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Identifying the bond and abrasion behavior of alkali activated concretes by central composite design method

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HIGHLIGHTS

- Bond strength and abrasion resistance of alkali activated concretes (AAC) were examined experimentally by CCD method.
- AASC were designed and produced considering the SC, SM, CT and ECT as the CCD's independent parameters.
- Compressive strength, split tensile strength, ultrasonic pulse velocity (UPV), abrasion and bond behavior of AAC were defined.
- Effects of each independent parameter on the dependent parameters were statistically analyzed.
- The optimum values of the parameters studied were defined as CT of 66 °C, ECT of 14.76 h, SC of 5.72% and SM of 1.0 for the defined multi-objective optimization problem.

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ABSTRACT

In this paper, bond strength and abrasion resistance of alkali activated concretes (AAC) were examined experimentally by using the central composite design (CCD) method. AAC were designed and produced considering the sodium concentration (SC), silicate modules (SM), curing temperature (CT) and exposed curing time (ECT) as the CCD's independent parameters. Twenty-one AAC mixtures were established depend on the various combinations of independent parameters in CCD at 95% confidence level. Effects of each independent parameter on the dependent parameters were statistically analyzed using experimental measurements and best possible combination of the independent parameters were defined for the maximization of the compressive strength, split tensile strength, UPV and bond behavior of AAC and for the minimization of abrasion value of AAC by solving the multi-objective optimization problems which is generated using the proposed regression models for the dependent parameters. Test results demonstrate that all studied independent parameters have the noteworthy effect on the properties of AAC statistically; however, the most effective independent parameter is SC. The optimum values of the parameters studied were defined as CT of 66 °C, ECT of 14.76 h, SC of 5.72% and SM of 1.0 for the defined multi-objective optimization problem.

1. Introduction

In 2020, globally, 4 billion tons of cement might be consumed and release of CO_2 to atmosphere due to the cement production and fuel combustion for the production are going to increase to coarsely 10% of worldwide CO_2 releases [1]. Due to the environmental and technical problems for the production and use of Portland cement, researchers and academicians have been focused on to find out an environmentally-friendly binder materials and investigated the alkali activated binders or geopolymer which are produced by the chemical reactions of industrial by-products or supplementary cementitious materials with the alkaline activators such as sodium hydroxide, sodium silicates or sodium carbonates [2]. When compared to ordinary Portland cement concrete, alkali activated binders have many brilliant properties such as thermal durability under high temperature, high early strength, excellent acid and freezing-thawing resistance and better heavy metal ions immobility in geopolymeric structure [3–5]. Alkaline activation is performed in three main categories with moderately calcium-rich materials, low-calcium materials and hybrid of moderately calcium rich and low calcium materials. Alkali activation of slag is defined as the activation of moderately calcium-rich materials. As is well known, main components of slag are calcium oxide

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(35–40%), silisium oxide (25–35%), magnesium oxide (5–10%) and aluminum oxide (5–15%). Slag also includes some minor components such as iron oxide, potassium oxide, manganese oxide and sulphure. Activation of slag with alkali is mainly depends on its chemical compositions and its vitreous structures. Degree of polymerization is directly related the glassy phase of slag and research showed that slag which has glassy phase higher than 90% is highly effective in terms of activation [6,7]. Slag, moderately calcium-rich material, is dominated by a calcium aluminosilicate hydrate (C—A—S—H) gel with a tobermorite-like (mostly Q^2, some Q^1 and Q^3) structure [8–10]. As known that chemical bonds of Si—O and Al—O are among the most stable covalent bonds in nature. Therefore, alkali activated binders have excellent compressive strength [11]. However, due to the rapid hydration at relatively higher curing temperature give rise to chemical shrinkage and lead to occurrence of micro-cracks in the matrix at early ages. This situation significantly affects the tensile behavior of AAC, contrary to the compressive strength, flexural or split tensile strength of AAC are considerably lower than that of the ordinary Portland cement concretes [12,13]. Türker et al. [13] illustrated that ratio of flexural strength to compressive strength was 17% for Portland cement mortar, 22% for ambient cured alkali activated slag mortar and 9% for elevated temperature cured alkali activated slag mortars. Pulling out of the cast in place steel rebar from the concrete specimens may be subjected to the direct tensile loads or shear loads or a combination of both shear and tension. In any pullout testing, rebar failure, pullout failure, splitting failure and concrete cone failure might be monitored. Bond behavior of Portland cement concretes depend on different parameters such as rebar diameter, concrete compressive strength, rebar development length, thickness of concrete cover, number of anchored rebar, and length to bar diameter ratio and it was investigated in literature in detail [14–19]. For the bond behavior of AAC, however, effects of abovementioned parameters are not investigated completely. Castel and Foster [20] studied the bond strength between blended slag and class F fly ash geopolymer concrete with steel reinforcement and concluded that 28-day bond strength and the overall bond stress–slip behavior of the geopolymer concretes were similar to those previously reported for ordinary Portland cement based concretes. Sarker [21] investigated the bond behavior of steel rebar which is embedded in fly ash geopolymer concrete and showed that fly ash based geopolymer concrete has relatively higher bond strength than ordinary Portland cement concrete.

Another important property of concrete is abrasion resistance which is surface resistance to rub of substances from top of concrete surface. ACI committee 201 defines as the abrasion resistance as to resist be worn away by rubbing and friction of foot traffic skidding, sliding, heavy traffic load trucking, and other abrasive materials [22]. Abrasion resistance of concretes is directly related to concrete strength, cement dosage, water-cement ratio, surface finishing, etc. Previous studies demonstrates that higher the compressive strength of concretes lower the rubbed of substances from the concrete surface. As mentioned earlier, alkali activated slag concretes has superior properties such as early strength, thermal resistance, and acid resistance. However, the presence of cracks induced due to the higher curing temperature exposed of alkali activated concretes might lead to the falling away in abrasion resistance as in tensile strength. By using the Taguchi design of experiment method, Mohebi et al. [23] studied the abrasion resistance of alkali activated slag concretes and illustrated that surface quality and applied curing regime are noteworthy effect on the abrasion resistance of AAS concrete. Karahan and Yakupoglu [24] explored the resistance of alkali activated slag mortars to abrasion and fire. In that study, it was demonstrated that use of sodium silicate and sodium meta-silicate in the activation of slag pan out the highest abrasion resistance and sodium hydroxide lead to the superior fire resistance.

As given above, in the literature, there is a few research papers related to the bond strength and abrasion resistance of the alkali activated or geopolymer concretes. However, in those papers, the properties mentioned were investigated individually and relationship between them is not explored. Therefore, in current research, bond strength and abrasion resistance of the alkali activated slag concretes were studied depend on the curing temperature (CT), exposed curing time (ECT), sodium concentration (SC) and silicate modules (SM) which are the main influential parameters on the properties of alkali activated concretes. The silicate modules of the mixtures are regulated by adding outside NaOH in the determined range by the help of literature. A restriction is occurred because of the water in the sodium silicate solution was more than necessary water for the constant alkali solution-slag ratio. Therefore upper limit of silicate modules is restricted. The other parameters range is also determined by the help of literature and some other trial before the experimental study. Experimental design was performed by using the central composite design (CCD) and test results were evaluated statistically. Influences of each independent parameter and their two factorial interactional effects on the properties were investigated experimentally and by variance analysis. Single, double and quadratic interactions of independent parameters were taken into consideration to obtain suitable regression models. While determining the regression models which were effective for each independent parameter, the inactive parameters were removed from the model. Therefore, the best describing model for each dependent parameter was obtained with 95% confidence level. Help of commercial software program, high correlation coefficient model (statistically significant), represents the best relationship between dependent and independent variables was chosen. By obtaining the statistically significant regression models for the test results, a multi objective optimization problem was defined and optimum values of the independent parameters were specified for the maximization of UPV, bond, compressive, and split tensile strength and the minimization of abraded substances from the AAC.

2. Experimental program

2.1. Experimental parameters and mix proportions

Experimental design was performed by CCD method, which is completely different from the classical experimental concept. In this method, firstly, independent parameters and their lowest and highest values must be defined. For current research, CT, ECT, SC and SM were defined as an independent parameters of the CCD, which are the most influential parameters on the properties of the alkali activated binders. CCD is an analytical technique and used to find out the effect of independent parameters on the dependent parameters. A two level four independent parameters (2^4) CCD was defined and minimum amount of variation to investigate the influence of each independent variable were determined. By considering the dependent variables might not be varied linearly with the defined independent parameters and to allow the quantification of the prediction of the responses, CCD plan was decided, in which dependent variables (responses) might be modelled as second order polynomial [25,26]. In order to improve the representability of independent variables, an area bound by coded value $-\alpha$ to $+\alpha$ from the central points were scattered and regression models were constructed on the scatter region. Therefore, a CCD test program was constructed depend on the $-\alpha$, -1, 0, +1 and $+\alpha$ coded values of the each independent variables. α is chosen