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Freeze–thaw resistance of alkali–slag concrete based on response surface methodology

Liangcai Cai, Haifu Wang *, Yawei Fu

Air Force Engineering University, Xi'an 710038, China

HIGHLIGHTS

- Response surface methodology (RSM) is used to study ASC's freeze–thaw resistance.
- The influence on the freeze–thaw resistance from high to low is A/S, slag content and sand ratio.
- The interaction of A/S and slag content is the most prominent.
- Air-void structure is a decisive factor, and space coefficient and specific surface area are related well to D_F.

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ABSTRACT

Alkali–slag concrete (ASC), with the frost resistant grade of above F300 and frost resistant coefficient D_F of about 90%, is prepared using slag and composite activator composed of Na_2SiO_3 and NaOH. Response surface methodology (RSM) is applied to study the freeze–thaw resistance of ASC. The effects of activator solution–slag ratio (A/S), slag content and sand ratio on the freeze–thaw resistance are analyzed using the softwares of Design Expert and Box-Benhnken Design (BBD). Models are established for D_F and the influence of air-void structure of hard concrete on the freeze–thaw resistance, respectively. The result shows that the D_F model coincides well with the test results and can be used to analyze and predict the freeze–thaw resistance of ASC. The influence on the freeze–thaw resistance from high to low is A/S, slag content and sand ratio. The interaction of A/S and slag content is the most prominent and air-void structure is the crucial factor. The air bubble space coefficient and its specific surface area have good correlation with D_F. The freeze–thaw resistance tends to better with smaller air bubble space coefficient and bigger specific surface area.

1. Introduction

In recent years, there are plentiful studies on a new green binding material–alkali–activated cement, which can be prepared by wastes containing kaolinite or aluminosilicate (such as kaolinite ore, coal gangue, slag or fly ash) and chemic activator. Under a strong alkaline solution, –O–Si–O–Al–O– in vitreous body structure is rapidly dissolved into solution to form $[SiO_4]^{4-}$ and $[AlO_4]^{5-}$ tetrahedral units, then new –O–Si–O–Al–O– binding materials with three-dimensional network structure are produced by shrinking and polymerization reaction. The production process of alkali-activated cement is simple, requiring much lower calcining temperature (600–800 °C), consuming 70% less energy sources and emitting 80–90% less CO_2 than Portland cement (PC), so it can be called a genuine green low carbon cement.

Nowadays, the properties of alkali-activated concrete has been widely studied [1–6]. Caijun et al. [7] introduced raw materials, the hydration and micro-structure development, the mechanical properties and durability and related standards and specifications of alkali-activated slag cement and concrete. Duxson et al. [8] talked the role of inorganic polymer technology in the development of alkali-activated concrete. Maragkos et al. [9] investigated the effect of the main synthesis parameters on the mechanical and physical properties of the slag-based geopolymers, as well as their macro- and micro-structure. Deyu et al. [10] summarized factors affecting the properties of the alkali–activated cement and placed emphasis on the properties of concrete made with alkali–activated binders. Saud [11] discussed effect of the different parameters including the activator type and dosage on durability of alkali-activated slag concrete. Yawei et al. [12] studied properties of selt-compecting alkali–activator concrete for airport pavement. However, there is only a few studies on the freeze–thaw resistance of alkali-activated concrete and alkali–slag concrete (ASC), and most of the studies focus on the influence of external environment on the freeze–thaw

* Corresponding author. Tel.: +86 2984787738.
E-mail address: 376404958@qq.com (H. Wang).

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Table 1
Composition 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

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 /(g/cm^3)	*B*	0.40	0.42	0.44
sand ratio	*C*	0.32	0.34	0.36

resistance. Vegas et al. [13] studied frost resistance of blended cements containing calcined paper sludge and performed freeze–thaw tests of different waste paper sludge calcined containings. Chul-Woo et al. [14] focused on investigating the durability of concretes containing fly ash and silica fume exposed to combined mode of deterioration. Yawei et al. [15] studied damage mechanics models of alkali–activated slag concrete under freeze–thaw cycle test. Susan et al. [16] examined engineering and durability properties of alkali-activated slag/metakaolin concrete. Peijiang et al. [17] investigated freeze–thaw durability of fly ash based alkali activated mortars which were cured under ambient conditions and discussed the importance of composition tailoring. Actually, the air-void structure in concrete is the most important factor [18] to freeze–thaw resistance of ASC. But relatively few researches are about the relation between the air-void structure and the freeze–thaw resistance. Solution–slag ratio (A/S), slag content and sand ratio are three factors derectly affecting air-void characteristic parameters (air bubble spacing coefficient, air bubble specific surface area) of hardened concrete, so this paper studies he freeze–thaw resistance of ASC by analyzing the influences of the three factors.

In analyzing the influences of various factors on material properties, the method of single-variable and orthogonal design are usually adopted. Although the method can achieve good results, its test quantity is large and the interaction among various factors cannot be analyzed. Response Surface Methodology (RSM) is an integration method of mathematics and statistics, which is usually adopted to reflect the effects of the variables on the target and their

Table 3
Design of tests based on BBD and test results.

Test number	Design of tests				Rusults of tests		
	A	B/(g/cm^3)	C	D_F/%	Air bubble spacing coefficient /mm	Air bubble specific surface area /mm^{-1}	Grades of freeze–thaw resistance
1	−1	−1	0	92.2	0.129	16.2	F300
2	1	−1	0	83.1	0.289	4.9	F300
3	1	0	−1	84.0	0.244	5.9	F300
4	0	0	0	91.3	0.141	14.9	F300
5	1	0	1	86.6	0.197	8.0	F300
6	0	0	0	90.7	0.157	12.8	F300
7	0	0	0	91.4	0.140	14.9	F300
8	0	1	−1	90.3	0.163	11.6	F300
9	−1	0	1	93.2	0.105	18.6	F300
10	0	−1	1	88.4	0.189	9.8	F300
11	1	1	0	89.3	0.174	10.5	F300
12	−1	0	−1	91.1	0.149	14.0	F300
13	0	−1	−1	86.2	0.203	7.8	F300
14	−1	1	0	98.1	0.086	20.1	F300
15	0	0	0	90.3	0.162	11.7	F300
16	0	1	1	92.7	0.124	17.4	F300
17	0	0	0	91.7	0.133	15.3	F300

Table 4
Variance analysis of the model.

	Quadratic sum	Freedom	Mean square	*F* value	*P* value
Model	20547.21	8	2568.40	57.61	<0.0001
Residual error	356.67	8	44.58		
Lack of fit	227.87	4	56.97	1.77	
Pure error	128.80	4	32.20		
Sum	20903.88	16			

Table 5
Significant test of the regression coefficients.

	Regression coefficient	Standard deviation	Lower confidence limit of 95%	Upper confidence limit of 95%	*P* value
A	−39.50	2.36	−44.94	−34.06	<0.0001
B	21.00	3.34	13.30	28.70	0.0002
C	11.63	2.36	6.18	17.07	0.0012
AB	0.75	3.34	−6.95	8.45	0.8279
A^2	−5.40	3.25	−12.90	2.10	0.1356
B^2	1.35	3.25	−6.15	8.85	0.6891
C^2	−18.15	3.25	−25.65	−10.65	0.0005
A^2B	9.25	4.72	−1.64	20.14	0.0858