Construction and Building Materials 73 (2014) 442–451

Contents lists available at ScienceDirect

Construction and Building Materials

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

Experimental investigation on annual changes in mechanical properties of structural concretes with various types of lightweight aggregates

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HIGHLIGHTS

- We investigate changes in mechanical properties of lightweight concretes.
- Types of LWA determine the evolution of density, strength and stiffness with time.
- Property ratios are useful to estimate long-term behaviors of LWA concretes.
- Empirical correlations can approximate the design guides of LWA concretes.
- Nondestructive method supports the robustness of measured stiffness.

ARTICLE INFO

Article history:
Received 10 June 2014
Received in revised form 3 September 2014
Accepted 24 September 2014

Keywords:
Lightweight aggregate
Compressive strength
Modulus of elasticity
Curing time
Elastic wave

ABSTRACT

This study presents the compiled experimental data of compressive strength and the modulus of elasticity for five different lightweight concretes cured up to 365 days and compares them with those for a normalweight concrete. Mechanical properties sharply increased during early stage approaching asymptotic values, depending on design strength codes. Various empirical relationships approximately represent the experimental data, with the different types of concrete exhibiting discrepancies within acceptable bounds. Results highlight that the time-dependent mechanical properties of concretes containing lightweight aggregates can be reasonably estimated using conventional empirical models, provided that values at 28 days of curing are accurately known. Relationship between measured strength and modulus provides the first approximations, corroborated by coinciding values from nondestructive testing. The evolution of density and the effect of curing conditions are also discussed. These experimental results demonstrate that the type of lightweight aggregate strongly influences the mechanical properties of concretes.

1. Introduction

The low density and high thermo-insulating capacity of lightweight aggregate concrete (LWAC) are its most distinct characteristics in comparison to normalweight-aggregate concrete [1]. While LWAC has been used in buildings and bridges for decades, it has recently received attention as a replacement material to reduce the dead load of existing bridges and to improve old, deteriorated superstructures by upgrading their load-bearing capacity [2,3]. The LWAC could be used economically, for example, to reduce the the large quantity of cables required for cable-stayed bridges or to allow concrete bridges with longer spans; there are already several LWAC bridges in the USA and Europe [4]. Furthermore, LWAC is also advantageous for the construction of super high-rise buildings by the benefit of reducing self-weight. The LWAC is also more insulating than normal concrete due to the high porosity of the lightweight aggregate. Passive energy-saving buildings require structural concretes with precisely manipulated thermal properties to achieve their energy efficiency; they often involve the use of LWAC to reduce thermal losses. Much work has sought to increase the energy efficiency of buildings by tailoring the thermal properties of the concretes used in their walls and roofs, with LWACs often being employed [5–8]. However, the mechanical properties of insulating LWAC may not be sufficient for its structural use as its thermal capacity is prioritized over its structural performance.

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http://dx.doi.org/10.1016/j.conbuildmat.2014.09.044
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The properties of the lightweight aggregate determine the thermal and mechanical behaviors of the resulting concrete depending on the type of raw materials and the production process. The relationships between the choice of aggregate and the density, compressive strength, and modulus of elasticity of the concrete have been evaluated through studies of, for example, peak strain evolution, the influence of LWAC made of fly ash, strength gaining, and durability [9–14]; Chung et al. [15] recently proposed a micro X-ray computed tomographic imaging method to evaluate the stiffness and strength of lightweight aggregate. Despite the thermal properties of LWACs having been extensively reported, the long-term monitoring of the mechanical properties of high-strength LWAC, which could be essential to assess the integrity of LWAC structures, is rarely reported. The accurate estimation of mechanical properties allows the safety of prestressed concrete structures to be evaluated during service life to prevent their unexpected deformation and to ensure their serviceability from a design perspective when creep and shrinkage may occur. It is noted that concrete usually develops a higher compressive strength than required by design [4].

The characteristics of the aggregate greatly affect the mechanical properties of concrete, because it occupies a large fraction of the concrete's volume; this is particularly the case for lightweight aggregate, which contains internal void spaces [9]. Because it has been shown that the strength of the aggregate may not be directly related to that of the concrete and that the use of small aggregate particles could alleviate the limitation on the strength of LWAC, the mechanical properties of concretes might be considerably influenced by their microstructures and the rate of cement hydration [12,16,17]. Design criteria for predicting the concrete strength and the modulus of elasticity with time (e.g., ACI, CEB–FIP codes) have been proposed based on empirical correlations as functions of density and compressive strength. A modification factor was adopted in design codes to account for the effect of lightweight aggregate on the estimation of the development of compressive strength and elastic modulus, regardless of the type, shape, and raw material of the aggregate, despite the variety of available aggregates for structural concrete composed of various raw materials.

This work presents an experimental investigation of the compressive strength and the modulus of elasticity of LWAC specimens with varying engineering design strengths and different types of aggregate for use in energy-saving buildings. Mechanical properties were tested using 900 cylindrical concrete samples, and 180 cubic specimens were used to measure density. Both properties were assessed during curing for up to 365 days. The results were analyzed and compared with proposed design codes. The selected specimens were also subjected to nondestructive assessment to test the prediction of their elastic properties. The long-term evolution of the measured properties can indicate the mechanical integrity of structures made of the LWACs.

2. Materials and methods

2.1. Materials

2.1.1. Lightweight aggregates

Five commercially available lightweight aggregates (Stalite, USA; Asanolite, Japan; Dols, China; Argex, Belgium; and Liapor, Germany) served as the coarse aggregates. They each satisfy the engineering standards of ASTM C 330 and BS EN 13055-1. They were subjected to 3D X-ray computed tomographic imaging that provided the spatial distribution of their internal air-void configuration (Table 1). The internal void space has the following orders; Stalite, Liapor, Asanolite, Dols and Argex and the sphericity is the highest in Dols followed by Liapor, Argex, Asanolite and Stalite. The Stalite generally has randomly distributed and closed pore space while Dols and Argex have shell-shaped pores. As Stalite is made of slate, the absorption capacity of water is relatively low compared with those made with clay. In fact, the low water absorption ensures the good consistency to control the mix proportion.

2.1.2. Raw materials

Locally available crushed granite with a specific gravity of 2.60 was used as a normal coarse aggregate. All aggregates were mixed with Type I Ordinary Portland Cement (Blaine fineness 3350 cm^2/g based on Korean standards) and thoroughly cleaned sea-sand (specific gravity 2.60 for fine aggregates). High-performance polycarboxylate-based superplasticizer was added at 0.5%, 0.7%, and 1.2% of the weight of cement content in accordance with the respective design strength class.

2.1.3. Mixing and curing

Table 2 summarizes the mix proportion for six different aggregate types. Each set was labeled 'N', 'S' 'A', 'D', 'G', and 'L' according to the type of coarse aggregate. Three design strength classes of 30 MPa, 40 MPa, and 50 MPa were applied according to the cylindrical compressive strength at 28 days; for example, 'S-50' represents the Stalite-based LWAC with a design cylindrical compressive strength of 50 MPa at 28 days. All mixtures were designed to obtain a slump of about 180 mm, and the air content was determined to be a constant of 2%. Note that all the lightweight aggregates were submerged for 24 h for water absorption before mixing. The slump of the mixtures ranged from 165 mm to 200 mm; the consistency of each fresh concrete batch was sticky and cohesive. Each specimen was cast according to the ASTM C192.

- Fifty cylinders of 100 mm diameter and 200 mm height were used for measuring the compressive strength and the modulus of elasticity (i.e., a total of 900 specimens).
- Ten 100 mm × 100 mm × 100 mm cubes were used for recording density changes under various curing conditions (i.e., a total of 180 specimens).

All cylindrical specimens were de-molded after 24 h and cured in water (20 ± 2 °C) until testing.

2.2. Methods

2.2.1. Mechanical testing

The compressive strength and the modulus of elasticity of all the mixtures were measured in accordance with ASTM C 39 and ASTM C 469, respectively. An axial extensometer (Instron Inc., model 3542RA) was attached to the side of cylindrical specimen, and an axial load was applied by a universal testing machine (maximum loading capacity 3500 kN) at a constant loading rate of 0.3 MPa/s. Average values were computed from measurements of three specimens for each mixture tested at 9, 28, 56, 91, 180, and 365 days. A circumferential extensometer (Instron Inc., model 3544) was used simultaneously with the axial extensometer to measure the diameter strain of the cylindrical specimens and to calculate Poisson's ratio at 365 days. These values were compared with the values estimated by wave velocity measurement.

2.2.2. Density testing

Natural drying caused the fresh density of the LWAC to decrease toward the equilibrium density (adopted by ACI committee 213) after 90 days of curing. Oven drying caused the density value to decrease by 50 kg/m^3 (Fig. 1). The criteria for testing standard density values vary depending on the concrete type and the chosen standard (e.g., the oven-dry density of LWAC is accepted in Europe within BS EN 206-1 [18], while the USA no longer accepts it). In this study, three values of density were measured for cubic specimens (in accordance with ASTM C 567 [19]) at 28, 91, 120, 180, and 365 days: wet density was measured in water at 20 ± 2 °C, and air-dry density was obtained under ambient conditions at a relative humidity of (50 ± 5)% and at 20 ± 2 °C, followed by 7 days of wet-curing. Specimens were dried in a ventilated oven at 105 ± 5 °C until the mass changed by less than 0.2% over a sufficient period of time (i.e., until the sample reached constant mass), and the oven-dry density was measured only at 28 days.

2.2.3. Elastic wave measurement

After 365 days of wet-curing, specimens were subjected to the measurement of P- and S-wave velocities by the piezo-transducers with frequency values of 50 kHz and 5 kHz, respectively. A pair of sensors was placed on either side of the specimen, and the first arrival time of propagating wave traces was captured to compute the wave velocity. Then, the constrained modulus M (e.g., $\varepsilon_x = \varepsilon_y = 0$) and shear modulus G were computed from the compressional (V_p) and shear velocities (V_s) and density (ρ) as follows:

$$M = V_p^2 \cdot \rho \text{ and } G = V_s^2 \cdot \rho. \tag{1}$$

They are also related to the bulk modulus B and Young's modulus E.

$$B = M - \frac{4}{3}G \text{ and } E = \frac{9BG}{3B + G} \tag{2}$$

The ratio between the P- and S-wave velocities is related to the Poisson's ratio ν.

$$\frac{V_p}{V_s} = \sqrt{\frac{M}{G}} = \sqrt{\frac{2(1-\nu)}{1-2\nu}} \text{ or } \nu = \frac{\frac{1}{2}\left(\frac{V_p}{V_s}\right)^2 - 1}{\left(\frac{V_p}{V_s}\right)^2 - 1} \tag{3}$$