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Fracture properties and response surface methodology model of alkali-slag concrete under freeze–thaw cycles

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HIGHLIGHTS

- Response surface methodology is used to study ASC's fracture toughness.
- Influence on K_{IC}^{S} is slag content > age > sol ratio, interaction of the former 2 is significant.
- K_{IC}^{Q} is about 50–70% of K_{IC}^{S} crack initiation should be the warning indicator of ASC structure.
- K_{IC}^{S} declines with more freeze–thaws. Rate and degree increase with sol ratio, slag content.
- Increased sol ratio reduces density, depolymerization. Gel material reduces toughness.

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ABSTRACT

Alkali-slag concrete (ASC) is prepared with Na_2SiO_3 and NaOH composite activator. Fracture properties of ASC under freeze–thaw cycles are studied using response surface methodology (RSM), Design Expert software and Box–Behnken design (BBD). The RSM model of fracture toughness is built, then the influence law of sol ratio, slag content, age on fracture toughness is put forward. The relationship between initiation fracture toughness (K_{IC}^{Q}) and unstable fracture toughness (K_{IC}^{S}) is established. The influence law of freeze–thaw, sol ratio and slag content on K_{IC}^{S} is built, and the impact mechanism of the two factors on K_{IC}^{S} is analyzed. Results show that the RSM model fits well and can be used to analyze and predict ASC fracture toughness. The influential significance rank for K_{IC}^{S} is slag content > age > sol ratio, and the most significant interaction is between slag content and age. K_{IC}^{Q} is about 50–70% of K_{IC}^{S}, crack initiation should be the warning indicator of ASC structure. Fracture toughness decreases with the increased freeze–thaw times, whose declining rate and degree increase with sol ratio and slag content. With sol ratio increasing, more intense is the alkali slag reaction, reducing density and hindering depolymerization. With more cementitious material content, effective water–cement ratio is relatively decreased, subsequent hydration is limited, some slag powder does not participate in the reaction, reducing ASC toughness.

1. Introduction

As a new high-performance concrete, ASC gradually becomes a hotspot in the engineering field for advantages such as environmental friendliness, high strength and high durability. ASC is prepared with waste rich in kaolinite or aluminum silicate mineral, such as kaolin quarry, coal, slag, fly ash, other minerals, and industrial by-products under the effect of chemical activator. During the chemical reaction, slag generates $[SiO_4]^{4-}$ tetrahedron and $[AlO_4]^{5-}$ tetrahedron through depolymerization of —O—Si—O—Al—O— chain invitreous structure, and polycondensate to generate a new —O—Si—O—Al—O— gelling material with network structure. Raw material sources of ASC range widely, they are easy to obtain locally and have simple production process, whose calcination temperature is only 600–800 °C, reducing energy consumption over 70%, and the CO_2 emission during manufacture is only 10–20% of Portland cement. So ASC is really a green low-carbon material.

Current studies on ASC are mainly in the reaction mechanism, alkali activator ratio, final product composition, structure, macro mechanics and durability under normal temperature [1–8]. Caijun et al. [9] introduced the ASC raw materials, hydration, microstructure development, strength, durability and relevant standards and regulations. Liangcai et al. [10] studied the ASC antifreeze durability. Hanjari et al. [11] researched the freeze–thaw

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damage of concrete materials and bonding properties. Karihaloo et al. [12] built the tri-line model by measuring the fracture energy of concrete. Pacheco-Torgal et al. [13] investigated the durability of alkali-activated binders. Yonggen et al. [14] studied the durability of alkali-activated slag concrete pavement. Gebregziabiher et al. [15] concluded the early age kinetics and microstructure development of ASC. Yawei et al. [16] put forward the ASC's damage model under the effect of freeze–thaw cycles. However, there are few studies on ASC fracture properties, the environmental impact on its performance is even more neglected, especially research on fracture performance of ASC under freeze–thaw is rarely reported. Freeze–thaw damage is the main cause of concrete deterioration in cold region, therefore, it is theoretically and practically significant studying ASC fracture properties under freeze–thaw effect.

Through rapid freeze–thaw cycle test and three-point bending fracture test, fracture parameters including double-K fracture toughness K_{IC}^{Q} and K_{IC}^{S}, horizontal crack mouth opening displacement (CMOD) and effective fracture length before and after freezing and thawing were studied. Using RSM and BBD, the influence and degree of sol ratio, slag content, age and their interactions on fracture parameters before and after freeze–thaw were studied. The Design Expert 7.0 software was used to build predictive models and analyze response surface for influence and mechanism of ASC fracture properties.

2. Test materials and methods

2.1. Raw materials and preparation

Specimens were fabricated with following materials:activator composed of Na_2SiO_3 sodium silicate (27.21% SiO_2, 8.14% Na_2O, Ms = 3.1) and NaOH complex solution, which density was 1.43 g/cm^3. Metallurgy blast furnace slag powder with specific surface area of 410 m^2/kg and density of 2.86 g/cm^3. Natural river sand with fineness modulus of 2.86, density of 2.63 g/cm^3, bulk density of 1.50 g/cm^3, and 0.5% clay content. Limestone gravel (45% 5–20 mm, 55% 20–40 mm) with density of 2.76 g/cm^3 and bulk density 1.69 g/cm^3. The main chemical composition of slag powder is shown in Table 1.

All mixtures were mixed by a 60L single horizontal axis compulsory mixer. The alkali activator was added with pre-dissolved method. When the activator solution and ground slag mixed, slag particles dispersed in water and formed a slurry. The feeding sequence and stirring time were:sand and slag (30 s) → stone (30 s) → activator solution (120 s). Then the mixture was molded and placed on a standard vibration bench for 60–90 s until the surface pan pulped.

According to common specimen size, 5 groups of 100 mm × 100 mm × 400 mm prism specimens were molded, each with 6 test pieces, which were placed 1 d at 20 °C room temperature after molding. Then they were numbered, demolded, and cured in the standard curing room immediately until test age.

2.2. Test methods

According to the rapid freeze–thaw method in ASTM C666, weight of the specimens and the elastic modulus were measured every 25 freeze–thaw cycles, the mass loss and relative dynamic elastic modulus were calculated.

Table 1
Chemical compositions of slag/w%.

CaO	SiO_2	Al_2O_3	MgO	MnO	Fe_2O_3	TiO_2	Loss
38.95	33.91	10.71	9.41	0.31	3.28	3.43	1.27

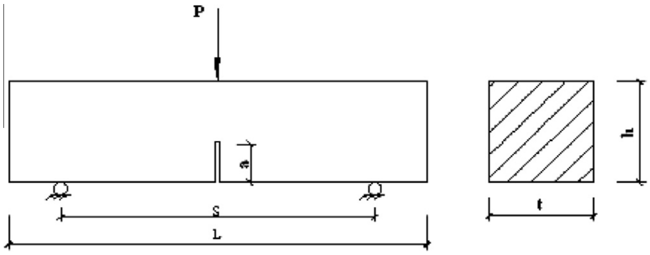

Fig. 1. Schematic diagram of three-point bending beam specimen.

According to DL/T 5332-2005 "fracture testing procedures of hydraulic concrete", notched three-point bending beam method was used in the experiment. Double-K fracture criterion was used in the fracture model, which introduced two fracture parameters: K_{IC}^{Q} and K_{IC}^{S}.

Specimen size used in the test and load diagram are shown in Fig. 1.

Where $L = 400$ mm is for specimen length, $S = 300$ mm for the span, $h = t = 100$ mm for section height and width respectively. Pre-incision was in the lower part and the upper part to withstand external load P, a/h was for the initial crack height ratio, which fixed at 0.4. The initial crack a was formed with pre-positioned 3 mm thick steel sheet in the test mode before pouring concrete. After pouring, specimens were cured for approximately 2 h (after initial setting, before final setting), then the steel sheet was extracted to form a reserve seam as precast joints in fracture toughness test. MTS 810 material testing machine and 3541 type of clip-on extensometer were used to measure the cross-section line deflection and pre-crack opening ends displacement.

CMOD was directly measured using clip-on extensometer and was connected to the computer with automatic collection system, which could draw the P-CMOD curve and then get critical horizontal crack mouth opening displacement ($CMOD_C$). At the same time, the test could also directly measure the load–displacement (P–V) curve and take the load when the specimens fracture at ultimate load P_{max}. After determining P_{max} and $CMOD_C$, stress intensity factors including K_{IC}^{C}, K_{IC}^{Q} and K_{IC}^{S} resulted from effective fracture length, horizontal crack tip opening displacement (CTOD) and closure stress $\sigma(w)$ could be calculated based on the fracture toughness formula derived from the double-K fracture criterion and DL/T 5332-2005 "fracture testing procedures of hydraulic concrete" [17–19].

3. RSM model design

3.1. Selection of response model

According to the model provided by response surface analysis software, quadratic response surface equation is selected, which can be expressed as:

Table 2
Levels of factors of RSM.

Factor	Code	Levels of code		
		−1	0	1
A/S	A	0.54	0.56	0.58
Slag content/(g/cm^3)	B	0.40	0.42	0.44
Age/d	C	28	60	92