

# **An Experimental Investigation of Mechanical Properties of Lightweight Foamed Concrete Subjected to Elevated Temperatures up to 600°C**

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## **Abstract**

Although Lightweight Foamed Concrete (LFC) has low mechanical properties compared to normal weight concrete, there is a possibility of using this material as partition or load-bearing wall in low-rise residential construction. Before it can be considered for use as a load-bearing element in the building industry, it is essential to obtain reliable information of its mechanical properties at ambient and elevated temperatures for quantification of its fire resistance performance. This paper will reports the results of experimental works that have been performed to examine and characterize the mechanical properties of LFC subjected to elevated temperatures. LFC with 650 and 1000 kg/m<sup>3</sup> density were cast and tested under compression and three point bending. The tests were carried out at ambient temperature, 100, 200, 300, 400, 500, and 600°C. The experimental results of this study consistently demonstrated that the loss in stiffness for cement based material like LFC at elevated temperatures occurs predominantly after about 90°C, regardless of density. This indicates that the primary mechanism causing stiffness degradation is microcracking, which occurs as water expands and evaporates from the porous body. As expected, reducing the density of LFC reduces its strength and stiffness. However, for LFC of different densities, the normalised strength and stiffness (ratio of elevated temperature value to ambient temperature value) – temperature relationships are very similar.

*Keywords: Lightweight foamed concrete; Lightweight concrete; Concrete material properties; Elevated temperatures; High temperatures, Lightweight material.*

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## **1. Introduction**

LFC is defined as a cementitious material having a minimum of 20 per cent by volume of mechanically entrained foam in the mortar slurry [1] in which air-pores are entrapped in the matrix by means of a suitable foaming agent. The air-pores are initiated by agitating air with a foaming agent diluted with water; the foam then carefully mixes together with the cement slurry to form LFC. Integrating the air-pores into the base matrix gives a low self-weight, high workability, excellent insulating values, but lower strength in contrast to normal strength concrete. LFC can be fabricated anywhere in any shape or building unit size. Over the past 20 years, LFC has primarily been used around the world for bulk filling, trench reinstatements, backfill to retaining walls and bridge abutments, insulation to foundations and roof tiles, sound insulation, stabilising soils

(especially in the construction of embankment slopes), grouting for tunnel works, sandwich fill for precast units and pipeline infill. However, in the last few years, there is developing interest in using LFC as a lightweight non-structural and semi-structural material in buildings to take advantage its lightweight and good insulation properties [2].

It should be pointed out that most of the investigations on LFC so far have focused on its ambient temperature properties only [3-8]. Among these, the majority are about mechanical properties of LFC [3,6,7] with only a very few on its thermal properties [4]. Quantitative information on fire resistance performance is extremely sparse. Nevertheless these available investigations do give some useful data of LFC mechanical properties at ambient temperature which can be used as the basis of further research.

For cement-based material like LFC, the degradation mechanisms upon exposure to high temperatures comprise of mechanical damage as well as chemical degradation; where each mechanism is dominant within a specific temperature range. Lin et al. [9] conducted studies to examine the microstructure of concrete exposed to elevated temperatures in both actual fire and laboratory conditions with the assistance of Scanning-Electron-Microscopy (SEM) and stereo microscopy. They established that the absorption of moisture from the surrounding medium provides a mechanism for the rehydration of calcium oxide and un-hydrated cement grains that refilled the void spaces. They observed long irregular fibers of calcium silicate hydrate (C-S-H) gel merged with ettringite (hexacalcium aluminate trisulfate hydrate) and calcium hydroxide (C-H) crystals formed as a result of rehydration.

In a study carried out by Schneider and Herbst [10], chemical reactions and the behaviors of calcium hydroxide, calcium carbonate, calcium silicate hydrate, non-evaporable water and micropores under various temperatures was examined. They found that the major increase of concrete permeability and porosity at high temperature was primarily produced by arising micro cracks and by changes of material inner structure, as well as by crack opening due to high gas pressure values. As a result, the permeability of concrete depends not only on temperature levels, moisture content and gas pressure but also upon the degree of cracks development.

As a two phase material with solid cement and air voids, the degradation mechanisms of LFC are principally caused by deprivation of the cement paste. Even though both mechanical and chemical degradation result in degradation of mechanical properties, the mechanisms take place at considerably different temperature ranges. The dehydration process in the cement paste becomes significant at temperatures above about 110 °C [11] and diminishes the calcium silicate hydrate (C-S-H) links which provide the primary load-bearing formation in the hydrated cement. Furthermore, due to low permeability of the cement paste, internal water pressure is built up during dehydration of the hydrated C-S-H, which increases internal stresses and induce micro cracks in the material from about 300°C, resulting in decreased strength and stiffness of the material [12]. At higher temperatures around 450°C, calcium hydroxide ( $\text{Ca(OH)}_2$ ), which is one of the most vital compounds in cement paste, dissociates, resulting in the shrinkage of LFC [13]. If the hot LFC is exposed to water, as in fire fighting,  $\text{CaO}$  in LFC turns into  $\text{Ca(OH)}_2$  to cause cracking and destruction of LFC. It is still extremely difficult to accurately predict these mechanisms and experimental investigation remains essential.

Therefore, the aim of this study is to experimentally examine and characterize the mechanical properties of LFC at elevated temperatures. Tests were carried out at different temperatures up to 600°C. Extensive compressive and bending strength tests will be performed for LFC of densities of 650 kg/m<sup>3</sup> and 1000 kg/m<sup>3</sup>.

## **2. Significance of research**

LFC is a relatively new construction material compared to normal strength concrete. The major factor limiting the use of LFC in applications is insufficient knowledge of the material performance at elevated temperatures. In building application, load carrying capacity and fire resistance are the

most important safety requirements. In order to comprehend and eventually predict the performance of LFC based systems, the material properties at ambient temperature and elevated temperatures must be known at first stage. To be able to predict the fire resistance of a building structure, the temperatures in the structure must be determined. For quantification of structural performance, knowledge of the mechanical properties, at elevated temperatures of the material is essential. LFC mechanical properties will be established, including compressive strength, compressive modulus, strain at maximum compressive strength, compressive stress-strain relationship, failure modes, flexural tensile strength and flexural tensile modulus.

### 3. Mix design and material constituents of LFC

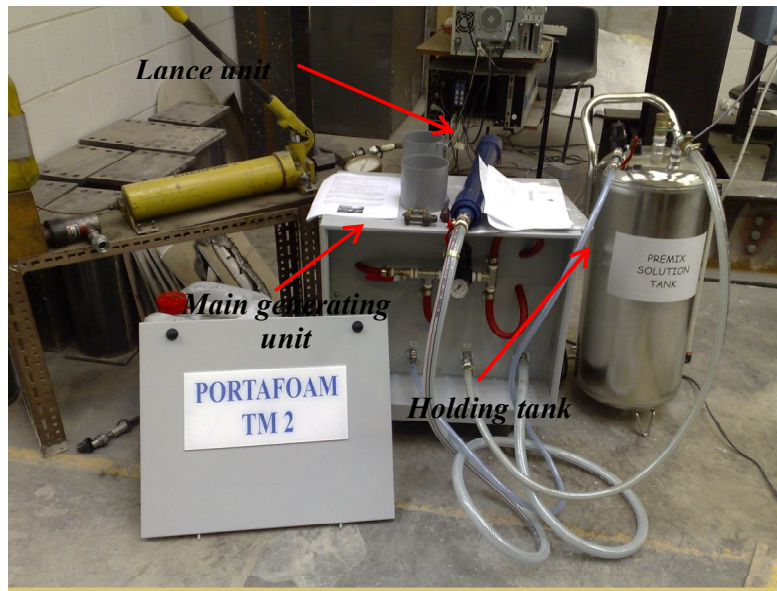
The LFC used in this study was made from ordinary Portland cement, fine sand, water and stable foam. Table 1 lists the details of the constituent materials. The main objectives of this research are to determine the mechanical properties of LFC at high temperatures. Therefore only a constant cement-sand ratio of 2:1 and water-cement ratio of 0.5 were used for all batches of LFC samples made for this research. A high cement-sand ratio (2:1) was chosen to achieve better compressive strength and water-cement ratio of 0.5 was found acceptable to achieve adequate workability [14]

LFC samples of two densities of 650 and 1000 kg/m<sup>3</sup> were cast and tested for mechanical properties test. The 650 kg/m<sup>3</sup> density was selected so as to enable comparison of mechanical performance between LFC and that of other building materials of similar density, such as gypsum board; the 1000 kg/m<sup>3</sup> density was used because LFC of this density would have a useful amount of mechanical properties to make it viable as a light load bearing infill material, which may be combined with thin-walled steel in lightweight composite panel construction.

**Table 1** Constituent materials used to produce LFC

Constituents	Type
Cement	Ordinary Portland cement [15]
Sand	Fine sand with additional sieving to eradicate particles greater than 2.36 mm, to improve the LFC flow characteristics and stability [16]
Stable foam	Noraite PA-1 (protein-based) surfactant with unit weight of around 70 to 80 gram/litre produced from Portafoam TM2 System. The surfactant solution consists of one part of surfactant to 33 parts of water.

All LFC samples for mechanical properties test were made in house. The stable foam was produced using foam generator Portafoam TM2 System (Figure 1), acquired from the Malaysian manufacturer ([www.portafoam.com](http://www.portafoam.com)). This system runs from an air compressor and consists of a main generating unit, a foaming unit, and a lance unit. The protein based foaming agent used was Noraite PA-1 which is suitable for LFC densities ranging from 600 kg/m<sup>3</sup> to 1600 kg/m<sup>3</sup>. Three identical specimens were prepared for each density and were tested at 28 days after mixing.



**Figure 1.** Portafoam TM2 foam generator system.

#### **4. Test methods**

A variety of test methods may be used to obtain different aspects of mechanical properties of materials at high temperatures, including the stressed test, the unstressed test, and the unstressed residual strength test [17]. In this research, the unstressed test method was adopted for convenience. In the unstressed test, the sample is heated, without preload, at a steady rate to the predetermined temperature. While maintaining the target temperature, load is applied at a prescribed rate until sample failure. Because the temperature is unchanged, the test is also referred to as steady state test, as opposed to transient test in which the specimen temperature changes with time.

##### **4.1 Heating of specimens**

Electric furnace was used for heating the LFC specimens to the various steady-state temperatures (100°C, 200°C, 300°C, 400°C, 500°C and 600°C). The furnace temperature exposure profiles were produced by a programmable microprocessor temperature controller attached to the furnace power supply and monitored by a Type K thermocouple located in the furnace chamber. Pre-testing checking of the furnaces showed that the furnace controller and furnace power system could maintain furnace operating temperatures within  $\pm 1^\circ\text{C}$  over the test range.

##### **4.2 Compression Test**

The compressive strength tests were carried out on 100 x 200 mm cylinders. To monitor the strain behaviour at ambient temperature during loading, two strain gauges were fitted on each sample for the ambient test only. Since no strain measurement was made at elevated temperatures, the ambient temperature strain measurements were used to confirm that the strain calculated based on the displacement of the loading platen was of sufficient accuracy. Four Type K thermocouples were installed in the central plane of each cylinder specimen. Loading was applied using an ambient temperature compression machine (Figure 2) after removing the test samples from the furnace (Figure 3). To minimise heat loss from the specimen to atmosphere, each specimen was wrapped with insulation sheets immediately after being removed from the electric furnace. For each set of test, three replicate tests were carried out to check consistency of the results.



**Figure 2.** Compression test using ambient temperature machine



**Figure 3.** High temperature electric furnace with specimens

#### **4.3 Three point bending test**

For convenience in this study, the three point bending test was carried out. The preparation of samples followed a similar procedure as delineated above for the compression tests. The specimens were rectangular parallelepipeds of height ( $h$ ) 25 mm, width ( $w$ ) 125 mm and length ( $l$ ) 350 mm. As shown in Figure 4, the LFC specimen was simply supported and was subjected to point load at the centre point. The length between the supports was  $L_s = 200$  mm, giving a  $L_s/h$  aspect ratio of 8 and sufficient to ensure predominance of bending behaviour. The load-deflection was recorded for the evaluation of flexural tensile strength.





**Figure 4.** Three point bending test set up and specimen dimensions

#### **4.4 Porosity measurements**

The porosity of LFC was determined by using the Vacuum Saturation Apparatus [18]. The porosity was calculated using the following equation:

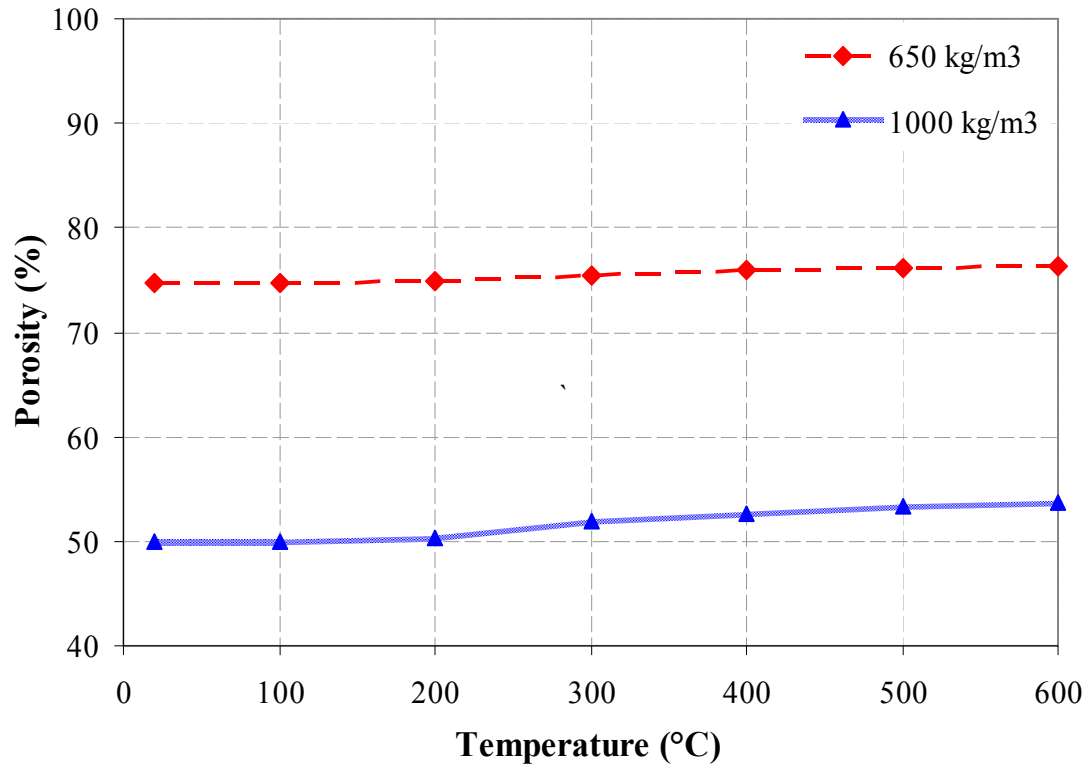
$$\varepsilon = \frac{(W_{sat} - W_{dry})}{(W_{sat} - W_{wat})} \times 100 \dots (1)$$

where  $\varepsilon$  is the porosity (%),  $W_{sat}$  is the weight in air of saturated sample,  $W_{wat}$  is the weight in water of saturated sample and  $W_{dry}$  is the weight of oven-dried sample.

### **5. Results and discussion**

#### **5.1 Porosity of LFC**

Usually, the porosity of cement based material changes when the temperature increases. These changes in porosity can be characterized by considering phase changes in the concrete at different temperatures. Figure 5 presents the total porosity for each mix as a function of the temperature. LFC of both densities experienced a slight monotonous increase in porosity with temperature. The initial porosity for 650 and 1000 kg/m<sup>3</sup> density was 74.8% and 50.0% respectively. Between 200°C and 300°C, the porosity increased considerably for the higher density LFC while the increase was more moderate for the lower density LFC due to decomposition of the different amounts of calcium silicate hydrate gel and sulfoaluminate. At 300°C, the measured porosity for 650 and 1000 kg/m<sup>3</sup> density was 75.5% and 51.9% correspondingly. For temperatures beyond 400°C, the measured porosity showed some increase corresponding to the decomposition of calcium hydroxide to form calcium oxide. At 600°C, the porosity was 76.3% and 53.7% for 650 and 1000 kg/m<sup>3</sup> respectively. Nevertheless, in general, due to the high porosity at ambient temperature, LFC may be considered to have constant porosity at various elevated temperatures.



**Figure 5.** Porosity of LFC as a function of temperature

Figures 6 show the pore size of LFC determined through image analysis tool which illustrate images of the internal structure of the 1000 kg/m<sup>3</sup> and 650 kg/m<sup>3</sup> density LFC at ambient temperature. From Figures 6, it can be seen that the void sizes are not uniform and the average void size is primarily a function of the LFC density. The same analysis of the images was also done for both densities after being exposed to high temperatures and the results indicate that the void size did not change much from that at ambient temperature.



(a) 650 kg/m<sup>3</sup> density



(b) 1000 kg/m<sup>3</sup> density

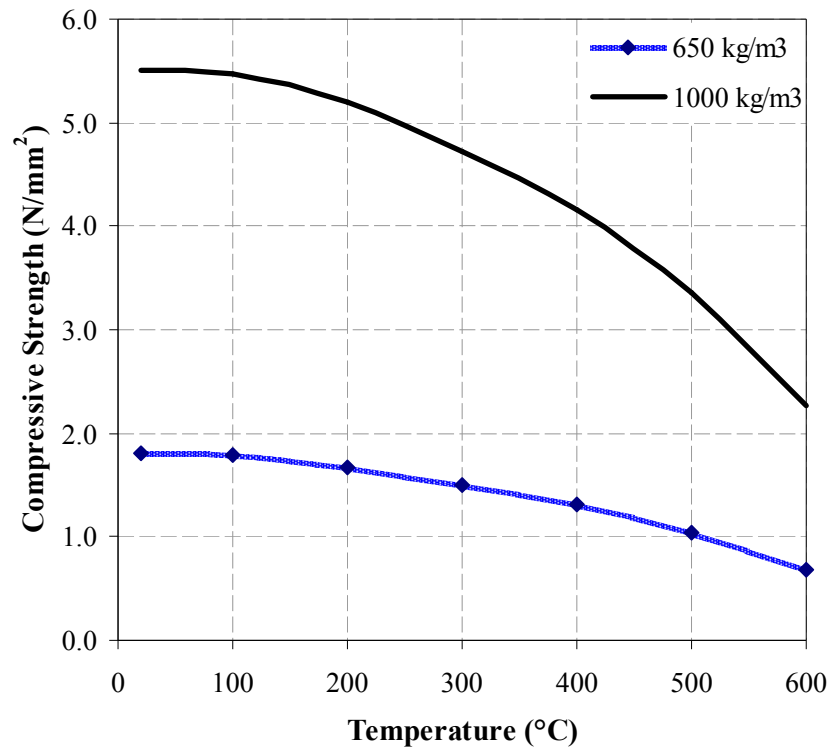
**Figure 6.** Pore sizes of LFC

## **5.2 Compressive strength of LFC**

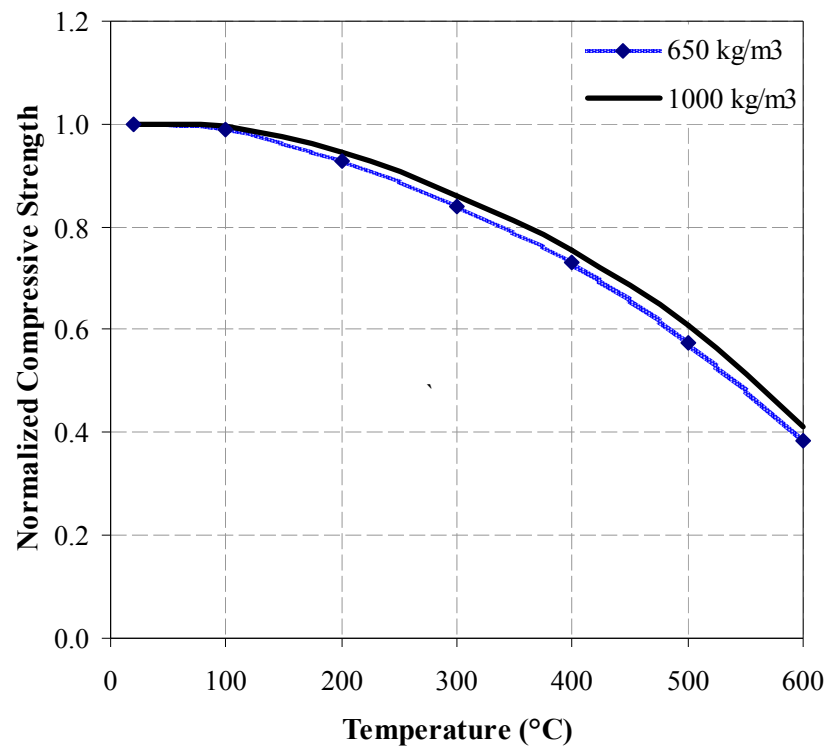
Figures 7 and 8 illustrate the compressive strength and normalized compressive strength of LFC as a function of temperature. It can be seen from Figures 7 and 8 that, for both densities, the LFC compressive strength decreased with temperature. On initial heating, the LFC made with Ordinary Portland Cement lost the absorbed, evaporable (free) water and then the chemically bound water. The loss of water would induce micro cracking resulting in some reduction in compressive strength. The compressive strength decreased slowly between 90°C to 170°C which due to the release of free water and some of the chemically bound water. The decrease in compressive strength between 20°C and 150°C corresponds to a reduction of the cohesion of the Van der Waal forces between the calcium silicate hydrate layers [18]. This decreases the surface energy of calcium silicate hydrate and leads to the formation of silanol groups (Si–OH: OH–Si) that presents weaker bonding strength. However, because this change only affects the concrete superficially, the reduction in concrete strength is not significant and the compressive strength of the LFC samples at 200°C still retained about 94% of the original unheated value. Between 200 °C and 400°C, decomposition of C-S-H gel and the sulfoaluminate phases caused cracks in the specimens [13]. These cracks had significant effects on the compressive strength of LFC [20]. At 400 °C, the LFC strength retained only about 75% of its initial value for both densities. Further degradation and loss of strength continued to take place at high temperatures. At temperature of 600°C, the LFC retained only about 40% of the original strength for both densities. Since the compositions of both densities of LFC are identical,



except for increased pores in the lower density LFC, it is not surprising that the normalised strength – temperature relationships of LFC of both densities are almost the same.



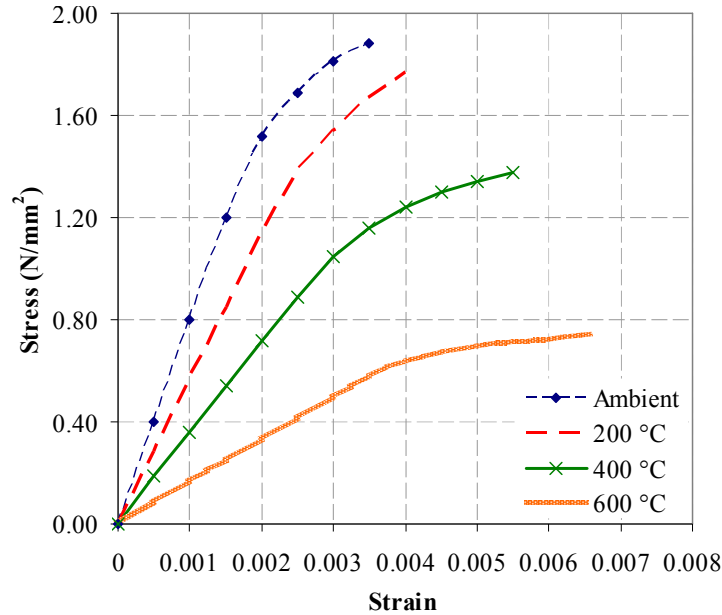
**Figure 7.** Compressive strength of LFC as a function of temperature



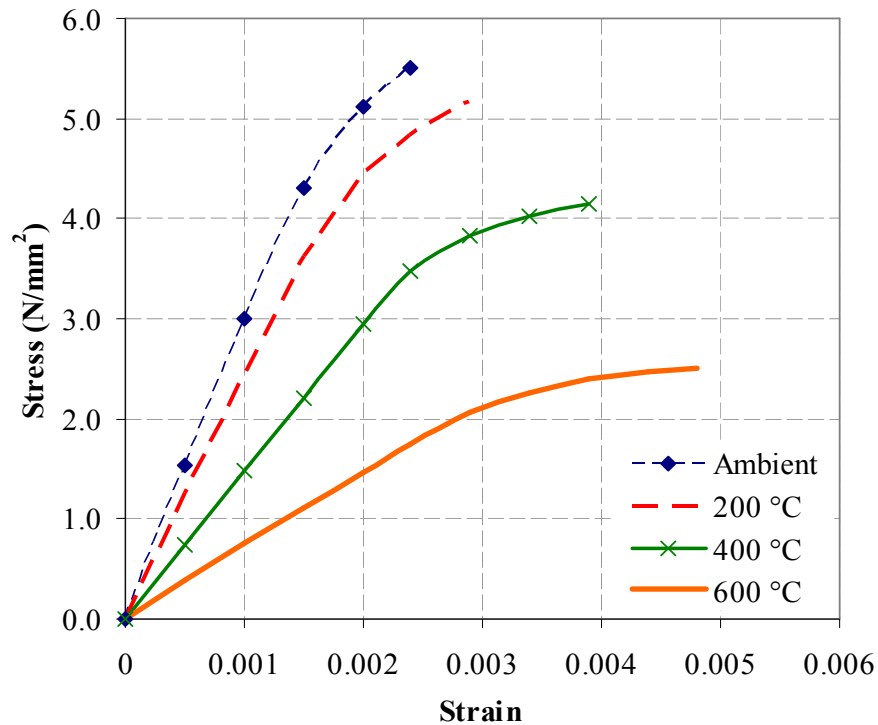
**Figure 8.** Normalized compressive strength of LFC as a function of temperature

### 5.3 Compressive stress-strain relationship of LFC

The tests were displacement controlled where the crack continued to develop and grew after the peak load was reached. However, since the test specimens failed in a brittle manner after reaching the peak stress, it was not possible to obtain the descending branch of the stress-strain relationship. Figures 9 and 10 present the average stress-strain curves at all different testing temperatures for the two densities.



**Figure 9.** Average LFC stress-strain relationships for 650 kg/m<sup>3</sup> density at different temperatures

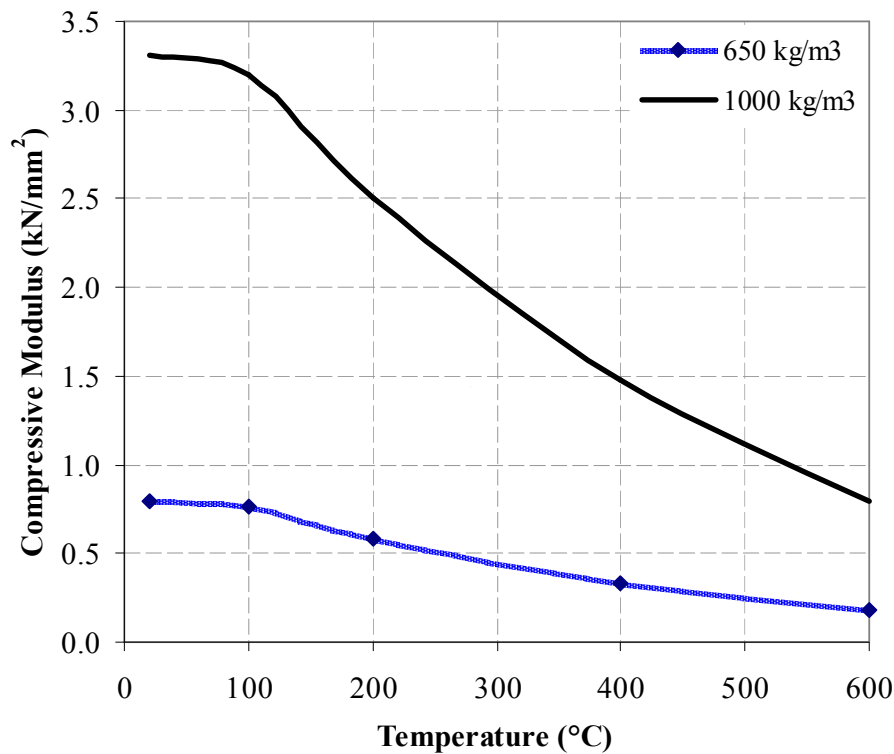


**Figure 10.** Average LFC stress-strain relationships for 1000 kg/m<sup>3</sup> density at different temperatures

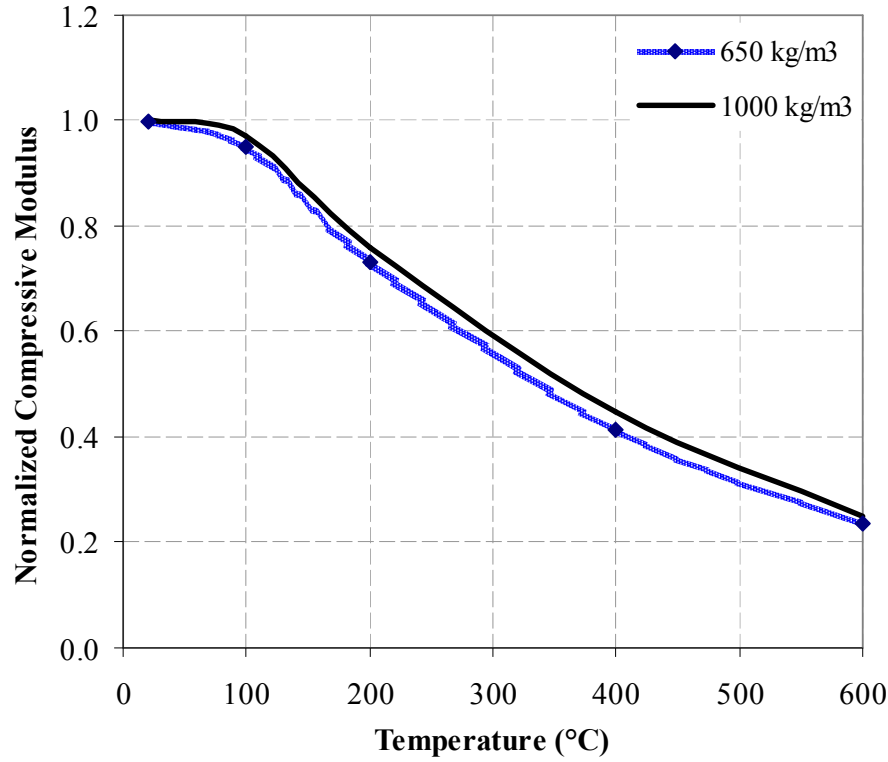
It can be seen from Figures 9 and 10 that for both densities at all temperature levels, the ascending branch was linear for stress up to 75% of the peak strength. The strain corresponding to the peak strength increased at increasing temperatures. For LFC of 650 kg/m<sup>3</sup> density, the maximum strains were 0.0034, 0.0039, 0.0055 and 0.0066 at ambient temperature, 200°C, 400°C and 600°C respectively; for the 1000 kg/m<sup>3</sup> density, the corresponding values were 0.0024, 0.0029, 0.0039 and 0.0048 at ambient, 200°C, 400°C and 600°C respectively. The increase in strain results from opening of cracks initiated by the heating at higher temperatures.

#### 5.4 Modulus of elasticity of LFC in compression

Figures 11 and 12 demonstrate the changes in modulus of elasticity of LFC in compression as a function of temperature. The modulus of elasticity was taken as the secant modulus at the point where the material changed from elastic to plastic behavior from the experimental compressive stress–strain curve. Compared to the reduction in LFC strength, the reduction in elastic modulus is greater. Both figures show that the loss in modulus of elasticity began immediately upon heating when the samples began to dry. The modulus of elasticity at 200°C, 400°C and 600°C was respectively about 75%, 40% and 25% of the original value for both densities. As with changes in normalised strengths of LFC of both densities at elevated temperatures, the normalised modulus of elasticity of LFC of both densities at the same temperature are almost the same.



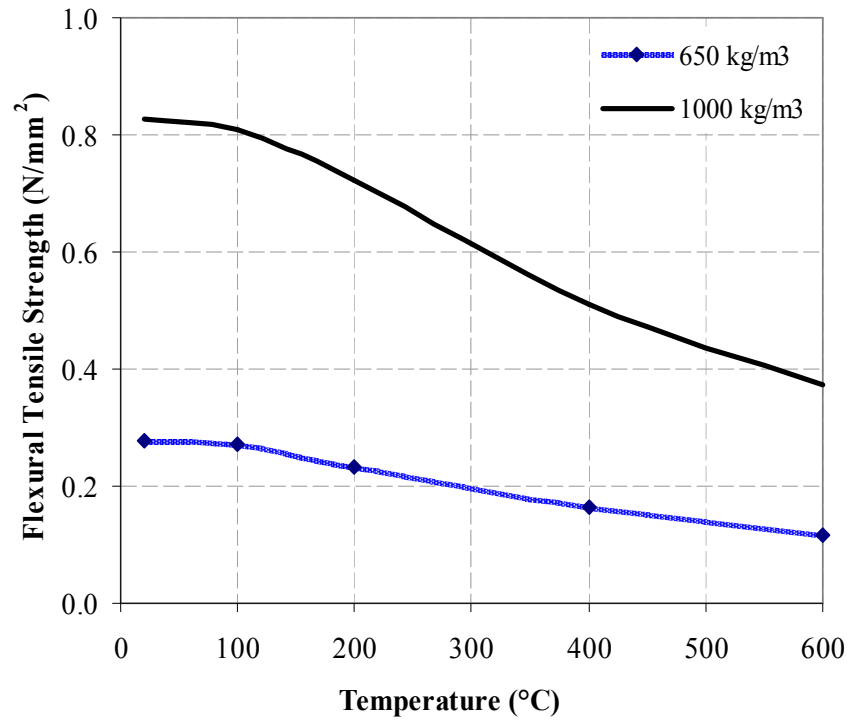
**Figure 11** Compressive modulus of LFC as a function of temperature



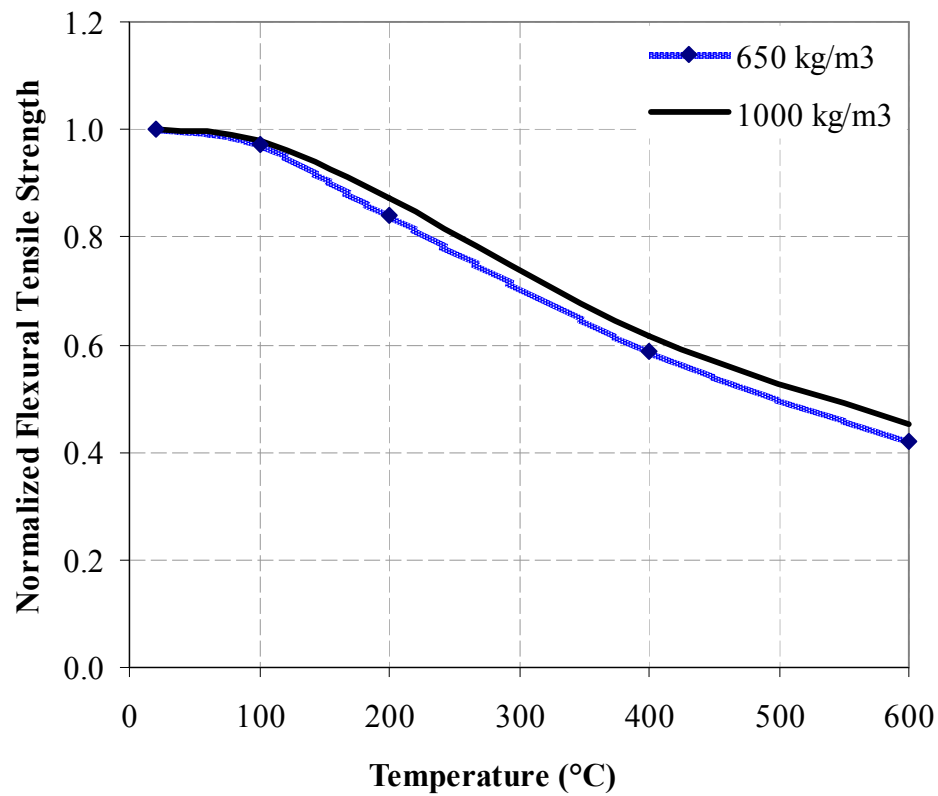
**Figure 12** Normalized compressive modulus of LFC as a function of temperature

### 5.5 Flexural tensile strength of LFC

Since LFC is a brittle material, the bending test was intended to give a measure of the flexural tensile strength of the LFC. Figures 13 and 14 present the variation in flexural tensile strength of LFC as a function of temperature. The reduction in flexural tensile strength of LFC occurred predominantly after 90°C, regardless of the density of LFC. Consistent with changes in the aforementioned mechanical properties of LFC, which indicates that the primary mechanism causing degradation is micro cracking, which occurs as the free water and chemically bound water evaporates from the porous body. When the chemical constitution of LFC started to break down between 200°C and 300°C due to decomposition of the C-S-H and sulfoaluminate phases ( $3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot \text{CaSO}_4 \cdot 12\text{H}_2\text{O}$  and  $3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 3\text{CaSO}_4 \cdot 31\text{H}$ ), cracks formed followed by a significant drop in tensile strength. At 400°C, the tensile strength was about 60% of the initial value for both densities. At 600°C, the flexural tensile strength was only about 40% and 45% for 650 kg/m³ and 1000 kg/m³ densities respectively.



**Figure 13** Flexural tensile strength of LFC as a function of temperature

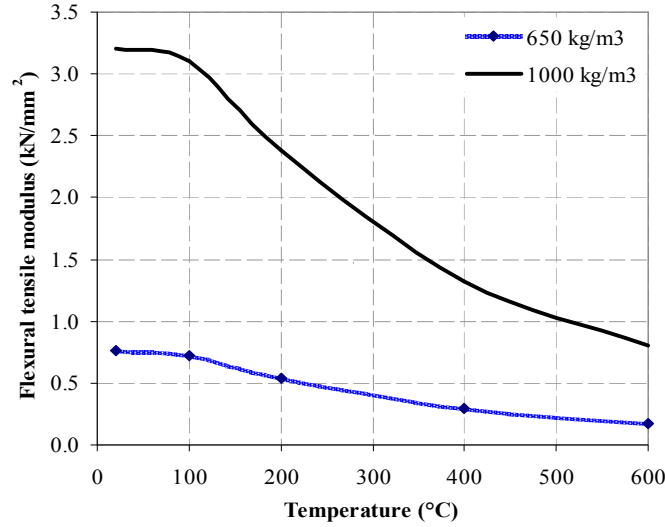


**Figure 14** Normalized flexural tensile strength of LFC as a function of temperature

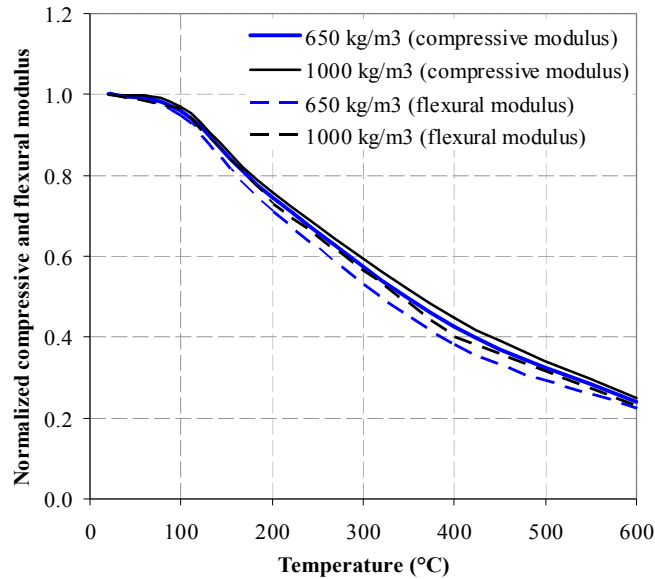


## 5.6 Flexural tensile modulus of LFC

Figures 15 and 16 illustrate the changes in flexural modulus of LFC as a function of temperature and comparison of the normalized flexural modulus with the normalized compressive modulus obtained from the cylinder tests. Although there are some differences, the variation of the normalized compressive modulus and normalized flexural modulus values are very similar for both densities at various temperatures.



**Figure 15** Flexural tensile modulus of LFC as a function of temperature



**Figure 16** Comparison of normalized compressive modulus and flexural tensile modulus of LFC as a function of temperature

## 6.0 Conclusions

This paper has presented the results of a series of experimental studies to study the mechanical properties of LFC at elevated temperatures. Compressive cylinder tests and three point bending tests were carried out for two different LFC densities at various temperatures from ambient up to 600°C. The mechanical properties included compressive cylinder strength, compressive modulus of elasticity, compressive stress-strain relationship, strain at the maximum compressive stress, porosity, flexural bending strength and modulus of elasticity.

The experimental results consistently demonstrate that the loss in stiffness for cement based material such as LFC at elevated temperatures occurs predominantly after about 90°C, regardless of density. This indicates that the primary mechanism causing stiffness degradation is microcracking, which occurs as water expands and evaporates from the porous body. As expected, reducing the density of LFC reduces its strength and stiffness. However, for LFC of different densities, the normalised strength and stiffness (ratio of elevated temperature value to ambient temperature value) –temperature relationships are very similar.

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