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Influence of waste glass powder usage on the properties of alkali-activated slag mortars based on response surface methodology

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HIGHLIGHTS

- RSM was used for the optimisation by maximising strengths.
- The optimum combination of 8.31% Na_2O and 14.57% GP was attained in AASGP mortar.
- The suitable amount of GP is effective in improving the properties of AAS mortar.
- Waste GP is an ideal admixture in AAS mortar.

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ABSTRACT

In this study, the effect of waste glass powder as a potential cementitious material on the strength, drying shrinkage and sulfate attack resistance of slag mortar activated by the mixture of water glass and sodium hydroxide was evaluated. Also, Central composite design and response surface method were used for the optimisation of the alkali content (sodium oxide equivalent) and replacement ratio of waste glass powder by maximising flexural and compressive strengths. The results of analysis of variance (ANOVA) indicated that the accuracy of the developed strength models based on response surface method was satisfactory. The optimal alkali content and replacement ratio of waste glass powder were found to be 8.31% and 14.57%, respectively. Under this condition, the experimental values of 3-, 7- and 28-day flexural strengths and 3-, 7- and 28-day compressive strengths of alkali-activated slag/glass powder mortar were 6.6 MPa, 7.1 MPa and 8.4 MPa, respectively and 49.2 MPa, 52.9 MPa and 66.4 MPa, respectively, which agreed closely with the predicted values since the percentages of error were negligible in the range of 0–2.38%. When the alkali content was 8.31%, the addition of 14.57% waste glass powder in alkali-activated slag mortar could improve the 3-, 7- and 28-day flexural and compressive strengths, reduce the dry shrinkage by up to 15.8% at 1 day and 20.3% at 120 days, and increase the resistance to sulfate attack.

1. Introduction

Slag is an industrial by-product obtained during the manufacturing of pig iron. Slag can be activated with alkaline solutions to form a new binder. Alkali-activated slag (AAS) binder reportedly exhibits excellent mechanical properties and durability [1,2], such as higher strength, higher chemical resistance, higher resistance to freeze-thaw cycles, and higher resistance to high temperature than ordinary Portland cement (OPC) [3,4]. The research and development of alternative binders are required for sustainable building materials. The environmental benefits of using AAS binder are obvious. For example, it can use more industrial by-products, consume less energy and release less carbon dioxide than OPC during the production process [5,6]. In addition, Slag can be partially or totally replaced by other by-products or wastes to prepare alkali-activated binders, like silica fume [7,8], fly ash [8–10], steel slag [11], lithium slag [12] and calcined reservoir sludge [13,14].

At present, as raw material for cement production or cement replacement in concrete, Slag is not available everywhere and its price is getting higher and higher due to limited supply. However, in China, 40 million tons of waste glass is generated annually, with only 13% of it being recycled [15]. Waste glass has been used as a partial substitute for OPC in mortar or concrete [16,17]. Previous studies have demonstrated that glass powder has adequate pozzolanic properties [17–19], and the properties of concrete can be

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effectively improved when glass powder is used as partial replacement of cement [20,21].

Glass powder (GP) is known to be rich in silica and it can be activated by alkaline media to form sodium silicate gel. Until now, very limited studies have been conducted on alkali activation of glass powder or the mixtures of slag and glass powder. Chen et al. [22] found alkali-activated glass inorganic binders could obtain high strength which was related to the activator and curing condition. Redden and Neithalath [23] reported that sodium hydroxide (NaOH)-activated glass powder binders could obtain higher compressive strengths than the activated fly ash mixtures at low heat curing temperatures, but the activated glass powder binders suffered the higher strength loss under moist curing conditions. Adding other materials, like slag or metakaolin, could be better to control the strength loss. Torres et al. [24] showed that the best 28-day strength was obtained at 27.7 MPa when the mixture of NaOH and sodium carbonate (Na_2CO_3) with 5% sodium oxide (Na_2O) was used to activate slag/waste glass (slag: waste glass = 70:30). The mechanical strength decreased with the increase of the waste glass content. Furthermore, in alkali (NaOH or NaOH/Na_2CO_3)-activated slag/waste glass binders, the slag was the main contributor to strength at early ages and the contribution of waste glass to the strength development was only after 28 days [25]. Avila-López et al. [26] studied the binders based on waste glass and limestone activated by NaOH/Na_2CO_3 with 9% Na_2O. The results revealed that the highest 28-day strength was 38.8 MPa and the hydration products mainly included C-S-H, a silica gel type phase, and crystalline phases such as pirssonite and gaylussite. In addition, Wang et al. [27] studied the use of waste glass sand (0%, 10% and 20%) instead of slag to prepare alkali- activated mortar. NaOH and sodium silicate solution were used as activator. The results showed that the slump increased with the alkaline solution (0.5%, 0.75%, 1%), the slump flow increased with the replacement of glass sand and the compressive strength increased with the alkaline solution and glass sand replacement.

These studies are mainly focused on NaOH or NaOH/Na_2CO_3 as activator to prepare alkali-activated binders based on glass or slag/glass. However, the type of activator has great influence on the strength of alkali-activated slag-based binders and the maximum strength can be achieved by using water glass solution [3,28]. Considering utilization of waste glass, the objective of this work was to study the feasibility of incorporating waste glass powder as a potential cementitious material in combination with slag to develop new binders activated with water glass. Response Surface Methodology (RSM) was used to determine the optimum mix-designed parameters (the alkali content and replacement ratio of glass powder) with maximum flexural and compressive strengths. Actually, RSM has been successfully applied in many areas, including physics, chemistry, biology, medical science and sociology for the probabilistic evaluation of a system and concrete industry for the optimising parameters [29,30]. Based on the optimum design parameters, the dry shrinkage and resistance to sulfate attack of alkali-activated slag/glass powder (AASGP) mortar were studied.

2. Materials and experimentation

2.1. Materials

Commercially available slag was used. The specific gravity and Blaine fineness of slag were 2.89 and 450 m^2/kg, respectively. The basicity coefficient $K_b = (CaO + MgO)/(SiO_2+Al_2O_3)$ was 1.06. Glass powder (GP) with a Blaine fineness of 500 m^2/kg was obtained by the grinding of cullet with various colors, from a glass recycling facility. Ordinary Portland cement (CEM I 42.5R) with a Blaine fineness of 368 m^2/kg was used as the reference binder. The chemical composition of these materials is listed in Table 1.

Water glass had a chemical composition of SiO_2 = 26% and Na_2O = 8% and the silicate modulus (M_S) was 3.2. Sodium hydroxide (NaOH) and water glass were mixed to make M_S (SiO_2/Na_2O) value of 1.0 on the basis of the previous studies [12,31]. Activator solution was prepared 1 day before the casting of mortars.

Crushed limestone sand (density = 2.65 g/cm^3, fineness modulus = 2.4) was used as fine aggregate in all mortar specimens.

2.2. Mix proportions and processing

2.2.1. Response surface methodology

Response surface methodology (RSM) explores the relationships between several explanatory variables and one or more response variables and it comprises a group of statistical and mathematical techniques for model building and model exploitation [30,32,33]. RSM is useful for modeling and analyzing the problems in which a response of interest is influenced by several input variables with the objective of optimizing this response [30,34].

When RSM is used to find the functional relationship between the response and various factors, the most commonly used design method is central composite design (CCD). A CCD is made orthogonal and rotatable by the choice of α, the axial distance from the design center. The value of α for rotatability is determined by the number of points (n_f) in the factorial portion of the design; in fact, $\alpha = (n_f)^{1/4}$. Therefore, the value of α for a design with two factors is 1.414. Furthermore, for providing reasonably stable variance of the predicted response, the center runs must be included in the CCD. Generally, three to five center points are recommended. Fig. 1 shows the CCD for k = 2 factors [34].

Additionally, in order to preserve the quality of the model, it is necessary to standardize the data with the coded variables. The values of these variables are in the range of −1 to 1. Eq. (1) is employed to define the relationship between the coded values (x_i) and real values (Z_i).

$$x_i = \frac{2Z_i - (Z_H + Z_L)}{Z_H - Z_L} \tag{1}$$

where x_i is the value in coded variable, Z_i is the real value, Z_H is the real value corresponding to 1 in coded variable, and Z_L is the real value corresponding to −1 in coded variable.

In AAS cement, the alkali content in activator has large influence on mechanical properties, which finally affects shrinkage [35–37]. Also, the amount of glass powder has apparent effect on the strength of AAS mortar. When the amount of glass powder was more than 20%, the strength of AAS mortar began to decrease [31]. Accordingly, two factors, namely Na_2O equivalent (Na_2O %) (x_1) and glass powder content(x_2), were considered in alkali-activated slag /glass powder (AASGP) mortar mix design and three levels (6%, 8% and 10% for the Na_2O equivalent; 10%, 15% and 20% for the glass powder content) for each factor were chosen in reference to existing study [15,21,31,38]. The coded variables and corresponding real values were given in Table 2. As shown in Eq. (2), a second order polynomial model was used to represent the response(y) as a function of the independent variables.

$$y = b_0 + b_1x_1 + b_2x_2 + b_3x_1x_2 + b_4{x_1}^2 + b_5{x_2}^2 \tag{2}$$

where y is the predicted response; x_1 and x_2 are individual effects of the Na_2O equivalent and glass powder content, respectively; x_1x_2 shows the interaction effect between Na_2O equivalent and glass powder content; x_1^2 and x_2^2 are quadratic effects of Na_2O equivalent and glass powder content, respectively; b_0 is the constant; b_1 and b_2