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The effect of mechanical load on transport property and pore structure of alkali-activated slag concrete

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HIGHLIGHTS

- The critical stress level of AAS under compressive load is in the range of 80%–90%.
- Water glass activated slag are compacted considerably by compressive load.
- There is no significant compacting effect in compression of NaOH activated slag.
- Closure of pores takes predominant in water glass activated slag under compression.

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ABSTRACT

It would make sense to detect the rules and mechanisms of degradation and mass transport of alkali-activated slag concrete (AASC) in actual service environment. In this paper, hydration products characterization implies higher crystallinity degree of C-S-H activated by NaOH and higher polymerization of the one activated by water glass. During compressive loading, Poisson's ratio of AASC keeps constant at the stress level ranging from 0 to 0.5, with an uprush takes place at stress level of 0.8–0.9. For slag concrete activated by NaOH, volume increases with stress level, while the volume of slag concrete activated by water glass decreases first and then increase with stress level. The apparent chloride diffusion coefficient of specimens activated by NaOH is 4–7 times smaller than the ones activated by water glass, which is verified by the results that volume of pores above 10 μm of water glass activated sample is nearly 20 times more than that of NaOH activated one. Slag concrete activated by water glass is compacted considerably by compressive loading contributing to the decrease in chloride diffusivity, while no significant compacting phenomenon is observed in slag concrete activated by NaOH. However, there is no significant compacting effect on capillary absorption for both specimens activated by two activators.

1. Introduction

The study on transport properties of damaged concrete is essential for predicting the service life of concrete structure. Over the last decade, extensive work has been carried on to understand the pore structure and transport properties of alkali-activated slag (AAS) materials [1–4]. However, for AAS concrete, there is still little research related to the pore structure and transport properties of concrete damaged by mechanical load.

Transport properties of ordinary Portland cement (OPC) under compression have been studied extensively [5–13]. Some studies show a slight increase in permeability of concrete specimens when it is loaded by low load [6–8], and the decreased permeability is also reported due to the closure of initial microcracks [10–13]. Under high compressive load, microcracks may propagate and become interconnected inside the concrete material. These microcracks form potential flow channels providing easy access to aggressive ions such as chloride and sulfate ions. With load further increasing, a critical stress will be exceeded resulting in serious damage, which leads to a sharp increase in permeability [6,7,13].

For AAS material, its pore structure and transport property are determined by raw material and activator type and concentration. In recent decades, studies related to activated fly ash/slag blends have been a focus. The incorporation of fly ash as an additional source of alumina and silica in activated slag binders affects the rate and mechanism of formation of the main binder gels [14–16]. Ismail et al. [14] reported that the formation of co-existing C-A-S-H and N-A-S-H gels is observed in blended slag-fly ash binders. In the microscale, increasing slag content gives an increase in pore network tortuosity and decrease in porosity [17].

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The initial pH of alkaline solution plays an important role in raw material dissolution [18,19], and the nature of anion in solution determines the reaction mechanism and strength development [20–22]. As compared with NaOH and Na_2CO_3, water glass-activated slag materials exhibit the lowest porosity and the finest pore structure, contributing to the highest strength [23–25]. Water glass is regarded as the most effective activator among NaOH and Na_2CO_3.

In this paper, an investigation on hydrate products of AAS is presented firstly. Then microcracks are induced in concrete specimens by mechanical uniaxial compression with load level from 35% to 80%. Meanwhile, volume change ratio and dynamic elastic modulus are applied to characterize damage and microcracking in AASC. Before and after loading, chloride diffusion and capillary absorption are investigated, and the evolution of pore size distribution and matrix-aggregate interface is analyzed. Furthermore, the effect of activator types (i.e. NaOH and water glass) and slag substituted by fly ash are given in this paper.

2. Experimental program

2.1. Preparation of specimens

Six concrete mixes of alkali-activated blast furnace slag and fly ash are selected and the mix proportions are given in Table 1. The chemical compositions of applied slag and fly ash are shown in Table 2. Aggregates consist of local river sand with maximum grain size of 5 mm and crushed basalt with maximum size of 20 mm, and both of them come from Qingdao. Two types of alkali solution are selected as activators: NaOH solution and water glass with a modulus of 1.8 (mixtures of liquid sodium silicate, NaOH, and distilled water).

Cubic concretes with dimensions of 100 × 100 × 100 mm and prismatic concretes with dimensions of 100 × 100 × 300 mm are fabricated, which were cured with a relative humidity of 95% and a temperature of 20 ± 3 °C until the age of 28 days.

2.2. Hydration products and microstructure characterization

The samples for Fourier Transform Infrared (FTIR) spectroscopy are prepared by mixing 1 mg of AAS paste powder cured for 14 days with 300 mg of KBr. The spectral analysis is performed in the range 4000–400 cm^{-1} with spectral evolution of 1 cm^{-1}. X-ray diffraction (XRD) analysis is applied to pastes specimen cured for 14 days using a Bruker D8 Advance diffractometer, with a step size of 0.020 and a count time of 4 s per step.

The morphology and element analysis of concretes are analyzed by Scanning Electron Microscopy (SEM) and Energy Dispersive Spectrometer (EDS), conducting on an EVO MA18 40XVP instrument at 25 kV. To obtain the details about the pore structure, mercury intrusion porosimetry (MIP) and nitrogen adsorption porosimetry are utilized. In order to avoid the damage to pores by high temperature, fractured particle samples with sizes less than 10 mm are dried in an oven at 60 °C until constant weight.

2.3. Mechanical properties and damage characterization

At the age of 28 days, concrete prisms (100 × 100 × 300 mm) are loaded with predetermined compressive stress levels (0, 35%, 50%, 65% and 80% of ultimate stress, respectively) and last for 15 min. The stress rate of loading and unloading is 0.45 MPa/s. During all the stages, strains are measured by four electrical strain gauges which are glued on the lateral surfaces and mid-height of each specimen, two in axial directions and the other two in transverse directions, which are shown in Fig. 1.

The evolution of Poisson's ratio and volumetric change ratio are introduced to characterize the damage degree. Volume change ratio (V_r) of the concrete prism is investigated after unloading, through which the damage evaluation can be deduced. A unit cube with side length of a is selected from the mid-height of prismatic concrete, and its V_r is calculated by the following equations:

$$\begin{aligned}
&V_0 = a \cdot \mathrm{a} \cdot \mathrm{a} \\
&V_u = [a \cdot (1 + \varepsilon_{\mathrm{xu}})]^2 \cdot [a \cdot (1 + \varepsilon_{yu})] \\
&\approx a^3 \cdot (1 + 2\varepsilon_{xu} + \varepsilon_{yu}) \\
&\Delta V = Vu - V_0 = a^3 \cdot (2\varepsilon_{xu} + \varepsilon_{yu}) \\
&V_r = \Delta V / V_0 = 2\varepsilon_{xu} + \varepsilon_{yu}
\end{aligned} \tag{1}$$

where V_0 and V_u are the volume of the unit cube before and after the loading test, respectively; ε_{xu} and ε_{yu} are the residual transversal strain and longitudinal strain after unloading, respectively. The negative value of V_r means volume reduction, which is caused by the compaction by compressive load. The positive value implies volume growth, and it is due to the generation and propagation of microcracks inside the concrete. Therefore, the variation of V_r is directly correlated to the variation of pore volume of concrete.

In addition, the measurement of dynamic elastic modulus (E_d) is also carried out before and after loading test using 'Grindosonic' apparatus. The decrease in the E_d is due to the appearance of microcracks, and it is extensively used as an index to evaluate the degree of damage for concrete materials [7,26,27].

Table 1
Mix proportions of AAS concrete, kg/m^3.

Code	Activator	Na_2O in Alkali solution, wt%	Alkali solution	Coarse aggregate	Sand	Slag	Fly ash
N7	NaOH	7%	184	1074	716	400	0
N9	NaOH	9%	184	1074	716	400	0
N9FA	NaOH	9%	184	1074	716	320	80
W7	Water glass	7%	184	1074	716	400	0
W9	Water glass	9%	184	1074	716	400	0
W9FA	Water glass	9%	184	1074	716	320	80

Table 2
Chemical composition of slag and fly ash, mass%.

	CaO	SiO_2	Al_2O_3	MgO	SO_3	Fe_2O_3	K_2O	Na_2O	TiO_2	MnO
Slag	41.60	26.81	17.79	0.48	2.03	9.28	0.39	0.31	0.72	0.34
Fly ash	5.79	66.8	17.93	1.50	0.50	4.03	1.32	0.26	1.07	0.06