



Experimental Investigation of Stress-Strain Behaviour of Lightweight Foamed Concrete under Axial Compression after Exposure to Elevated Temperatures

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ABSTRACT

Even though lightweight foamed concrete has low mechanical properties compared to normal weight concrete, there is a potential 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 necessary to acquire reliable information of its mechanical properties at ambient and high temperatures for quantification of its fire resistance performance. This paper will present the results of experiments that have been carried out to examine and characterize the compressive stress-strain relationship of foamed concrete at high temperatures. Foamed concrete with 650 kg/m³ and 1000 kg/m³ density were cast and tested. The compression tests were carried out at ambient temperature, 100, 200, 300, 400, 500 and 600°C.

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Introduction

Foamed concrete is not a new material in the construction industry. It was first patented in 1923 (Valore, 1954) and a limited scale of production was instigated in 1923. The use of foamed concrete was very limited until the late 1970s, when it was started to be consumed in Netherlands for ground engineering applications and voids filling works. In 1987 a full-scale assessment on the application of foamed concrete as a trench reinstatement was carried out in the United Kingdom and the achievement of this trial led to the extensive application of foamed concrete for trench reinstatement and other applications followed (Brady et al., 2001). Since then, foamed concrete as a building material has become more widespread with expanding production and range of applications.

Although foamed concrete has low mechanical properties in comparison with normal weight concrete, there is a possible of utilizing this material as partition or load-bearing wall in low-rise residential construction. Before it can be considered for use as a load-bearing component, it is essential to obtain dependable information of its mechanical properties at ambient and high temperatures for quantification of its fire resistance performance. Mechanical properties of concrete due to exposure to high temperatures have been studied since a long time ago. Nevertheless, there is no such extensive study of mechanical properties of foamed concrete at high temperatures.

Lin et al. (1996) conducted studies to investigate the microstructure of concrete exposed to high temperatures in both actual fire and laboratory conditions with the assistance of Scanning-Electron-Microscopy (SEM) and stereo microscopy. They found that the absorption of moisture from the surrounding medium provides a mechanism for the rehydration of calcium oxide and unhydrated cement grains that refilled the void spaces. They observed that long irregular fibers of C-S-H gel combined with ettringite and C-H crystals and formed as a result of rehydration.

In a study carried out by Schneider and Herbst (1989), chemical reactions and the behavior 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 microcracks 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 crack development.

It can be pointed out that the degradation mechanisms of cement-based material like foamed concrete upon exposure to high temperatures include chemical degradation and mechanical deterioration where each mechanism is dominant within a specific temperature range. The dehydration process in the cement paste becomes significant at temperatures above about 110 °C (Khoury et al., 2002) 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 built up during dehydration of the hydrated C-S-H, which increases internal stresses and induce microcracks in the material from about 300°C, resulting in decreased strength and stiffness of the material (Hertz, 2005). At higher temperatures around 450°C, calcium hydroxide (Ca(OH)₂), which is one of the most vital compounds in cement paste, dissociates, resulting in the shrinkage of foamed concrete.

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 (Phan and Carino, 2003). In this research, the unstressed test method was adopted for convenience. In the unstressed test, the sample was heated, without preload, at a steady rate to the predetermined temperature. While maintaining the target temperature, load was 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.

Set-Up For Compression Tests



Figure 1. High temperature electric furnace with specimens

Two different electric furnaces were used for heating the foamed concrete specimens to the various steady-state temperatures. One furnace had a maximum operating temperature of 450°C (low temperature furnace), and the second furnace had a maximum operating temperature of 1000°C (high temperature furnace). Each of the furnaces was capable of holding three specimens. The low temperature furnace had a temperature range of 50°C to 450°C and was used for four of the reported thermal exposure conditions: 100°C, 200°C, 300°C and 400°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. The high temperature furnace (Figure 1) had a maximum operating temperature of 1000°C. This furnace was used for exposing concrete specimens to 500°C and 600°C. This furnace was also controlled by a programmable microprocessor temperature controller attached to the furnace power supply based on feedback temperature reading from a Type K thermocouple located in the furnace chamber. Pre-testing checking of the furnaces showed that both furnace controllers and furnace power system could keep furnace operating temperatures within $\pm 1^\circ\text{C}$ over the test range.

The compressive tests were carried out on 100 x 200 mm cylinders. The specimens were removed from moulds after 24 hours of casting and then cured in a water tank at $20 \pm 2^\circ\text{C}$ for 28 days. Prior to testing, the specimens were removed from the curing tank and put in the oven for 24 hours at 105°C. After 24 hours, all the specimens were removed from the oven and their ends were ground flat. To monitor the strain behaviour at ambient temperature during loading, two strain gauges was fitted on each sample for the ambient test only. These ambient temperature strain measurements were used to confirm that the strain calculated based on the displacement of the loading platen was of sufficient accuracy. Since it was difficult to measure strain at high temperatures, the displacement of the loading platen was used to calculate the strain for the high temperature tests. Four Type K thermocouples were installed in the central plane of each cylinder specimen to measure the specimen temperature, as shown in Figure 2.

Loading was applied using an ambient temperature machine after removing the test samples from the furnace. Each specimen was wrapped with insulation sheets immediately after being removed from the electric furnace to minimise heat loss from the specimen to atmosphere. For each set, three replicate tests were carried out to check consistency of results. The target temperatures were 20°C (room temperature), 100, 200, 300, 400, 500, and 600°C.

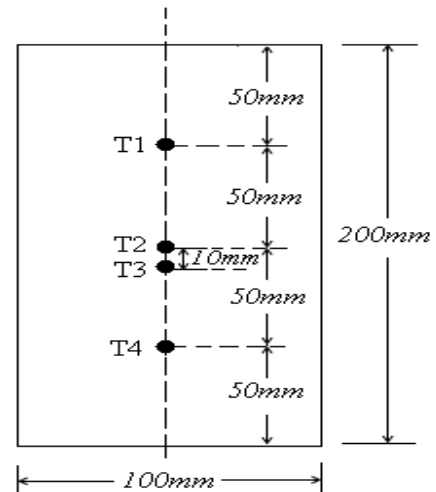


Figure 2. Typical 100 x 200 mm cylinder specimen with thermocouples arrangement

During the loading process, the temperature of each sample (thermocouple T3) was measured and it was found that the temperature was stable throughout the testing period. Figure 3 shows typical temperature variations throughout the loading phase for specimens of 1000 kg/m³ density. As can be seen, because the duration of loading was short (just over one minute), there was very little heat loss and the temperature change was less than 0.5°C.

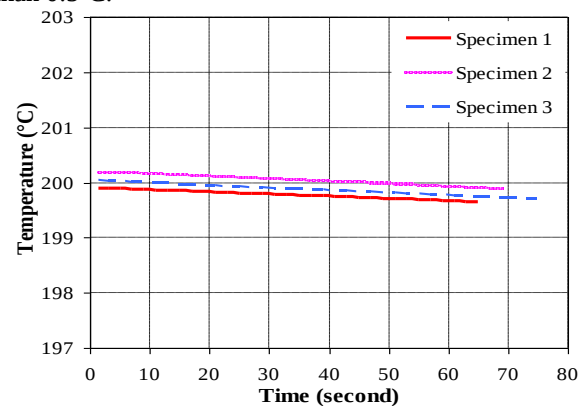


Figure 3. Temperature change during test of specimens of 1000 kg/m³ density at target temperature of 200°C

Results And Discussions

The engineering stress-strain relationships of foamed concrete were determined from the measured load and deflection results using the original specimen cross-sectional area A_0 and length L_0 . Due to difficulty of using strain gauges at high temperatures, the deflection used to calculate the strain was that of the movement of the loading platen. Strains were measured at ambient temperature to confirm this method. Figure 4 compares the measured strain and that calculated using the displacement of the loading platen for the ambient temperature test. This comparison demonstrates that it is sufficiently accurate to use the loading platen displacement to calculate the axial strain of the test specimen.

The tests were displacement controlled where the crack continue to develop and grow after the peak load is 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 5-8 present typical stress-strain relationships for the three duplicate samples at different temperatures for the 650 kg/m³ density specimens and Figures 9-12 are for the 1000 kg/m³ density specimens. It was clear that all the three duplicate samples

produced very consistent results. Figures 13 and 14 present the average stress-strain curves at all different testing temperatures for the two densities.

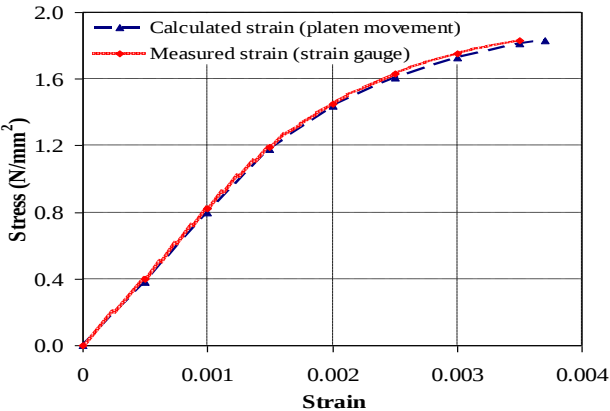


Figure 4. Comparison of measured strain and calculated strain (based on movement of the loading platen) for foamed concrete of 650 kg/m³ density at ambient temperature

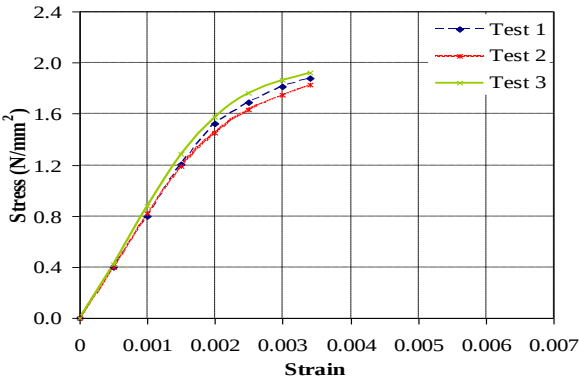


Figure 5. Stress-strain relationship for foamed concrete of 650 kg/m³ at ambient temperature

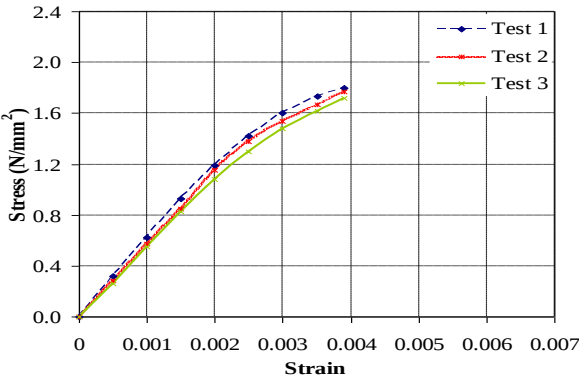


Figure 6. Stress-strain relationship for foamed concrete of 650 kg/m³ at 200°C

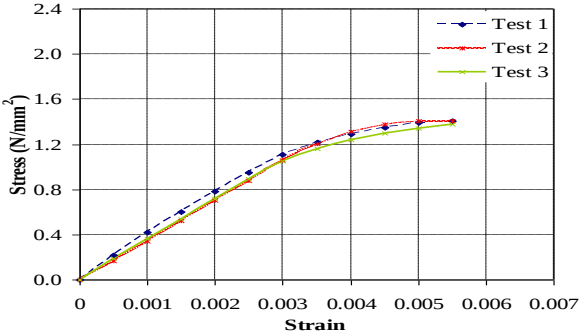


Figure 7. Stress-strain relationship for foamed concrete of 650 kg/m³ at 400°C

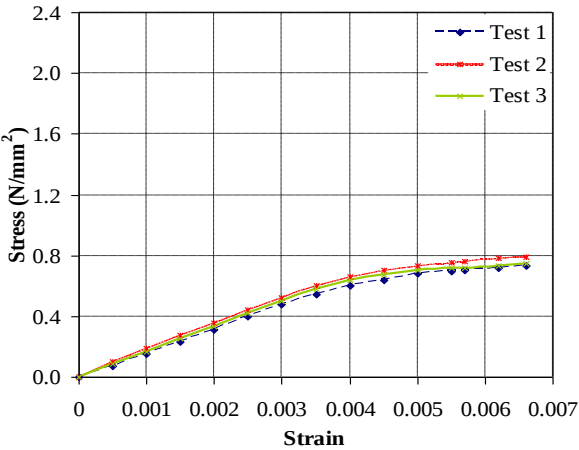


Figure 8. Stress-strain relationship for foamed concrete of 650 kg/m³ at 600°C

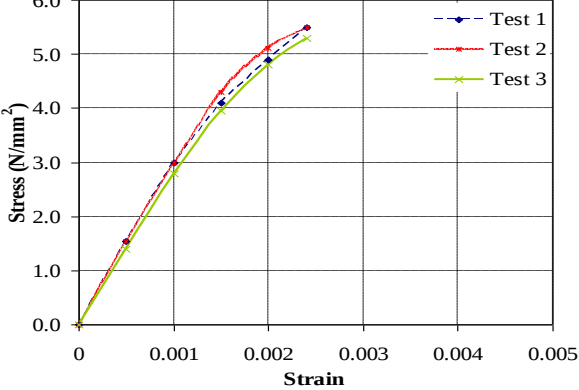


Figure 9. Stress-strain relationship for foamed concrete of 1000 kg/m³ at ambient temperature

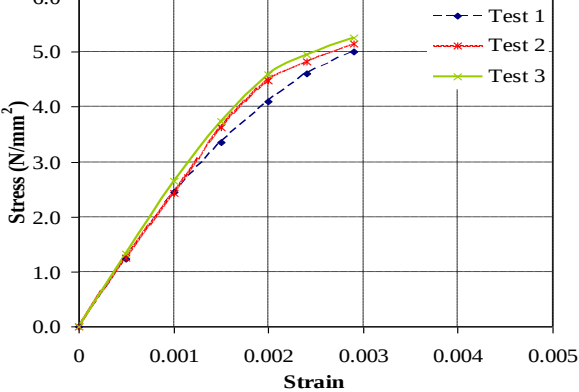


Figure 10. Stress-strain relationship for foamed concrete of 1000 kg/m³ at 200°C

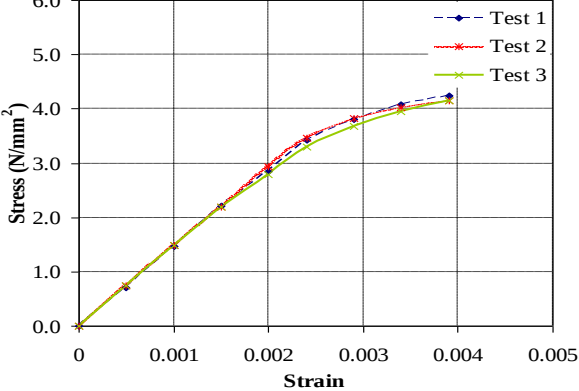


Figure 11. Stress-strain relationship for foamed concrete of 1000 kg/m³ at 400°C

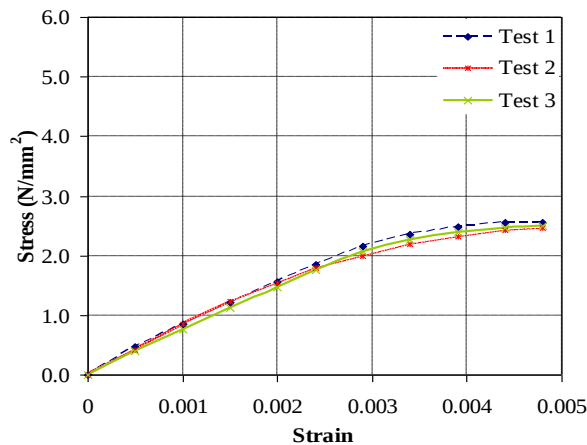


Figure 12. Stress-strain relationship for foamed concrete of 1000 kg/m³ at 600°C

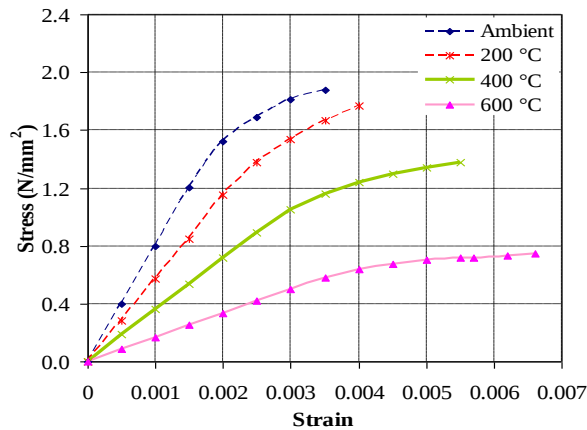


Figure 13. Average stress-strain relationships for foamed concrete of 650 kg/m³ at different temperatures

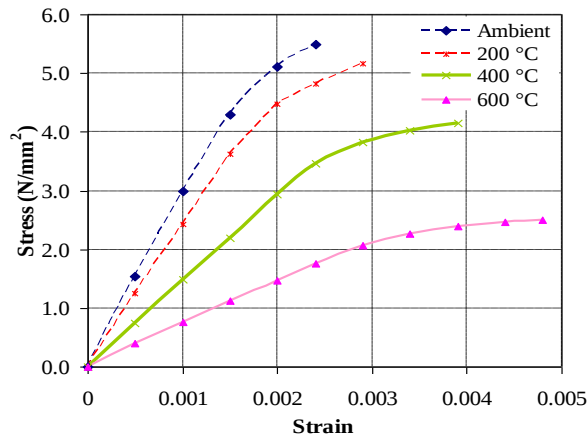


Figure 14. Average stress-strain relationships for foamed concrete of 1000 kg/m³ at different temperatures

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 foamed concrete of 650 kg/m³ 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/m³ 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. Table 1

shows, for both densities and all temperatures, the elastic strain at the maximum stress, the maximum strain at the maximum stress and the ratio of these two strains. It appears that an average constant ratio of about 1.78 may be used for all cases.

Table 1. Elastic strain at the maximum stress, maximum strain at the maximum stress and the ratio of these two strains for both densities at different temperatures

Density (kg/m³)	Temperature (°C)	Elastic strain at maximum stress	Maximum strain at maximum stress	Ratio of maximum strain at peak stress to elastic strain at peak stress
650	Ambient	0.0019	0.0034	1.79
	200	0.0022	0.0039	1.77
	400	0.0030	0.0055	1.83
	600	0.0037	0.0066	1.78
1000	Ambient	0.0013	0.0024	1.85
	200	0.0016	0.0029	1.81
	400	0.0023	0.0039	1.70
	600	0.0028	0.0048	1.71

Conclusions

This paper has presented the results of an extensive series of experimental studies to attain stress-strain relationship of foamed concrete at high temperatures. Compressive cylinder tests were carried out for a range of foamed concrete densities at different temperatures from ambient up to 600°C. The primary mechanism causing strength and stiffness degradation is micro-cracking, which occurs as water expands and evaporates from the porous body. As expected, reducing the density of foamed concrete reduces its strength. For both densities at all temperature levels, the ascending branch was linear for stress up to 75% of the peak strength. The strain equivalent to the peak strength increased at increasing temperatures. The increase in strain results from opening of cracks instigated by the heating at higher temperatures.

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