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Abrasion resistance of alkali-activated slag concrete designed by Taguchi method

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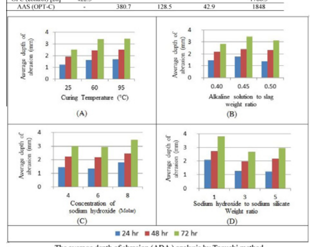
HIGHLIGHTS

- Alkali-activated slag (AAS) concrete showed proper abrasion resistance.
- The optimal mixture of the AAS concrete was achieved by Taguchi method.
- Water curing increased the abrasion resistance of AAS concrete.
- Eco-mechanical performance of AAS mixture was better than that of normal concrete.

GRAPHICAL ABSTRACT

Mixture proportions for the AAS mixture and the control mix.

Mix	Cement (kg/m^3)	Slag (kg/m^3)	NaOH solution (kg/m^3)	Sodium silicate (kg/m^3)	Aggregates (kg/m^3)
OPC (control) [28]	422.3	-	-	-	1788.3
AAS (OPT-C)	-	380.7	128.5	42.9	1848



The average depth of abrasion (ADA_t) analysis by Taguchi method

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ABSTRACT

In this study, abrasion resistance of Alkali-Activated Slag (AAS) concrete was investigated according to ASTM C1138. Four affecting factors including curing temperature, alkaline solution to slag weight ratio, concentration of sodium hydroxide solution and sodium hydroxide to sodium silicate weight ratio were considered to achieve the maximum compressive strength and abrasion resistance of AAS concrete using the Taguchi design of experiment method. Based on the results, the mixture with alkaline solution to slag weight ratio of 0.45, sodium hydroxide concentration of 6 M and sodium hydroxide to sodium silicate weight ratio of 3, that had been cured at 95 °C, and the mixture with alkaline solution to slag weight ratio of 0.4, sodium hydroxide concentration of 6 M and sodium hydroxide to sodium silicate weight ratio of 3, that had been cured at 25 °C, were obtained as the optimal mixtures for maximum compressive strength and abrasion resistance, respectively. The results also showed that abrasion resistance of AAS concrete was significantly increased by improving the quality of surface and changing the curing regime. Water curing as an appropriate method improved the surface conditions and considerably increased the abrasion resistance of AAS concrete too. In addition, the results showed that the CO_2 footprint of AAS concrete was approximately 51% less than that of Ordinary Portland Cement (OPC) concrete and therefore the eco-mechanical performance of AAS concrete was superior.

1. Introduction

Concrete advantages such as flexibility in shaping and molding, ease of production, fire resistance and more economy have turned it to one of the most widely used construction materials [1]. On the other hand, its negative environmental effects such as high consumption of energy and raw materials and significant CO_2 emissions from cement industry are related to the production of Ordinary Portland Cement (OPC) [2,3]. The problems of OPC, as mentioned above, have motivated researchers to consider alternative kinds of concrete for the development of infrastructure. During the last few decades, numerous advantages of alkali-activated binders as suitable alternatives for OPC concrete have attracted the

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attention of researchers. These binders are made by activating industrial by-products (such as blast furnace slag, fly ash, and rice husk) with an alkaline solution [4,5]. Alkali-activated slag (AAS) concrete is the combination of Granulated Blast Furnace Slag (GBFS), alkaline solution, that are usually sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) [6,7], and the conventional aggregates. AAS concrete have several advantages compared to OPC concrete such as an appropriate rate of strength development, high compressive strength [8,9], good resistance to chemical attack [10,11], freeze-thaw cycles [12] and chloride ion penetration [13]. The main factors affecting the mechanical properties and durability of AAS concrete are the composition of slag, concentrations of alkaline solution [14], oven curing time and temperature [15] and alkaline solution to slag weight ratio [16].

Despite extensive researches done on the mechanical properties and durability of AAS concrete, its hydraulic abrasion resistance has not been investigated yet. Dams, tunnel lining and other hydraulic structures are important concrete structures with long service life and high cost of maintenance. One of the most important durability issues in these hydraulic structures is abrasion erosion (wear), which is considered to determine the service life of hydraulic structures [17]. Concrete erosion in hydraulic structures occurs due to cavitation, abrasion and chemical attack. Abrasion erosion damages are created by the impact of water born silt, sand, gravel, rocks, ice, and other types of debris on the concrete surface during the operation of hydraulic structures [18]. In general, failure mechanism of abrasion occurs in three stages; in the initial stage, water molecules permeate on the surface and the peeling (crusting) occurs. In the second stage, the impact of suspended solids in the water cause cracks in the concrete surface. In the third stage, the failure occurs [19]. The abrasion erosion resistance of concrete is markedly influenced by such material properties as concrete strength, aggregate properties and quality, fiber and fly ash addition, mixture proportion and two other factors including curing conditions and surface finishing [20–22]. The abrasion resistance is most frequently described with Bohme's disc using a cubic sample abraded on a steel disc [23]. But, in the case of hydraulic structures, the abrasion resistance is determined by ASTM C 1138 (underwater method). It simulates the concrete wear caused by the water born particles at a speed lower than the cavitation speed [24].

On the other hand, structural concrete elements have to satisfy environmental requirements without compromising mechanical performances and the environmental aspects must be considered within a set of other design aspects. Therefore, the efficiency and validity of the AAS mixtures should be evaluated and it is necessary to analyze the eco-mechanical properties of concrete by means of quantitative tools like eco-mechanical indicators, in which both ecological and mechanical aspects are taken into account [25–27]. For example, Swamy considered the total carbon dioxide emitted to deliver 1 MPa of compressive strength, as possible values of eco-mechanical indicator [25].

In this study, abrasion resistance of some AAS concrete made of granulated blast furnace slag of Isfahan steel plant was investigated according to ASTM C1138 [24]. Four affecting factors (at 3 levels), including oven curing temperature, alkaline solution to slag weight ratio, concentration of sodium hydroxide solution and sodium hydroxide to sodium silicate weight ratio, were considered to evaluate the compressive strength and abrasion resistance of AAS concrete. Taguchi design of experiment method, which revealed its strengths for designing alkali-activated binders [28–32], was used to achieve the optimal mixture with maximum compressive strength and abrasion resistance. An experimental investigation was then conducted to examine the effect of water curing regime on the mechanical properties of AAS concrete. Finally, the efficiency of the optimal mixture was evaluated by means of eco-mechanical indicator (I-ratio) that is ratio between the quantity of CO_2 released by the production of binder materials, and the mechanical performance. This indicator was calculated for the optimal mixture and was compared with the value calculated for ordinary concrete.

Table 1
Chemical compositions of Granulated Blast Furnace Slag.

CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	SO_3	K_2O	Na_2O	Element
34.80	37.50	6.40	0.51	8.60	2.49	0.90	0.38	Mass (%)

Table 2
The considered levels for each parameter in Taguchi design of experiment.

Parameters	Level 1	Level 2	Level 3
Curing temperature (°C)	25	60	95
Alkaline solution to slag weight ratio	0.4	0.45	0.5
Concentration of sodium hydroxide solution (M)	4	6	8
Sodium hydroxide to sodium silicate weight ratio	1	3	5

Table 3
L9 array has been suggested by Taguchi method for 4 parameters at 3 levels.

Experiment series	Parameter1	Parameter2	Parameter3	Parameter4
	Levels			
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

Table 4
Detail of trial mixtures.

Mixture	Curing temperature (°C)	Alkaline solution to slag weight ratio	Concentration of sodium hydroxide solution (Molar)	Sodium hydroxide to sodium silicate weight ratio
1	25	0.4	4	1
2	25	0.45	6	3
3	25	0.5	8	5
4	60	0.4	6	5
5	60	0.45	8	1
6	60	0.5	4	3
7	95	0.4	8	3
8	95	0.45	4	5
9	95	0.5	6	1

Table 5
Mixture proportioning (kg/m^3).

Mixture	Slag	Sodium silicate solution	Sodium hydroxide solution	Aggregates	Added water	Slump (mm)
1	394.3	78.9	78.9	1848	98.0	46
2	380.7	42.8	128.5	1848	72.7	40
3	368.0	30.7	153.3	1848	63.9	42
4	394.3	26.3	131.4	1848	80.3	45
5	380.7	85.7	85.7	1848	99.6	47
6	368.0	46.0	138.0	1848	46.6	46
7	394.3	39.4	118.3	1848	84.2	42
8	380.7	28.6	142.8	1848	52.4	45
9	368.0	92.0	92.0	1848	81.7	44