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The mechanical characteristics of steam-cured high strength concrete incorporating with lightweight aggregate

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HIGHLIGHTS

- Influences of lightweight aggregate on static/dynamic mechanical properties of steam-cured concrete were investigated.
- The relationship between elastic modulus, damping ratio and compressive strength of steam-cured concrete incorporating lightweight aggregates were established.
- The mechanisms responsible for mechanical characteristics of steam-cured concrete with lightweight aggregate were discussed.

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ABSTRACT

In order to mitigate the thermal damage of steam curing process at elevated temperature on microstructure of concrete and thus prepare high quality steam-cured concrete, the effects of type and absorbing-water rate of lightweight aggregate on static and dynamic mechanical properties of steam-cured concrete were investigated by serials experiments in present paper. The temperature evolution of different positions in steam-cured concrete without and with lightweight aggregate during steam curing period was also tested. Result indicates that, compared to control sample without lightweight aggregate, the compressive strength of steam-cured concrete with 30% ceramsite sand replacing the same volume river sand is slightly higher while the one of sample with 30% expanded clay ceramsite is lower at 28-day age. Under the same compressive strength level, the static/dynamic elastic modulus of steam-cured concrete with 30% lightweight aggregate is lower than that of control sample, and the damping ratio of steam-cured concrete with 30% ceramsite sand is higher. Incorporation of lightweight aggregate into concrete will result in a delay of temperature rise, which is very important for alleviating the thermal damage of steam-cured concrete caused by elevated temperature at early age and thus is favourable of improving the compressive strength.

1. Introduction

Various techniques have been developed to provide the required concrete strength level in a short time. One of the techniques commonly used in practice is curing concrete under heating and an atmospheric steam pressure (steam-cured concrete). Recently, steam-cured concrete was widely used to manufacture prefabricated elements of high-speed railway foundation structure such as girder, track slab and sleeper in China.

To ensure good performance of the concrete for the precast concrete elements, some researchers have investigated the static mechanical behavior and microstructure of concrete under heat treatment condition. Compared with the normal-cured concrete, the concrete exposed to elevated temperatures shows an accelerated hydration, non-uniform distribution of hydration products [1,2], higher compressive strength at an early age and lower compressive strength at a later age [3,4]. The equilibrium between C–S–H and ettringite in concrete is affected by the temperature [5]. At high temperature (for instance during steam curing), the ettringite becomes more soluble, the sulphate concentration in the solution increases and the quantity of sulphate bound to the C–S–H also increases [6].The denser inside of the C–S–H and the decrease of the ettringite content at elevated temperature lead to higher capillary porosity and lower compressive strength of concrete [7]. In order to avoiding the adverse effect on concrete caused by elevated temperature, several measurements including addition of mineral admixture, optimization of steam curing regime and etc. were developed. The effects of mineral admixtures on the properties and microstructure of steam-cured concrete have also been investigated by many researchers [8–12]. Ho and co-workers reported that the heat curing produces very finer products

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compared with standard curing of the ordinary Portland cement concrete at 7 days. The expansive deformation of cement-based materials during steam curing can be effectively reduced by choosing a water-binder ratio no more than 0.3 and partially replacing cement by mineral admixture [13]. Long et al. evaluated the damage effect of steam curing on concrete by experiments of the water sorptivity test, scanning electronic microscope (SEM) and mercury intrusion porosity (MIP) tests [14]. Results show that, because of the heat-damage effect caused by elevated temperature, there is a larger gradient distribution in the pore structure and water sorptivity between the exposed surface and the interior of the steam-cured concrete compared with the concrete under normal temperature curing.

Expanded clay ceramsite and other lightweight aggregate possess unique properties due to its porous characteristics, including thermal insulation, water-absorbing/releasing and etc. The incorporation of them can reduce the bulk density of concrete and that has significant influence on the mechanical properties of concrete [15–19]. The water-releasing role of saturation expanded clay ceramsite provides a remarkable internal curing effect on concrete during hydration process of cement which will benefit the improvement of microstructure of concrete. However, there is a lack of studies conducted on steam cured lightweight aggregate concrete or concrete partially incorporating lightweight aggregate. And how the water absorption and releasing characteristics of lightweight aggregate affect the properties of steam-cured concrete is also rarely reported.

Based on the above, this paper comparatively studies the static and dynamic mechanical properties of steam-cured and standard-cured concrete with expanded clay ceramsite partially replacing normal weight aggregate by serial experiments. And the corresponding mechanisms are also discussed. This work is expected to provide some technical support for exploring new methods in preparing high quality steam-cured high strength concrete.

2. Experimental details

2.1. Raw materials

Ordinary Portland cement (abbreviated as P.O 42.5) similar to ASTM Type I cement, class F fly ash (FA) and ground granular blast furnace slag (GGBS) were used as the binder of mixtures, the chemical compositions and loss on ignition of them were shown in Table 1. Polycarboxylate superplasticizer (SP) with 26% water-reducing rate was employed to improve the workability of mixture. Normal crushed limestone (NA), river sand (NS) and clay lightweight aggregate with different density and size were used in this experiment. The crushed limestone has a size of 4.75–20 mm and an apparent density of 2680 kg/m^3. The fineness modulus of river sand is 2.9. The physical properties of expanded clay ceramsite and ceramsite sand were shown in Table 2, and the pictures of them were shown in Fig. 1.

2.2. Mixing, curing and preparation of specimens

Concrete with normal aggregates was prepared as the control sample (J). Based on the control sample, the other concretes were prepared by substituting 30% volume crushed limestone with dry, 1-h presoaked and 24-h presoaked expanded clay ceramsite (CL) or replacing 30% volume river sand with dry and 24-h presoaked ceramsite sand (SL), abbreviated as CL-0, CL-1, CL-24, SL-0 and SL-24, respectively. The mixing proportions and slump of fresh samples were shown in Table 3.

The specimen preparation was performed at room temperature. The mixing procedures of sample were as follows. Firstly, mixture including binder and aggregate was placed into mixer and premixed for 30 s in dry state, and then water and superplasticizer were poured and mixed for another 90 s. After the slump of fresh mixtures were tested, the sample cast into moulds by 60 s vibration with a vibrator of 50-Hz frequency and 0.3–0.6 mm amplitude. The cubic specimens with a size of 100 × 100 × 100 mm for compressive test and prismatic specimens with a size of 100 × 100 × 300 mm for dynamic and static mechanical properties test were prepared. The specimens were divided into two groups according to curing condition. One was cured under standard curing condition of (20 ± 2) temperature and more than 90% humidity (abbreviated as B) after demoulded at one day. The other parts were treated by steam curing(abbreviated as Z).In this study, the steam-curing regime applied has a total duration of 14 h heat treatment cycle, which consists of 2 h preheating, 2 h heating, 8 h treatment and 2 h cooling. The treatment temperature was 60 °C. After steam curing finished, the specimens were removed from the moulds and continually cured under the standard curing condition.

In order to study how the water absorption of CL and SL influences the mechanical properties of steam-cured concrete, three water absorption states of CL, namely dry state, absorbing water 1 h and absorbing water 24 h were chosen. Due to low water absorption rate, two water absorption states for SL, namely dry and absorbing water 24 h were employed. Then, concrete samples with different water absorption lightweight aggregate were prepared according to the same mixing procedures.

2.3. Testing methods and procedures

The properties including compressive strength, static and dynamic elastic modulus and damping ratio of specimens were tested at specific ages, respectively. The dynamic mechanical properties of the specimens with a size of 100 × 100 × 300 mm were tested by the resonance frequency method according to ASTM C 215, employing the E-modumeter system (E-Meter Mk II type) produced by the James Instruments Inc, as shown in Fig. 2. The average value of the five testing specimens was used as the result of dynamic elastic modulus. The damping ratio ζ of the specimen was obtained according to Eq. (1) and the corresponding acceleration attenuation curve. All the specimens were kept at a room with a temperature of (20 ± 3) °C and a relative humidity of (75–65)% when the dynamic properties were tested.

$$\zeta = \frac{1}{2n\pi} \ln\left(\frac{A_1}{A_n}\right) \tag{1}$$

where, A_1 and A_n is the acceleration peak value at the first cycle and n cycles after impacting action on the specimen, respectively. In this investigation, the six cycles (10th, 20th, 40th, 60th, 80th, and 100th

Table 1
Chemical compositions of cement, FA and GGBS (by wt%).

Type	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Loss on ignition/%
Cement	19.0	5.1	4.6	61.4	1.8	1.9	4.3
FA	53.2	10.1	21.5	2.9	–	0.6	5.7
GGBS	26.1	13.8	14.2	33.6	8.1	–	2.1