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Characterization of High Temperature Modulus of Elasticity of Lightweight Foamed Concrete under Static Flexural and Compression: An Experimental Investigations

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ABSTRACT. This paper focused on an experimental works that have been performed to examine the young's modulus of foamed concrete at elevated temperatures up to 600°C. Foamed concrete of 650 and 1000 kg/m^3 density were cast and tested under compression and bending. The experimental results of this study consistently demonstrated that the loss in stiffness for cement based material like foamed concrete at elevated temperatures occurs predominantly after about 95°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-temperature and stiffness-temperature relationships are very similar.

Keywords: lightweight foamed concrete; young modulus; flexural strength; elevated temperature; bending stress.

1. INTRODUCTION

Foamed concrete is a vast majority of concrete containing no large aggregates, only fine sand and with extremely light weight materials containing cement, water and foam. It is classified as lightweight concrete material having a minimum of 20 per cent by volume of mechanically entrained foam in the mortar slurry. Foamed concrete is produced by entrapping numerous small bubbles of air in cement paste or mortar. Mechanical foaming can take place in two principal ways; by pre-foaming a suitable foaming agent with water and then combining the foam with the paste or by adding a quantity of foaming agent to the slurry and whisking the mixture into a stable mass with the required density. The most commonly used foam concentrates are based on hydrolyzed protein or synthetic foaming agents. They are formulated to produce air bubbles that are stable and able to resist the physical and chemical forces imposed during mixing, placing and hardening.

The demand of LFC is becoming higher now where this material has increased many folds in recent years due to its inherent economies and advantages over conventional concrete in a range of structural and semi-structural applications. Foamed concrete is more sensitive to water demand compared to normal concrete. If too little water is added to the mixture, the water will not be adequate for initial reaction of the cement and the cement will withdraw water from the foam, causing rapid degeneration of the foam. If too much water is added in the mixture, segregation will take place causing variation in density. Fresh foamed concrete has the appearance of a light-grey mousse or milk-shake and it is the volume of slurry to foam which dictates the casting density of the foam concrete. The density of foamed concrete is determined by the ratio of foam to slurry. With an appropriate control in dosage of foam and methods of production, a wide range of densities (400–1600 kg/m^3) of foamed concrete can be produced hence providing flexibility for application such as structural elements, partition, insulating materials and filling grades. Foamed concrete is physically has a self-levelling and self-compacting nature where it fills the smallest voids, cavities and seams within the pouring area.

Up to now, foamed concrete has been used principally as a filler material in construction and civil engineering works. Nevertheless, its good thermal and acoustic performance indicates its strong potential as a material in building construction. The development of hydrolyzed protein based foaming agents and specialized foam generating equipment has improved the stability of the foam, making it possible to manufacture foamed concrete for structural applications.

The degradation mechanisms ofr cement-based material like foamed concrete upon exposure to elevated temperatures comprise of mechanical damage as well as chemical degradation; where each mechanism is dominant within a specific temperature range. 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 [1] 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 microcracks in the material from about 300°C, resulting in decreased strength and stiffness of the material [2]. 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 LFC [3]. If the hot LFC is exposed to water, as in fire fighting, CaO in LFC turns into $Ca(OH)_2$ to cause cracking and destruction of LFC. It is still extremely difficult to accurately predict these mechanisms and experimental investigation remains essential. Thus, the aim of this study is to experimentally examine and characterize the elastic modulus of foamed concrete at elevated temperatures. Tests were carried out at different temperatures up to 600°C. Extensive compressive and bending strength tests will be performed for foamed concrete of densities of 650 and 1000 kg/m^3. Figure 1 and Figure 2 shows the utilization of foamed concrete in some projects.

Figure 1: Road in Holland is being widened and foamed concrete was used for the road sub-base

Figure 2: Placement of foamed concrete with the use of removable shuttering

2. MATERIALS

2.1 Cement

Portland cement obtained from Cima Group of Companies Sdn. Bhd. (Perak, Malaysia) was used in this study. The Portland cement used complies with the Type I Portland cement as in ASTM C150.

2.2 Sand

Fine sand with additional sieving to remove particles greater than 2.36 mm was used in the mix, to improve the foamed concrete flow characteristics and stability as in BS12620.

2.3. Water

Through this experimental study tap water was used for the manufacture the foamed concrete samples.

2.4 Surfactants

The surfactants (foaming agent) used was Noraite PA-1 (protein based) which is suitable for foamed concrete densities ranging from 600 to 1600 kg/m^3. Noraite PA-1 comes from natural sources and has a weight of around 80 gram/litre and expands about 12.5 times when used with the foam generator. The stable foam was produced using foam generator Portafoam TM2 System.

3. Experimental setup

Unstressed test technique was implemented for ease of this research. 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. The electric furnace was used to heat the foamed concrete specimens to the various steady-state temperatures. 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 ±1°C over the test range. Compressive strength tests were carried out on 100 x 200 mm cylinders. In order to monitor the strain behaviour at ambient temperature during loading, two strain gauges was 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 3) after removing the test samples from the furnace. 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 results.

Figure 3: Compression test using ambient temperature machine

The three point bending test was carried out for convenience in this study. 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 *(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.

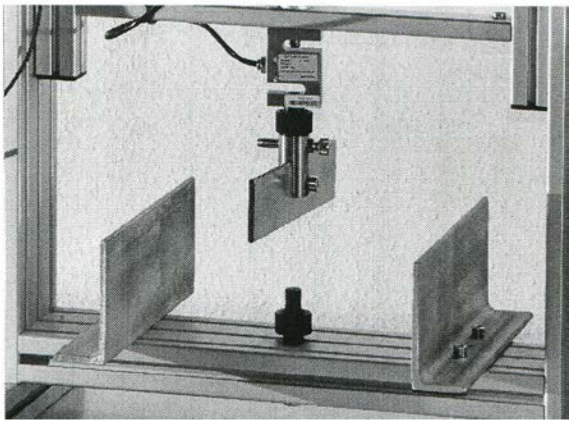
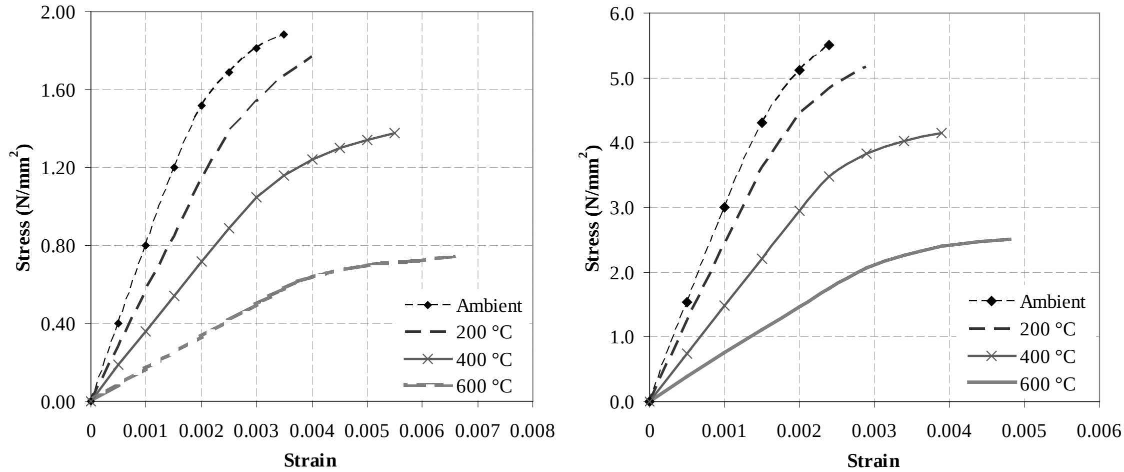


Figure 4: Setup for three point bending strength test

4. Experimental Results

4.1 Stress-strain under compression

Figure 5 (a-b) displays the average stress-strain curves at all different testing temperatures for the two densities. It can be seen from Figure 5 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 foamed concrete of 650 kg/m^3 density, the maximum strains were 0.0034, 0.0039, 0.0055 and 0.0066 at ambient temperature, 200, 400 and 600°C in that order; for the 1000 kg/m^3 density, the corresponding values were 0.0024, 0.0029, 0.0039 and 0.0048 at ambient, 200, 400 and 600°C correspondingly. The increase in strain results from opening of cracks initiated by the heating at higher temperatures.



a) 650 kg/m^3 b) 1000 kg/m^3

Figure 5: Stress-strain relationships under compression at different temperatures

4.2 Modulus of elasticity under compression

Figures 6 and 7 demonstrate the transformations in modulus of elasticity of foamed concrete under 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 behaviour from the experimental compressive stress–strain curve. Compared to the reduction in foamed concrete 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 foamed concrete of both densities at elevated temperatures, the normalised modulus of elasticity of foamed concrete of both densities at the same temperature are almost the same.

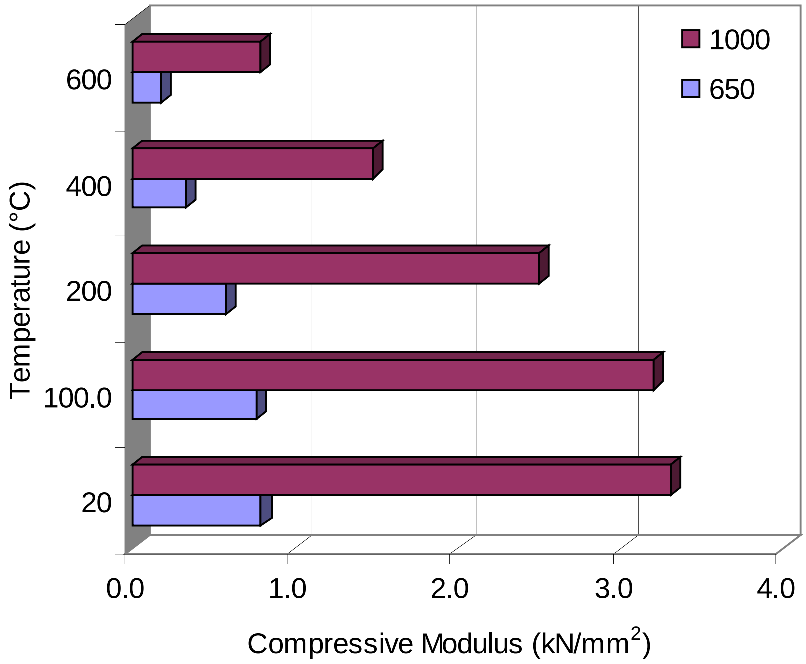


Figure 6: Compressive modulus of foamed concrete as a function of temperature

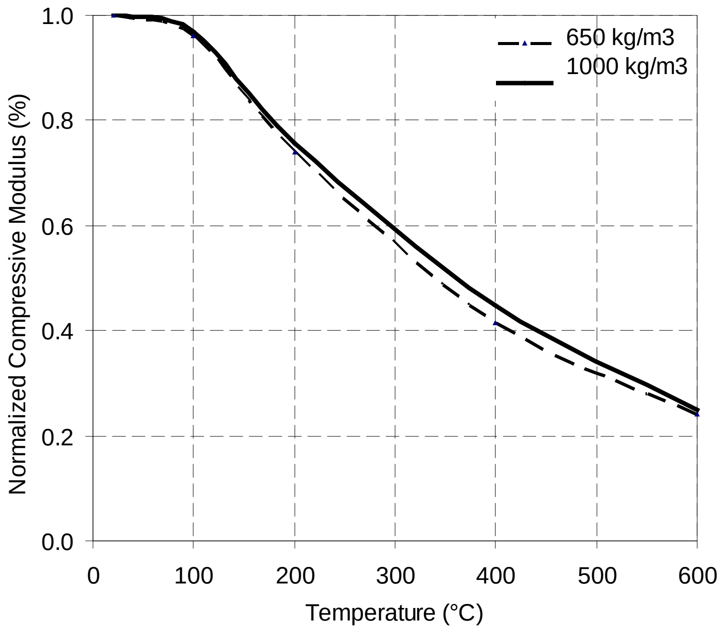


Figure 7: Normalized compressive modulus of foamed concrete as a function of temperature

4.3 Elastic modulus of foamed concrete under bending

Figures 8 and 9 illustrate the changes in bending modulus of foamed concrete as a function of temperature and compare the flexural modulus with the compressive modulus obtained from the cylinder tests. Although there are some differences, the compressive modulus and flexural modulus values are very similar for both densities and at different temperatures.

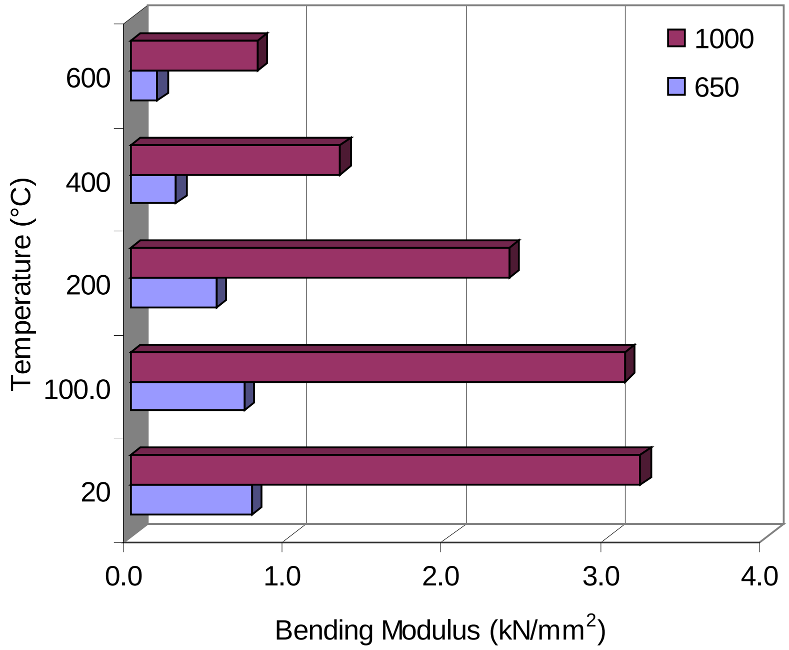


Figure 8: Bending modulus of foamed concrete as a function of temperature

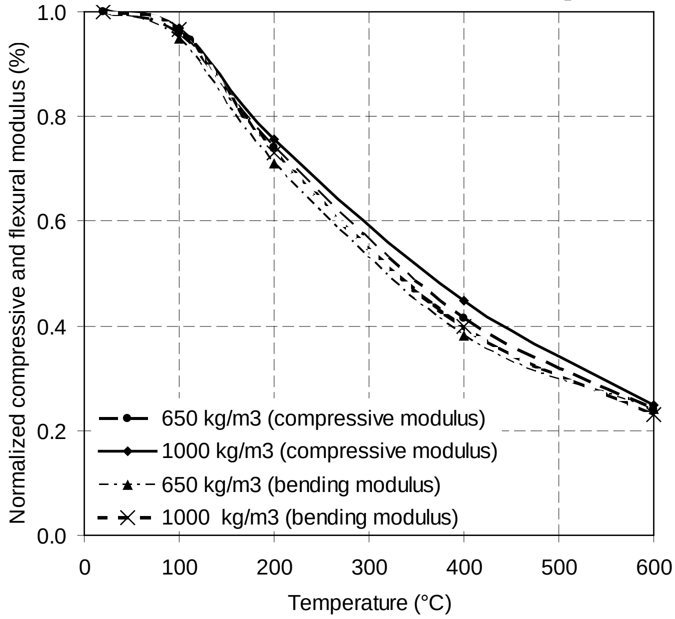


Figure 9: Comparison of normalized compressive modulus and flexural tensile modulus of foamed concrete as a function of temperature

4.4 Mode of failure under compression

LFC specimens exhibited brittle failure at all temperatures levels, failing soon after reaching their peak strength. For the LFC of 650 kg/m^3 density, the end portion of the failed specimens resembled 'double cone pattern' (Figure 11) at the top and bottom at 400 °C and when exposed to temperature of 600 °C, the specimens failed in an irregular pattern as shown in Figure 12. For LFC of 1000 kg/m^3 density, vertical cracks appeared in the broken specimens with double cone pattern at top and bottom at 400 °C (Figure 14); at 600 °C, it experienced the same mode of failure as the LFC of 650 kg/m^3 density (Figure 15).

Figure 10: Failure mode of 650 kg/m^3 density at ambient temperature

Figure 11: Failure mode of 650 kg/m^3 density at 400°C

Figure 12: Failure mode of 650 kg/m^3 density at 600°C

Figure 13: Failure mode of 1000 kg/m³ density at ambient temperature

Figure 14: Failure mode of 1000 kg/m³ density at 400°C

Figure 15: Failure mode of 1000 kg/m³ density at 600°C

5. CONCLUSION

It can be seen that the experimental results zhowed that the loss in stiffness for cement based material like foamed concrete at high 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 foamed concrete reduces its strength and stiffness. However, for foamed concrete of different densities, the normalised strength and stiffness-temperature relationships are very similar.

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УДК 69

Характеристика модуля высоких температур эластичности легкого пено-бетона при статическом изгибе и сжатии: экспериментальное исследование

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Аннотация. В работе изучается экспериментальные работы, проводившиеся с целью изучения модуля Юнга пенно-бетона при повышении температуры до 600°C. Пено-бетон плотностью 650 и 1000 кг/м3 был протестирован при сжатии и изгибе. Результаты эксперимента показали, что потеря жесткости для материалов на основе цемента, таких как пенно-бетон при повышении температуры происходит преимущественно при 95°C, независимо от плотности. Это означает, что первый процесс, приводящий к уменьшению жесткости – микрорастрескивание, который происходит в результате расширения воды и испарений пористого тела. Как ожидалось, уменьшение плотности легкого пено-бетона приводит к уменьшению его силы и жесткости. Тем не менее, для легкого пено-бетона разной плотности нормализация силы-температуры и жесткости-температуры очень схожи.

Ключевые слова: легкий пено-бетон; модуль Юнга; прочность на изгиб; повышенная температура; напряжение при изгибе.