Construction and Building Materials 154 (2017) 687–696

Contents lists available at ScienceDirect

Construction and Building Materials

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

Research on dynamic mechanical properties of alkali activated slag concrete under temperature-loads coupling effects

Wu-Jian Long *, Jing-Jie Wei, Yu-Cun Gu, Feng Xing

Guangdong Provincial Key Laboratory of Durability for Marine Civil Engineering, Shenzhen Durability Center for Civil Engineering, College of Civil Engineering, Shenzhen University, Shenzhen 518060, Guangdong, PR China

HIGHLIGHTS

- DMA properties of standard cured AASC are higher than natural cured AASC.
- Dissipated energy reaches its maximum value when AASC under stress and at 180 °C.
- Standard cured AASC had a denser internal structure than natural cured AASC.
- Production of AASC produces 20.2% less CO_2 emissions compared to same strength OPC.

ARTICLE INFO

Article history:
Received 7 May 2017
Received in revised form 2 August 2017
Accepted 4 August 2017
Available online 17 August 2017

Keywords:
Curing condition
Alkali-activated slag concrete
Dynamic mechanical properties
Microstructure
Ecological analysis

ABSTRACT

The 28-day dynamic mechanical properties of alkali-activated slag concrete (AASC) under standard and natural curing conditions were investigated using a dynamic mechanical analysis (DMA) device. The DMA results showed that the dynamic mechanical properties of the standard cured AASC were higher than the natural cured AASC when concrete heated from −45 °C to 250 °C. The dissipated energy reached its maximum value when AASC under stress were heated to approximately 180 °C. The microstructural analysis revealed that the pores of standard cured AASC were smaller than those under natural conditions in terms of the number of pores, volume and specific surface area. An economic and ecological analysis showed that compared with ordinary Portland cement concrete (OPC) in the same strength grade, the production of AASC consumes 2.4% less energy and produces 20.2% less CO_2 emissions.

1. Introduction

Currently, Portland cement is the most widely used cementitious material in construction. Global Portland cement consumption increased from 2.31 billion tons in 2005 to 4.1 billion tons in 2015, which was also accompanied by a large increase in CO_2 emissions. Continuous use of this type of cementing material significantly limits the development of sustainable concrete. Alkali-activated slag concrete (AASC) is a green material produced by using an alkali-activated slag cementitious material instead of a pozzolanic-based cementitious material [1–3]. Compared with conventional Portland cement concrete (PC), AASC has a number of advantages such as good corrosion resistance, high early strength and low carbon emissions, etc. As a result, alkali-activated slag cementing materials have already been widely used in practical engineering applications to replace conventional cement-based cementing materials [4–7].

Numerous studies have been conducted to investigate the properties of AASC. Ding et al. compared the mechanical properties of three types of alkali-activated concretes (AAC), and found that the differences between AAC and OPC largely depend on the proportions of raw materials used in the concrete; specifically, the slag to fly ash ratio is a very influential factor [8]. Watstein [9], Collins and Sanjayan [10,11] studied the mechanical properties of AASC and found that AASC had higher compressive strength than OPC prepared with similar mixing proportions. Bakharev et al. [12,13] studied the carbonation resistance and acid resistance of AASC and found that AASC exhibited lower carbonation resistance but higher acid resistance than OPC. Law et al. [14] evaluated the durability of AASC in terms of compressive strength, water absorption, carbonation depth and rapid chloride ion permeability and found that AASC showed lower durability than OPC. Yuan et al. [15] studied the shrinkage compensation and microstructure of AASC with an expanding admixtures composed of anhydrite and quick lime as the expanding source and found that the expanding admixtures was an effective measure to compensating the shrinkage of AASC. Chi et al. [16] studied the high-temperature resistance of AASC and

---

* Corresponding author.
E-mail addresses: longwj@szu.edu.cn, alainens@hotmail.com (W.-J. Long).

http://dx.doi.org/10.1016/j.conbuildmat.2017.08.015

discovered that AASC had excellent high-temperature resistance. While numerous studies of AASC have been carried out, however, few studies on the dynamic mechanical properties of AASC were reported.

Dynamic thermomechanical analysis is widely used to study steel, rubber, synthetic fibers and coatings, polymers, composites and timber [17–23]. There are very few studies on the variation of the dynamic mechanical properties of AASC with different temperatures. Curing conditions have a significant impact on the mechanical properties of AASC. Therefore, using DMA to investigate the thermodynamic properties of AASC cured under various conditions is important to understand the properties of AASC under low frequency waves. The low frequency waves, in the range 1–10 Hz for earthquakes, cause a large amount of damage; depending on the geological conditions they can travel considerable distances and may match the resonant fundamental frequency of buildings [24].

The dynamic mechanical properties of AASC can be used to characterize its damping capacity. An investigation of the variation of the storage modulus, loss modulus and loss factor of AASC cured under standard and natural conditions with different temperatures is important for research of the energy dissipation and damping capacity of AASC as well as for understanding the properties of AASC under the combined effect of high/low temperature and a dynamic load. The present study investigated the dynamic mechanical properties and microstructural morphology of AASC cured under standard and natural conditions using the DMA and environmental scanning electron microscopy (ESEM). Additionally, the economic and ecological efficiency of AASC and OPC of the same strength grade was analysed in this study to provide the necessary theoretical basis and engineering data for applications of AASC in engineering projects.

2. Experimental program

2.1. Raw material characterization

2.1.1. Alkali solution and supplementary cementitious materials (SCMs)

The binders used for the production of alkali activated concrete mixtures were an alkali solution (liquid sodium silicate) and two supplementary cementitious materials SCMs (blast-furnace slag and Class F fly ash). The liquid sodium silicate (LSS) was obtained from a local supplier and was composed of 14.26% Na_2O + 26.92% SiO_2 + 54.24% H_2O by mass with a density of 1562 kg/m^3. The modulus of the LSS is 1.95. The density values of the blast-furnace slag and fly ash are 2.5 g/cm^3 and 1.98 g/cm^3, respectively, and their Blaine specific surface area values are 409.5 m^2/kg and 424.0 m^2/kg, respectively. The chemical compositions of the blast-furnace slag, and fly ash are shown in Table 1.

2.1.2. Aggregates

Crushed granite aggregates were used as the coarse aggregate and standard sand was used for the fine aggregates. The aggregates were tested and conformed to the properties required in ASTM C127 [25]. The physical characteristics of the coarse and fine aggregates are shown in Table 2. The grain-size distributions of the coarse aggregate and sand are summarized in Table 3 and Fig. 1.

2.2. Test methods

2.2.1. Test principle

DMA (as shown in Fig. 2) characterizes the properties of a material based on the state of its molecular motion. Molecular motion and physical form determine the dynamic modulus (stiffness) and damping (energy consumed during oscillation) of a material. A dynamic thermomechanical analyser is designed based on the basic time–temperature superposition principle (i.e., increasing the frequency when the temperature is fixed is equivalent to increasing the temperature when the frequency is fixed). A dynamic thermomechanical analyser applies a sinusoidal alternating force with varying amplitude to the specimen while controlling the temperature, which allows the specimen to deform while controlling the time. In addition, when using a dynamic thermomechanical analyser, there is a phase angle (i.e., loss angle (δ)) lag for the strain response of the specimen. A dynamic thermomechanical analyser can simultaneously obtain the variation curves of the storage modulus (E'), loss modulus (E'') and loss factor ($\tan\delta$) of the specimen for changes in temperature, frequency and time. Based on these variation curves, the mechanical properties of the specimen can be represented for a broad range of temperatures and frequencies. The storage modulus is directly proportional to the mechanical energy stored in the specimen during the action of a stress. The loss modulus signifies the energy dissipated by the specimen during the action of a stress (loss = heat loss). A higher loss modulus means that the damping is higher. The loss factor is the ratio of elasticity to viscosity. A higher loss factor means more energy is dissipated and the degree of inelastic deformation is higher. In addition, the magnitude of the loss factor is unrelated to the geometric factor. The composite modulus is the ratio of the peak stress (stress amplitude) to the peak strain (strain amplitude). $M^* = E' + iE'' = E'(1 + i\ \tan\ \delta)$. Fig. 3 shows the relationship among the storage modulus, loss modulus, composite modulus and loss angle.

2.2.2. Test parameters

Based on the literature review [26–28] and the preliminary experiments, the mix proportions of AASC used in this investigation were as follows: coarse aggregates, 469.6 kg/m^3; natural standard sand, 384.8 kg/m^3; blast-furnace slag, 480 kg/m^3; fly ash, 52.8 kg/m^3; sodium silicate, 250.36 kg/m^3; and additional water, 50.63 kg/m^3. In addition, the mixture was placed into a 20 mm × 20 mm × 20 mm cubic mould after mixing. Fig. 4 shows the mixing sequence of AASC.

According to the ASTM C31 [29] and C192 [30] standards for concrete cured in a laboratory under standard and natural conditions, an impermeable thin film was used to cover the surface of each prepared AASC specimen, which was then cured in a standard curing chamber with temperature of 20 ± 2 °C and relative humidity no less than 95% for 24 ± 4 h, after the specimen was demoulded. Subsequently, some AASC specimens were placed in a natural environment (temperature: 28 ± 2 °C; relative humidity: 50 ± 5%) for 28-day further curing, while the other AASC specimens were placed in a standard curing chamber (temperature: 20 ± 2 °C; relative humidity: >95%) for 28-day further curing. Afterwards, some AASC specimens cured under these two conditions were selected and subjected to Barrett-Joyner-Halenda (BJH) nitrogen

Table 1
Chemical compositions of the fly ash and blast-furnace slag (mass %).

Ingredient	CaO	SiO_2	Al_2O_3	MgO	SO_3	TiO_2	Fe_2O_3	K_2O	MnO	Na_2O	SrO	ZrO_2
Fly ash	2.68	49.9	26.9	0.4	2.31	1.35	14	1.51	0.11	0.16	0.06	0.15
Blast-furnace slag	44.7	27.3	13.7	8.48	2	1.44	0.74	0.45	0.42	0.36	0.12	0.06