed temperature. Source: Self-elaboration.

	Exposed temperature (°C)					
Specimen	20	105	200	400	600	800
Control	100	98	91	73	43	4
0.1CNF	100	99	95	82	54	17
0.2CNF	100	99	95	83	57	19
0.3CNF	100	98	93	81	57	24
0.4CNF	100	99	95	82	60	26
0.5CNF	100	98	94	80	56	22
0.6CNF	100	98	93	79	52	13

Figure 8. Compressive strength of 1450 kg/m^3 density foamcrete as a function of temperature. Source: Self-elaboration.

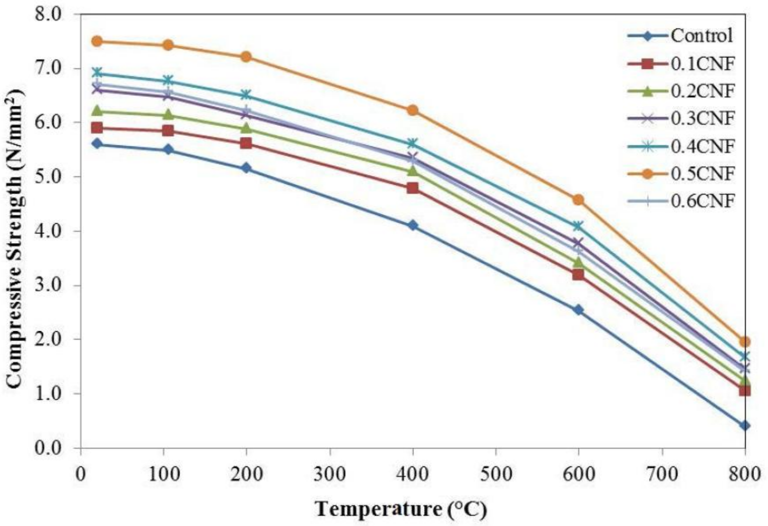


Figure 9. Normalized compressive strength of 1450 kg/m^3 density lightweight foamcrete as a function of temperature. Source: Self-elaboration.

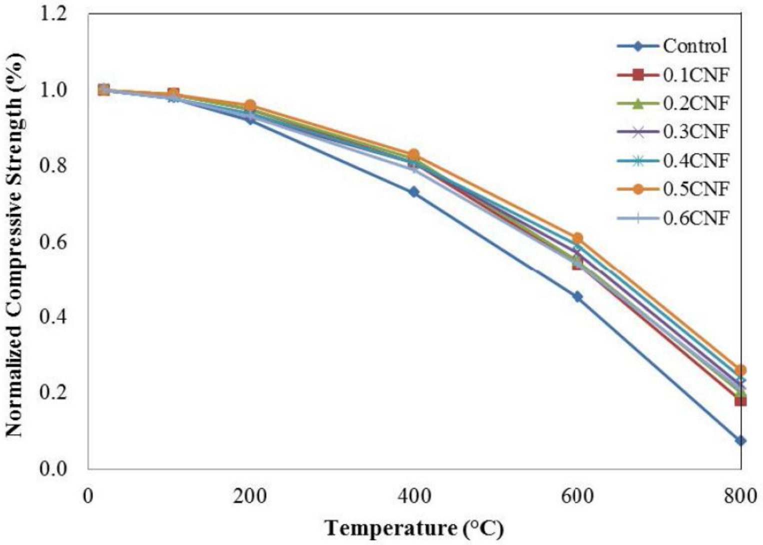


Table 5. Percentage of 1450 kg/m^3 density lightweight foamcrete compressive strength retained at predetermined exposed temperature. Source: Self-elaboration.

	Exposed temperature (°C)					
Specimen	20	105	200	400	600	800
Control	100	98	92	73	45	7
0.1CNF	100	99	95	81	54	18
0.2CNF	100	99	95	82	55	20
0.3CNF	100	98	93	81	57	22
0.4CNF	100	98	94	81	59	24
0.5CNF	100	99	96	83	61	26
0.6CNF	100	98	93	79	54	21

Influence of High Temperature on Flexural Strength

Foamcrete is known as fragile material; hence, the bending test was proposed to give a measure of the flexural quality of foamcrete incorporated with CNF. Figure 10, 12, and 14 show the flexural strength of 650, 1050, and 1450 kg/m^3 densities foamcrete as a component of temperature, while Figure 11, 13 and 15 exhibit the normalized flexural strength of 650, 1050 and 1450 kg/m^3 densities foamcrete that were exposed at different temperatures. In addition, Table 6, 7 and 8 envisage the percentage of flexural strength retained at predetermined temperatures for 650, 1050, and 1450 kg/m^3 densities foamcrete, correspondingly.

The foamcrete samples were exposed to the temperatures at 100, 200, 400, 600, and 800°C for the purpose of establishing the impact of elevated temperatures on the flexural strength of the foamcrete samples. The decrease in flexural quality of foamcrete happened basically after 100°C, paying little attention to the density of foamcrete. This is consistent with the changes in the previously mentioned compressive quality of foamcrete, which shows that the essential component causing corruption is micro cracking that occurs as free water and artificially bound water dissipate from the porous body.

At the point when the chemical constitution of foamcrete began to break down in the range of 200°C and 400°C because of the decay of the calcium silicate hydrate and sulfoaluminate stages ($3CaO.Al_2O_3.CaSO_4.12H_2O$ and $3CaO.Al_2O_3.3CaSO_4.31H$), the arrangement of cracks occurred and there was a noteworthy drop in tensile strength. At 400°C, the tensile strength of foamcrete incorporated with CNF was about 74%-85% of the initial value for every one of the three densities. Nevertheless, for foamcrete without CNF, the flexural strength retained only on average 69% of its room temperature strength for all three densities. Hence, this shows that CNF has the ability to resist crack at high temperature which permits the intemperance of fluid over pressure in the cementitious matrix of foamcrete, allowing greater flexural strength to be retained at 400°C compared to the control samples.

At 800°C, foamcrete incorporated with CNF retained an average between 13%-26% of its initial value for all three densities. On the other hand, the compressive strength for control specimen retained only on average 5% for 1050 and 1450 kg/m^3 densities. Nevertheless, the sample completely lost its compressive strength for 650 kg/m^3 density. The normalized flexural strength-temperature relationship for all three densities is almost the same, which is consistent with other observed properties.

Figure 10. Flexural strength of 650 kg/m^3 density foamcrete as a function of temperature. Source: Self-elaboration.

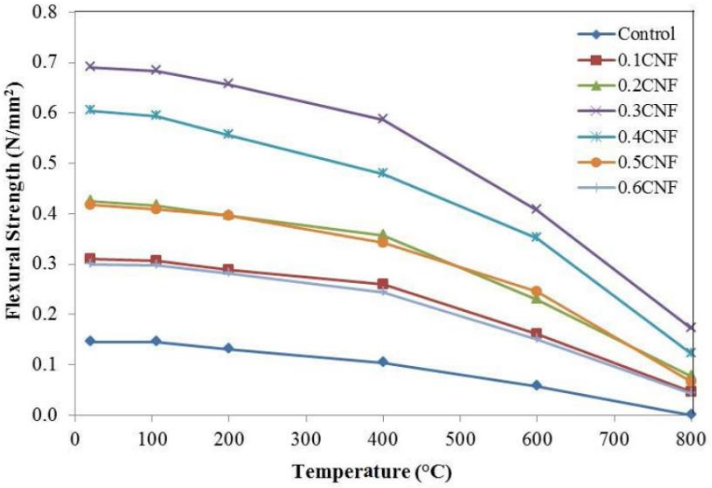


Figure 11. Normalized flexural strength of 650 kg/m^3 density lightweight foamcrete as a function of temperature. Source: Self-elaboration.

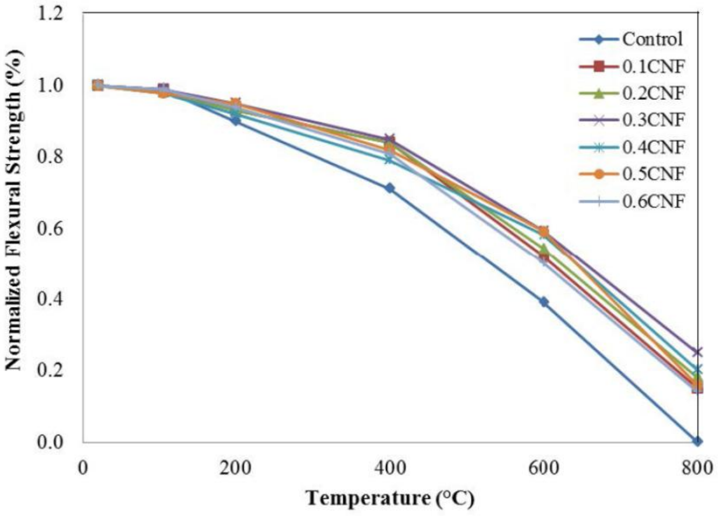


Table 6. Percentage of 650 kg/m^3 density lightweight foamcrete flexural strength retained at predetermined exposed temperature. Source: Self-elaboration.

	Exposed temperature (°C)					
Specimen	20°C	105°C	200°C	400°C	600°C	800°C
Control	100	99	90	71	39	0
0.1CNF	100	99	93	84	52	15
0.2CNF	100	98	93	84	54	18
0.3CNF	100	99	95	85	59	25
0.4CNF	100	98	92	79	58	20
0.5CNF	100	98	95	82	59	16
0.6CNF	100	99	94	81	50	14

Figure 12. Flexural strength of 1050 kg/m^3 density foamcrete as a function of temperature. Source: Self-elaboration.

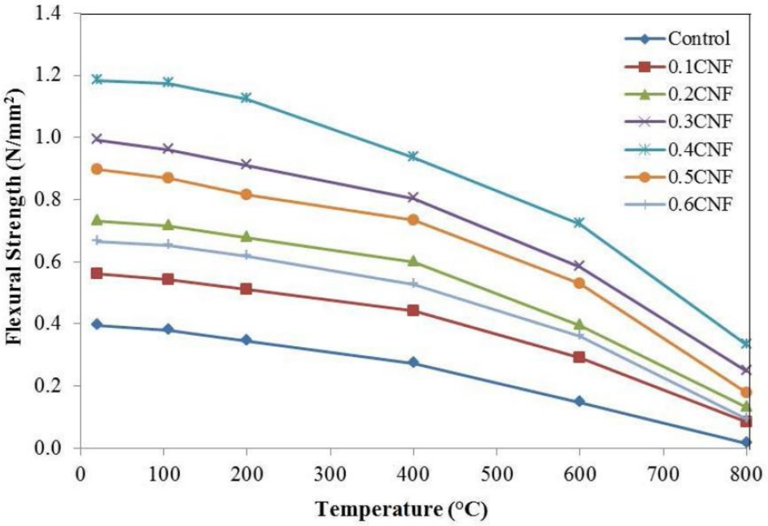


Figure 13. Normalized flexural strength of 1050 kg/m^3 density lightweight foamcrete as a function of temperature. Source: Self-elaboration.

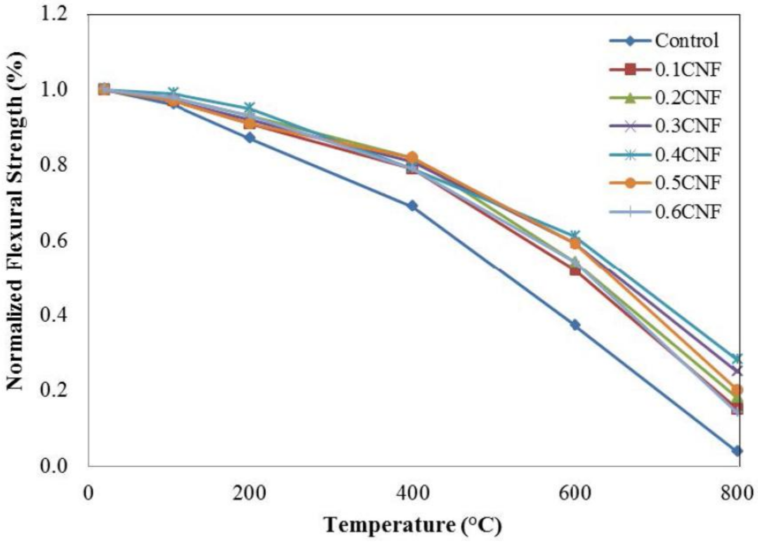


Table 7. Percentage of 1050 kg/m^3 density lightweight foamcrete flexural strength retained at predetermined exposed temperature. Source: Self-elaboration.

	Exposed temperature (°C)					
Specimen	20°C	105°C	200°C	400°C	600°C	800°C
Control	100	96	87	69	37	4
0.1CNF	100	97	91	79	52	15
0.2CNF	100	98	93	82	54	18
0.3CNF	100	97	92	81	59	25
0.4CNF	100	99	95	79	61	28
0.5CNF	100	97	91	82	59	20
0.6CNF	100	98	93	79	54	14

Figure 14. Flexural strength of 1450 kg/m^3 density foamcrete as a function of temperature. Source: Self-elaboration.

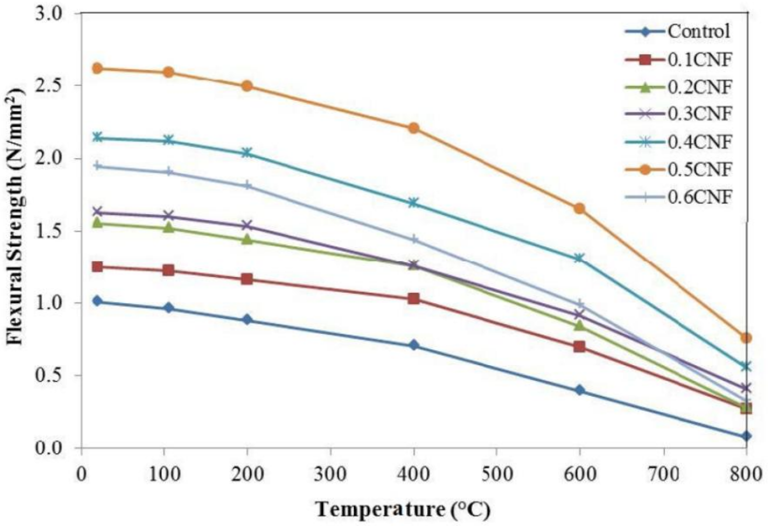


Figure 15. Normalized flexural strength of 1450 kg/m^3 density lightweight foamcrete as a function of temperature. Source: Self-elaboration.

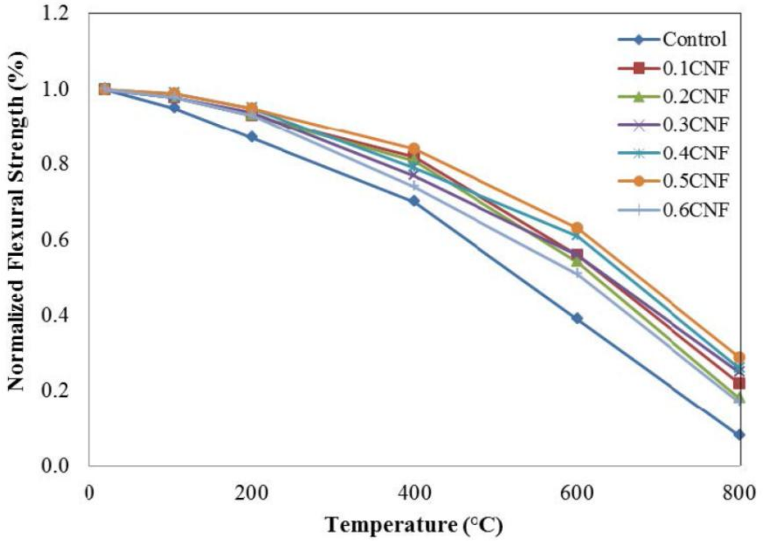


Table 8. Percentage of 1450 kg/m^3 density lightweight foamcrete flexural strength retained at predetermined exposed temperature. Source: Self-elaboration.

	Exposed temperature (°C)					
Specimen	20°C	105°C	200°C	400°C	600°C	800°C
Control	100	95	87	70	39	8
0.1CNF	100	98	93	82	56	22
0.2CNF	100	98	93	81	54	18
0.3CNF	100	98	94	77	56	25
0.4CNF	100	99	95	79	61	26
0.5CNF	100	99	95	84	63	29
0.6CNF	100	98	93	74	51	17

Correlation between flexural and compressive strengths at elevated temperatures

Figure 16 to 18 demonstrate the correlation between flexural strength and compressive strength of all volume fractions of foamcrete at elevated temperatures for 650, 1050 and 1450 kg/m^3 densities respectively. As can be seen from these figures, there is a significant amount of scatter in the data. The R^2 value for the trend-line drawn through all of the results from all batches is indicative of how closely the flexural strength is correlated to compressive strength. The regression analysis represents the patterns that best depict the connection between flexural strength and compressive strength which were described as a linear function. The regression line with the R^2 value near to the value of 1 was recorded as the regression line that best describes the trend of the flexural and compressive strengths data. As predicted, the flexural and compressive strengths of foamcrete incorporated with CNF reduced with the upsurge of the temperature. For all the densities tested, the presence of CNF remarkably enhanced the flexural and compressive strengths at each predetermined temperature. These relationships would make it easier for engineers to characterize the mechanical behavior of foamed concrete with addition of CNF at elevated temperatures for modeling or designing based on a relatively limited number of standard tests.

Figure 16. Correlation between flexural and compressive strengths at elevated temperature for 650 kg/m^3 density. Source: Self-elaboration.

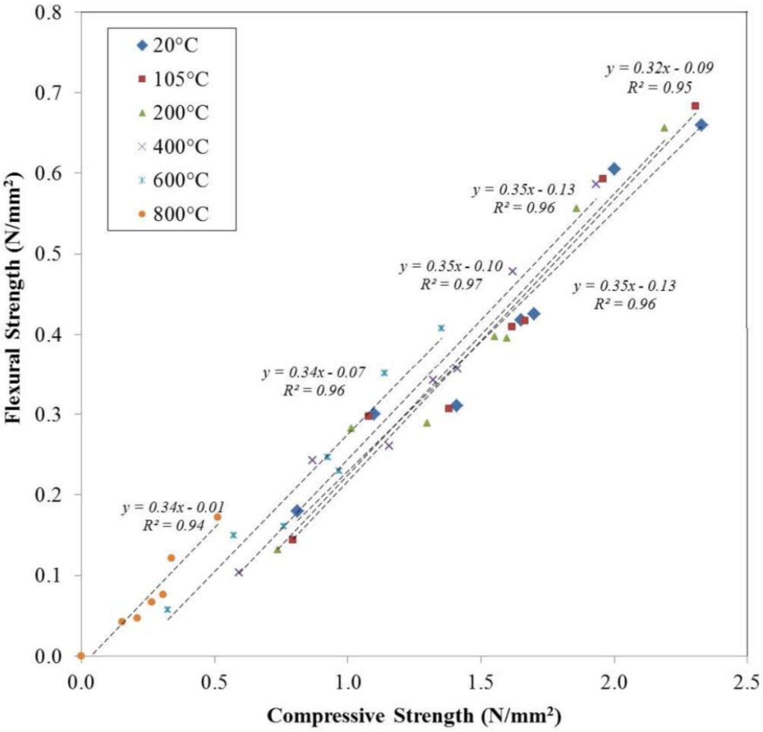


Figure 17. Correlation between flexural and compressive strengths at elevated temperature for 1050 kg/m^3 density. Source: Self-elaboration.

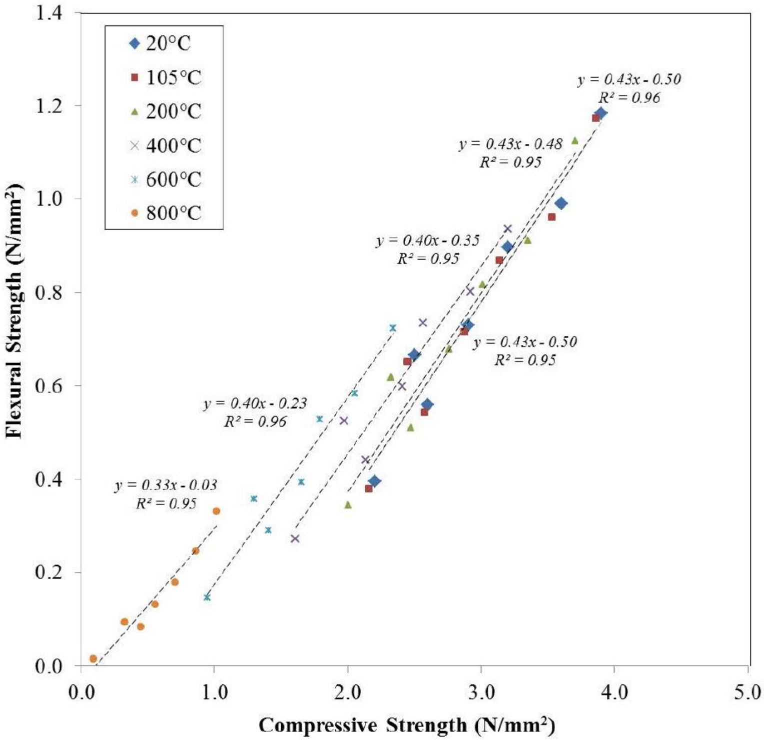
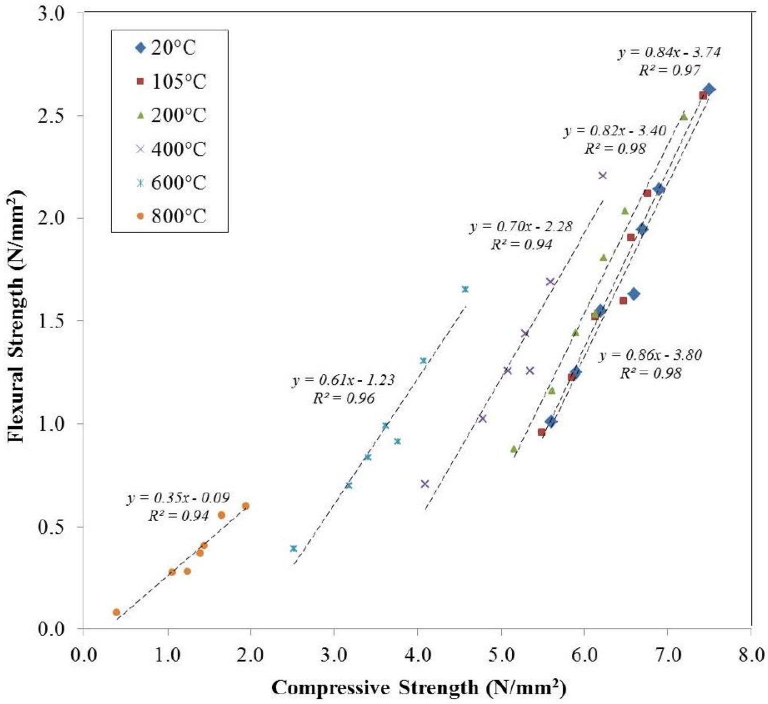


Figure 18. Correlation between flexural and compressive strengths at elevated temperature for 1450 kg/m^3 density. Source: Self-elaboration.



Conclusions

- One of the most imperative physical deterioration processes that impact the strength of concrete structures is high temperature. Hence, the boundless information on mechanical properties of fiber incorporated with foamcrete that is exposed to raise temperature is shown to be critical for a more extensive utilization of this material. The foamcrete samples were exposed to the temperatures of 100, 200, 400, 600, and 800°C in investigating the impact of elevated temperature on the compressive quality of the foamcrete samples.
- An increase in the temperature prompts the modifications in the foamcrete matrix. Foamcrete that is incorporated with natural fibers can offer progressively ductile structure contrasted with plain foamcrete matrix at high temperature.
- One of the expected outcomes refers to the compressive quality of foamcrete incorporated with CNF that decreases when the temperature increases. Meanwhile, the incorporation of CNF particularly enhanced the compressive quality at each predetermined temperature for all densities investigated in the present study. This demonstrates that CNF has strong bonding and good quality of chemical properties that are unique to it.
- The foamcrete lost its free or evaporable water and afterward the artificially bound water at the fundamental warming stage. The loss of water would support micro cracking that result in certain decrease in compressive strength. Meanwhile, the compressive quality of foamcrete gradually decreases between 100°C to 200°C because of the release of free water and some of the synthetically bound water. The decrease in compressive quality is due to the increase in chemical energy. In this case, further addition of the quantity of layers that are absorbed on the surface of the solids tends to increase the incoherent forces between the distinctive calcium silicate hydrate stratums.
- The decrease in foamcrete quality is insignificant considering that the compressive quality of the foamcrete samples with CNF at 200°C still managed to be kept on average 95% of the first unheated value for all densities. In this temperature range, the control foamcrete samples remained 90% on average of its original strength. The post peak compressive quality obviously features the role of CNF which shows that the stress distribution between the faces of the cracks by CNF is obvious and able to enhance ductility contrasted with the control foamcrete.
- In this case, calcium silicate hydrate gel deteriorated and the sulfoaluminate stages instigated cracks in the samples between the temperatures of 200°C to 400°C. These cracks formation leads to significant consequences for the compressive strength of foamcrete. Meanwhile, the control foamcrete quality at 400°C remained only around 73% of its initial value for each of the three densities. However, the compressive quality of foamcrete incorporated with CNF remained on average 81% of its room temperature strength for each of the three densities. This demonstrated that CNF has an uncracking impact by permitting the dissemination of fluid over

pressure in the cementitious matrix of foamcrete that allows higher compressive quality held at 400°C contrasted with the control samples.

- The dehydration of calcium hydroxide happens within the temperature scope of 400°C - 600°C, which leads to the shrinkage and strength loss of foamcrete. At the point when the temperature reached 600°C, foamcrete incorporated with CNF remained between on average 52%-61% of its initial value for each of the three densities. However, the compressive quality for control samples remained at normal percentage of 42% for 650 kg/m^3, 1050 kg/m^3, and 1450 kg/m^3 densities.
- The foamcrete incorporated with CNF around 800°C retained on average between 14%-29% of its initial value for each of the densities. However, the compressive quality for control specimens remained on the average of 7% for 1050 and 1450 kg/m^3 densities. Nevertheless, the samples totally lost its flexural quality for the density of 650 kg/m^3.
- The decrease in flexural strength of foamcrete happened mainly after 100°C despite the density of the foamcrete. This is in line with the alterations in the previously mentioned compressive quality of foamcrete, which demonstrates that the essential instrument that causes the degradation is micro cracking that occurs as the free water and synthetically bound water vanish from the permeable body.
- The development of cracks occurred when the substance constitution of foamcrete began to break down in the range of 200°C and 400°C because of the decay of calcium silicate hydrate and sulfoaluminate stages which caused a critical drop in flexural quality of foamcrete.
- The flexural quality of foamcrete incorporated with CNF at 400°C was about 74%-85% of the initial value for each of the three densities. Nevertheless, the flexural quality for foamcrete without incorporation of CNF remained on the average of 69% of its room temperature quality for each of the densities. This shows that CNF can prevent crack formation at high temperature, thus allowing intemperance of fluid over pressure in the cementitious matrix of foamcrete which then enables a more noteworthy flexural strength that remained at 400°C in contrast to the control specimens.
- Foamcrete reinforced with CNF remained on the average between 13%-26% of its initial value for each of the three densities at 800°C. Meanwhile, the compressive quality for control specimen remained an average of 5% for 1050and 1450 kg/m^3 densities. In any case, the sample with the density of 650 kg/m^3 completely lost its flexural quality.
- Overall, foamcrete incorporated with CNF obviously contributed to ductility enhancement. In addition, CNF is able to prevent crack formation at high temperature, thus allowing the intemperance of fluid over pressure in the cementitious matrix of foamcrete which produced more noteworthy compressive and flexural strengths.

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