Construction and Building Materials 96 (2015) 622–631

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Computational modeling of the mechanical response of lightweight foamed concrete over a wide range of temperatures and strain rates

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HIGHLIGHTS

- Uniaxial compression tests are conducted at various temperatures and strain rates.
- The characteristics of the stress-strain curve are analyzed and a model is developed.
- The relationships between model parameters and material density are discussed.
- The temperature effect of the material is illustrated based on the calculation model.

ARTICLE INFO

Article history:
Received 9 April 2015
Received in revised form 31 July 2015
Accepted 9 August 2015

Keywords:
Lightweight foamed concrete
Density effect
Temperature effect
Damage evolution
Calculation model

ABSTRACT

Theoretical and experimental studies on the nonlinear mechanical properties of lightweight foamed concrete under uniaxial compression are conducted over the temperature range of 223–343 K and the strain rate range of 0.001–118/s in this paper. The experimental results show that the mechanical properties of the materials under uniaxial compression are strongly dependent on the density and temperature, but are weaker on strain rate. Based on the experimental results, the characteristics of density effect and temperature effect are analyzed and a calculation model is developed to describe the nonlinear mechanical behavior of lightweight foamed concrete. The model takes into account the effect of material damage, density and temperature. The experimental verification and the error analysis show that the model is shown to be able to predict the nonlinear deformation behavior of lightweight foamed concrete over a wide range of temperatures and densities.

1. Introduction

Due to its special microstructure morphology and mechanical properties, lightweight foamed concrete is widely used as energy absorbers in various industries, for example, engineered material arresting system (EMAS). There are many ingredients influencing lightweight foamed concrete ability of energy absorption, such as density and nonlinear mechanical properties of the materials. Therefore, it is very necessary to study the nonlinear mechanical behavior of lightweight foamed concrete. The nonlinear mechanical properties of lightweight foamed concrete share some characteristics with the properties of metal foams and polymeric foams. Under the uniaxial compression, the stress–strain curves of these foams can be divided into three stages: the linear elastic stage, the plateau stage and the densification stage [1–3]. However, the components and the structure of lightweight foamed concrete are more complex compared with metal foams and polymeric foams, and there are less research literatures on its mechanical properties. Therefore, with the extensive use of lightweight foamed concrete, the mechanical properties of the materials have drawn great attention of researchers.

Some experimental studies have been conducted to investigate the nonlinear response of lightweight foamed concrete under uniaxial compression [3–5]. Valore [4] studied varies factors that affect the strength of porous concrete, including the size and shape of specimen, the properties of matrix material, the porosity formation and the curing methods, loading direction, as well as the moisture content. Hengst and Tressler insisted that at constant density, the major factor affect the strength of porous concrete is the crack size, which is correlated with the size of holes [6]. Park studied the effect of the components of foamed concrete on the mechanical properties of the materials, and held that the content increasing of silica fume, fly ash and glass fiber can improve the mechanical properties of foamed concrete [7]. Visagie and Kearsely found the compressive strength of foamed concrete would decrease with the increase

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http://dx.doi.org/10.1016/j.conbuildmat.2015.08.064
0950-0618/

of the diameter of the aperture over the dry density ranges of 0.5–1 g/cm^3, while the porosity of the materials has little effect on the compressive strength when the dry density is over 1 g/cm^3 [8]. Guo et al. studied systemically the compression behavior of one kind of new foamed concrete composite at the room temperature and strain rate ranges from 0.001/s to 0.1/s, and found that this material is insensitive to strain rates during the strain rate ranges, while the densities of this material have a great influence on the compression behavior [3]. Besides, few theoretical and numerical models had also been developed to describe the mechanical properties of foamed concrete recently. Hoff studied the relationship between the porosity and the compression strength of foamed concrete, and insisted that there be a certain calculating formula of strength and porosity for given cement content [9]. The prediction model proposed by Kearsely and Wainwright showed that the model from Hoff can efficiently predict the compression strength of foamed concrete at different time and densities [5]. Zhou et al. studied the characteristics of the compressive stress–strain curve of foamed concrete, and found that there are four steps in foamed concrete compression process, namely plateau step, compacting step, yield step and decline step, the compression mechanical property is affected by matrix material, volume weight, morphology and distribution of pore, etc. [10]. Gibson and Ashby derived the equation of compression strength and relative density of brittle foams, by which could get the parameter to describe the volume fraction of hole edge and the fracture strength of hole wall [1]. Recently, Guo et al. developed a compression phenomenological constitutive model of foamed concrete by analyzing platform crushing stress, compacting strain and density [3]. The theoretical study on the compressive mechanical properties of foam concrete in the above literature is almost all to set up the mathematics model through the relationship between the strength and porosity, matrix material and so on. However, there is not a more comprehensive study on the failure mechanism of the materials as well as on the macroscopic factors of affecting the compressive strength, such as strain rate, temperature, and relative density.

In this paper, the uniaxial compression tests on the mechanical properties of one kind of new lightweight foamed concrete at the temperature range of 223–343 K and the strain rate range of 0.001–118/s are carried out. The deformation mechanism and the mechanical characteristics of the materials are analyzed and discussed. Based on the experimental results, a calculation model describing the nonlinear compressive behavior of lightweight foamed concrete is established in this paper, which includes the effect of material damage, density and temperature.

2. Experimental investigation

2.1. Materials

The lightweight foamed concrete studied in this paper, mainly used in engineered material arresting system (EMAS). This new lightweight foamed concrete adds some polyester fiber materials into the generic foamed concrete using traditional manufacturing process [11–13]. The material of the polyester fiber is PP, the length is 6 mm, the melting temperature is 165–175 °C, and the fiber diameter is 25–45 μm. The mass of PP accounts for about 0.85% of the mass of the cement. The foaming agent used in this paper is 35% hydrogen peroxide. The main components of lightweight foamed concrete are cement, water, heavy calcium and fly ash. The particle size of the cement is about 10 μm. The particle size of the heavy calcium is about 18 μm. The calcium–cement ratio is 0.4, and the water–cement ratio is 0.8. The final optimization design scheme for the chemical constituents and mix proportion of the raw materials is determined through trial and error. The detailed preparation process of standard sample is as follows:

(a) Mix the foaming agent and purified water thoroughly using agitator at room temperature, and whisk until the mixture is smooth. Then, add the mixture of clay, cement, sand, fly ash, polystyrene fiber and water into the mixed froth, and using the water reducer and the coagulation accelerator to make the mixture uniform flow slurry.
(b) Fill the Φ = 80 mm, h = 60 mm mold with the uniform flow slurry, and vibrate it on the shaking table and smooth the upper surface with a spatula. Then, after letting it stand at room temperature for 3 days, demold and place it in constant humidity cabinet with the relative humidity of 90%, this stage will continue for 30 more days. Finally, paste numbering in the specimen for the subsequent experiments.

The microstructure of the experimental materials was scrutinized using field emission scanning microscopy, and the scanning microscopic photos are shown in Fig. 1. It can be observed from Fig. 1a that the distribution and orientation of the pore wall materials are uniform approximately, and the thickness of hole wall is about 40 μm. As can be seen from Fig. 1b, the hole wall of the materials is accumulated by varieties of the salt crystals arranged without order at higher magnification. The crystal is a slender cylinder, and the maximum diameter is about 1 μm. In addition, the arrangement of the grain is loose, so it can be inferred that the weak crystal boundary is the essential reason of the low compression strength of the lightweight foamed concrete.

2.2. Testing equipment

In order to cover a wide range of loading speeds, material tests are conducted on two types of testing machines: (1) a CSS-4410 electric universal testing machine equipped with a temperature chamber for low strain rate tests; (2) a DYN-9250 drop weight impact testing machine equipped with a temperature chamber for high-rate impact tests. During the loading process, the CSS4410 electric universal testing machine measures the displacements by automatic recording the movement distance of the crossbeam, and acquires the compressive load by high precision pulling and pushing dual-purpose load transducer installed on the crossbeam. The measuring range of compressive load is the sensor capacity of 2–100%, and the precision of the sensor is 0.5%. Based on the collected data from testing machine and the geometric size of specimen, the stress–strain curves of test materials are obtained by mathematical calculation method at low strain rates. The DYN-9250 drop weight impact testing machine adjusts the level of strain rate and its stability by controlling the weight of the hammer head and the initial height of free falling with the assistant of the Impulse control software. The testing machine releases the drop hammer to make it free falling in order to impact specimen, and collects a series of experimental data by using the Impulse data acquisition software in the process of impact. Finally, the curves of calculation results are generated by using the Impulse software at high strain rates.

2.3. Experimental program and results

Lightweight foamed concrete is a heterogeneous and anisotropic multi-phase composite material. Because the components of the material are complex and be many influence factors, the mechanical properties data obtained from the tests have the certain characteristics of discreteness. In order to carry on the system analysis of the experimental data, three major factors which influence the mechanical properties of lightweight foamed concrete are emphatically considered in this paper, and so as to provide valuable reference for the engineering design, namely material density, experimental temperature and strain rate. Test conditions are designed as three schemes as follows: (1) the effects of different density on the compressive strength of lightweight foamed concrete are studied when the temperature and strain rate are constant; (2) the effects of different temperature on the compressive strength of the materials are investigated when the density and strain rate are constant; (3) the effects of different strain rate on the compressive strength of the materials are discussed when the temperature and density are constant. The typical stress–strain curves of four different densities of lightweight foamed concrete specimens at the temperature of 293 K and strain rate of 0.1/s are shown in Fig. 2. The typical stress–strain curves of lightweight foamed concrete specimens with the density of 0.23 g/cm^3 and strain rate of 0.1/s under four different temperatures are shown in Fig. 3. The typical stress–strain curves of lightweight foamed concrete specimens with the density of 0.18 g/cm^3 and temperature of 293 K under six different strain rates are shown in Fig. 4. The typical stress–strain curves of lightweight foamed concrete specimens with the density of 0.37 g/cm^3 and temperature of 293 K under six different strain rates are shown in Fig. 5.

The results showed that the engineering stress–strain curves of low-density lightweight foamed concrete in low strain rate have the obvious characteristics of three stages, namely the linear elastic stage, the crushing plateau stage and the densification stage. The curves in low strain rate are smoother by comparison with high strain rate. The curves show the zigzag fluctuation at high strain rate and especially the larger fluctuation in the transition region of elastic segment and crushing plateau segment. In addition, as the density of the materials increases the ranges of fluctuation increases correspondingly. According to the analysis of the stress–strain curves of different density (0.18 g/cm^3, 0.20 g/cm^3, 0.27 g/cm^3 and 0.37 g/cm^3) lightweight foamed concrete in Fig. 2, it can be found that for a certain temperature and strain rate, the stress value at the same deformation amount increases as the density of the materials increases, and the crushing plateau segment of the curves