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Models for Prediction the Strength and Stiffness of Foamed Concrete at Ambient Temperature

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Abstract.
Since the foamed concrete employed in this study used the same Portland cement as in normal weight concrete for which a number of strength models have been developed, this paper is intended to assess whether any of these models would be suitable for foamed concrete. The aim of this investigation is to propose a model to predict the strength and stiffness of foamed concrete, based on existing mechanical property predictive models. This model is expected to assist manufacturers and future researchers to develop improved products with reduced cost of experimentation. Whilst full-scale tests to regulatory standards will still be necessary for final accreditation purpose, much of this may be avoided by developing a method to predict the strength and stiffness of foamed concrete at ambient and elevated temperatures during the development stage.
Keywords: foamed concrete; lightweight concrete; stiffness; mechanical property; compression strength; porosity model.

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. Since then, foamed concrete as a building material has become more widespread with expanding production and range of applications.

Over the past 20 years, foamed concrete 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 foamed concrete as a lightweight non-structural and semi-structural material in buildings to take advantage its lightweight and good insulation properties. foamed concrete can have a wide range of densities and each density is produced for a particular type of application.

For foamed concrete at ambient temperature, porosity represents the most important factor in affecting its strength. Hoff (1972) proposed a single strength-porosity model for cellular concrete with cement paste by combining the space taken by evaporable water and air-voids. Tam et al. (1987) reported a model for strength of foamed concrete based on Feret's equations for a limited set of operating conditions. This equation was enhanced by integrating the degree of hydration through Power's gel-space ratio concept. Balshin proposed an equation which provided a good fit to the plot of compressive strength against porosity for slate based autoclaved aerated concretes (Watson, 1980), at all ages of foamed concrete made of cement paste containing high percentage of ash (Kearsley and Wainwright, 2002) and foamed concrete containing high amount of fly ash as replacement to sand (Nambiar and Ramamurthy, 2008)

Strength-porosity model

Balshin (1949) strength-porosity relationship will be considered to assess the effects of porosity on compressive strength of foamed concrete, which may be expressed using the following form:

$$f_c = f_{c,0}(1-\varepsilon)^n \quad .....(1)$$

where f_c is the compressive strength of foamed concrete with porosity ε, $f_{c,o}$ is the compressive strength at zero porosity and n is a coefficient to be determined.

Figure 6.1 plots the recorded foamed concrete compressive strength-porosity relationship for different foamed concrete densities at ambient temperature. Using Balshin's strength-porosity relationship, the best correlation is obtained with n=2.4, which was represented by the solid curve in Figure 1. A correlation coefficient of 0.914 indicates a good correlation between this model and the test results. Thus, the compressive strength of foamed concrete at ambient temperature can be expressed as a power function of porosity as follow:

$$f_c = 39.2(1-\varepsilon)^{2.4} \quad .....(2)$$

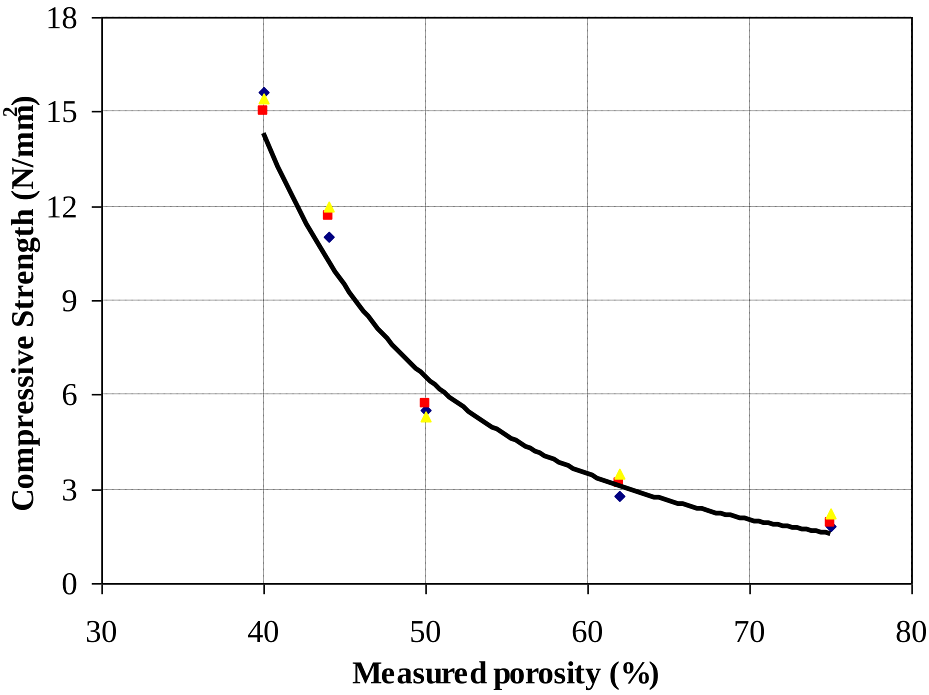

Figure 1. Compressive strength-porosity relation for foamed concrete at ambient temperature

For interest, a similar study was carried out by others for foamed concrete of different densities at ambient temperature. From the experimental results of this study for foamed concrete at different temperatures, the same exercise was undertaken. The results are summarised in Table 1 and compared with results by others for other types of concrete. The *n* values of foamed concrete obtained in this study show some consistency, but are different from other researchers. The *n* values of this study are much lower than from other studies, indicating that the foamed concrete of this study suffered less void induced loss of strength.

Table 1. *Comparison of n-values in strength-porosity model for different concretes*

Researchers	Concrete type	Mix composition	Constants	
			$f_{c.o}$ (N/mm²)	n
Hoff (1972)	Foamed concrete (FC)	Cement paste	115-290	2.7-3.0
Narayanan and Ramamurthy (2000)	Aerated concrete (non autoclaved)	Cement-sand	26.6	3.2
Kearsley and Wainwright (2002)	Foamed concrete	Cement with and without fly ash	188	3.1
Present work	FC (ambient) FC (200°C) FC (400°C) FC (600°C)	Cement-sand	39.2 38.5 28.1 19.5	2.4 2.4 2.4 2.6

Modulus of elasticity-porosity relationship

As acknowledged by the author, the strength-porosity relationship proposed by Balshin (Equation 1) has so far only been used to determine the compressive strength of porous material. This section will explore whether this equation (Equation 1) is also appropriate to establish the modulus of elasticity-porosity relationship for foamed concrete. In order to do so, the experimental results of modulus of elasticity for all densities will be plotted as a function of porosity. Figure 2 shows the recorded foamed concrete modulus of elasticity-porosity relationship for different foamed concrete densities at ambient temperature. Surprisingly, the same relationship can be used. The best correlation was found by using n=2.8, shown by the solid curve in Figure 2. A correlation coefficient of 0.936 indicates strong relationship between the model and the test results. Thus, the following modulus of elasticity-porosity relationship of foamed concrete at ambient temperature is obtained:

$$E_c = 32.9(1-\varepsilon)^{2.8} \quad .....(3)$$

where E_c is the compressive modulus of foamed concrete at ambient temperature and ε is porosity.

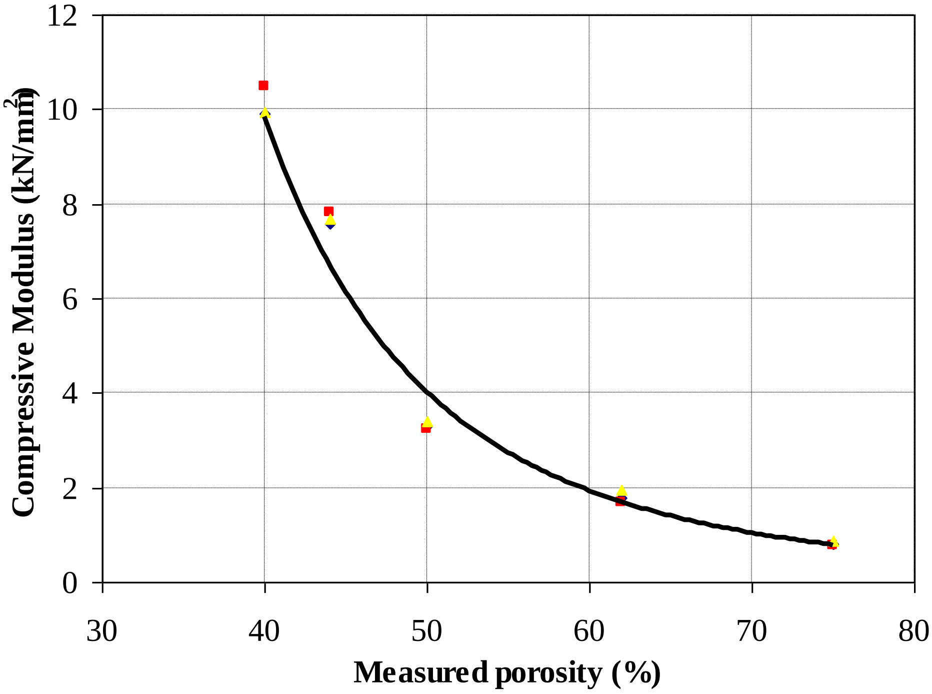

Figure 2. Modulus of elasticity-porosity relation for foamed concrete at ambient temperature

From the experimental results of this study for foamed concrete at different temperatures, the same exercise was undertaken to obtain the modulus of elasticity-porosity relationships. The results were summarised in Table 2 which shows a constant *n* value at different temperatures.

Table 2. *Summary of $E_{c.o}$ and n values for modulus of elasticity-porosity relationship at different temperatures according to Balshin's model*

Temperature (°C)	Constants	
	$E_{c.o}$ (kN/mm²)	*n*
Ambient	32.9	2.8
200	24.7	2.8
400	15.0	2.8
600	8.2	2.8

4. Modulus of elasticity-compressive strength relationship

Jones and McCarthy (2005) proposed a relationship linking the modulus of elasticity with the compressive strength of foamed concrete (Equation 3) at ambient temperature.

$$E_c = 0.42 f_c^{1.18} \quad .... (4)$$

where E_c is the modulus of elasticity (kN/mm²) and f_c is the compressive strength (N/mm²).

Although Equation 4 is considered applicable only for a minimum compressive strength of 5 N/mm², Figure 3 showed that the same modulus of elasticity-compressive strength relationship exists for foamed concrete across the entire strength range.

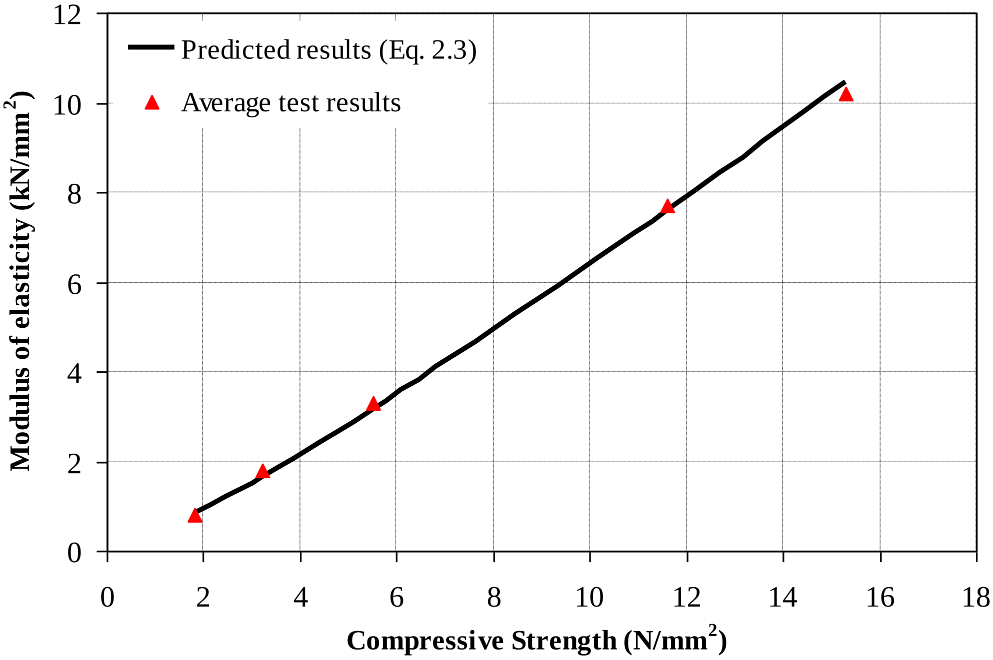

Figure 3. Modulus of elasticity-compressive strength relation for foamed concrete at ambient temperature

Porosity-density relationship

Through using Equation 2 and Equation 3, it was possible to obtain an accurate assessment of the compressive strength and modulus of elasticity of foamed concrete. Nevertheless, these models require input of the porosity value. Unfortunately, porosity was a property not frequently measured outside the laboratory, and therefore it is necessary to provide a model to obtain the porosity. The simplest method to calculate the porosity value was to relate it to foamed concrete density. Since the pores inside foamed concrete were created due to addition of foams, by knowing the solid density of cement paste (without foam), one can easily predict the porosity of foamed concrete of any other density using the following equation:

$$\varepsilon = \frac{\rho_{sc} - \rho_{dry}}{\rho_{sc}} \quad ..... (5)$$

where ε is the porosity, ρ_{sc} is the solid density of cement paste (without foam) and ρ_{dry} is the dry density of foamed concrete.

The accuracy of Equation 5 was checked by comparing the porosity values calculated using Equation 5 and the measured porosity values using the Vacuum Saturation Apparatus for different foamed concrete densities, as shown in Figure 4. It should be noted that an average solid density of cement paste (ρ_{sc}) of 2100 kg/m^3 was established through the experiment. The agreement is excellent.

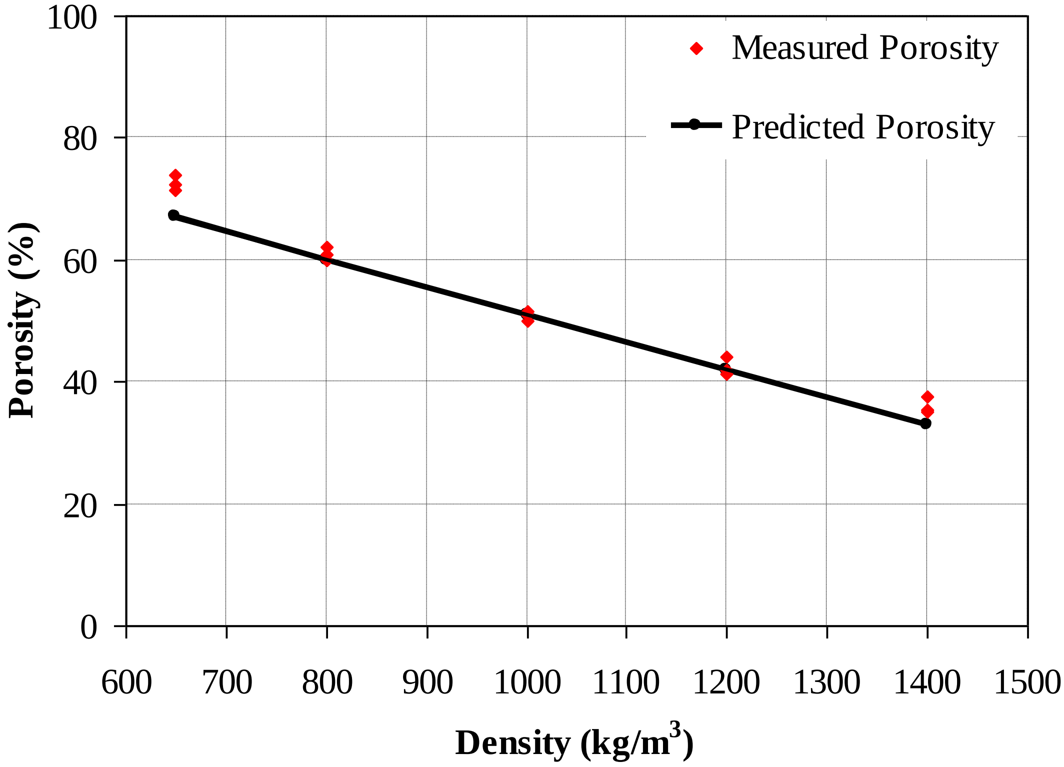

Figure 4. Comparison of predicted porosity with measured porosity as a function of density

Conclusions

This paper has presented a number of predictive models for strength of foamed concrete at ambient and elevated temperature. The experimental results were compared with predictive models based on normal weight concrete. Since the mechanical properties of foamed concrete come from Ordinary Portland Cement, thus the change in mechanical properties of foamed concrete may be predicted using the mechanical property models for normal weight concrete. Balshin equation (Equation 1) may be used to calculate both the ambient temperature compressive strength and compressive modulus of elasticity, as a function of porosity of foamed concrete. Nevertheless, for improved accuracy, ambient temperature mechanical property tests were still recommended.

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