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Optimization of CWP-BFS Blended Geopolymer Concrete Using BWM-based Taguchi Method

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Abstract - The feasibility of blending ceramic waste powder (CWP) with blast furnace slag (BFS) to produce geopolymer concrete has seen limited investigation. This study aims to optimize the mixture proportions of CWP-BFS blended geopolymer concrete for superior mechanical and durability characteristics using the best-worst method (BWM) for multi-criteria optimization. The design of the experiments was carried out using the Taguchi method for five factors, each having four levels. The resulting CWP-BFS geopolymer concrete mixtures of the L_{16} orthogonal array were proportioned using different binder content, BFS replacement percentage, alkali-activator solution to binder ratio (AAS/B), sodium silicate (SS) to sodium hydroxide (SH) ratio (SS/SH), and SH solution molarity. Test methods included compressive strength and water absorption. The two quality criteria were given equal weights to determine the optimal levels of factors. The method revealed that the optimum mix had a binder content of 450 kg/m^3, BFS replacement percentage of 60%, AAS/B of 0.5, SS/SH of 1.5, and SH solution molarity of 10 M. Experimental findings endorse the utilization of CWP in geopolymer concrete as a means of alleviating the adverse environmental impact associated with its disposal.

***Keywords*:** Ceramic waste powder, Slag, Geopolymer, Optimization, Concrete

1. Introduction

During the last decade, there has been consistent research on the valorization of industrial by-products in the manufacture of alkali-activated concrete [1, 2]. The integration of fly ash, expanded perlite, granulated blast furnace slag (BFS), ceramic waste powder (CWP) revealed promising results since such waste materials are rich in siliceous, carbonate, and aluminous compounds [3-7].

CWP is a by-product generated during the final polishing process of ceramic tiles. Nearly 22 billion tons of CWP are produced per year, which might lead to severe consequences if not congruously disposed of. Hence, numerous studies have evaluated the suitability of CWP as a precursor binder in the development of alkali-activated concrete [8, 9]. For example, Zhang et al. found that CWP addition improved the compressive strength of alkali-activated BFS fly-ash concrete, particularly when subjected to a 300°C curing regime. However, the corresponding responses exhibited a considerable drop in strength with higher curing temperatures [10]. Rashad and Essa reported that partially replacing BFS with CWP into alkali-activated BFS pastes in the range of 5-50% enhanced the compressive strength and water absorption, although it altered the workability responses [11]. Komnitsas et al. showed that the dual effect of using finer particles of ceramic tile waste and elevated curing regimes resulted in remarkable improvement in the mechanical performance of geopolymer mixtures [12]. Sun et al. demonstrated that the use of CWP as the single precursor binder in the production of geopolymer achieved adequate strength responses yet under elevated temperature and prolonged curing time [13]. Mohammodi et al. highlighted the importance of pre-defining the chemical ratios in the alkali-activated reaction in order to obtain superior mechanical results under conventional curing regimes [9]. Based on the aforementioned, such classical methods for assessing the efficiency of the developed geopolymer mixtures require extensive experimental studies to find the optimum content, owing to the complexity of the chemical reactions involved with different parameters. Hence, many scientists have shifted their interest toward adapting systematic optimization methods before conducting the experimental program [14-17].

Algaifi et al. used the response surface methodology to optimize and predict the optimal content of CWP in BFS-based self-consolidating alkali-activated concrete. The authors found that the optimum content of 31% CWP satisfied the desired mechanical and durability performance, particularly when specimens were exposed to acid attack [18]. Teimortashlu et al. employed the Taguchi method to optimize the compressive strength of tertiary blended self-compacting concrete, in which three factors at four different levels were considered [19]. Similarly, Mehta et al. adopted Taguchi's optimization procedure for geopolymer mixtures. The corresponding signal-to-noise ratios (S/N) results showed that the optimum compressive strength could be achieved when using fly ash replacement by OPC at 20%, sodium hydroxide of 15 M, and curing temperature of 80°C [20].

Limited investigations have assessed the feasibility of blending ceramic waste powder (CWP) with blast furnace slag (BFS) to produce geopolymer concrete. Based on the literature, it is clear that geopolymer mixtures containing CWP have not been optimized for superior strength and durability properties yet. In fact, such a process is complex, as multiple factors must be considered concurrently along with different performance criteria, which may necessitate an extensive number of specimens/experiments. Accordingly, this work aims to find the optimum mixture proportions of CWP-BFS geopolymer concrete using the BWM multi-response optimization method. Research findings provide evidence of the effective use of CWP in geopolymer concrete while mitigating the severe environmental effects linked to its disposal.

2. Experimental Program

2.1. Materials

CWP sourced from waste ceramic tiles along with commercially available BFS were combined in this study to serve as the precursor binders. Their corresponding specific surface areas were 5550 and 4548 cm^2/g, respectively. Desert dune sand (0/4 mm) and dolomitic limestone aggregates (4/19 mm) were used. Their specific gravity, specific surface area, and fineness modulus were 2.7/2.82, 116.9/2.49 cm^2/g, and 1.45/6.82, respectively. The alkaline activator solution (AAS) was formulated by combining sodium silicate (SS) and sodium hydroxide (SH). The SS was classified as grade N with 63.4% H2O, 26.3% SiO2, and 10.3% Na2O, whereas the SH was prepared by mixing 98% pure SH flakes with various amounts of water to formulate different SH solution molarities of 8, 10, 12, and 14 M. A commercially available high-range water reducer was used to secure adequate consistency of the concrete.

2.2. Sample preparation and test methods

The mixing sequence consisted of homogenizing the dry materials in a pan mixer for three to five minutes. The AAS was then gradually introduced to the mix, followed by the high-range water reducer, and stirred for another 3 minutes to secure adequate consistency of the concrete. The ambient temperature and relative humidity during mixing and sampling hovered around 25±2°C and 50±5%, respectively. The fresh mixes were cast into cubic (100 mm), cylindrical (100×200 mm), and prismatic (100×100×500 mm) steel molds for strength and durability assessment. The specimens were demolded after 24 hours, then cured at ambient temperature until the testing age of 28 days. Furthermore, the mechanical properties were characterized by the compressive strength (f'c), which was determined following ASTM C39 [21]. For the durability tests, the water absorption (W_{abs}) was obtained using ASTM C642 [22]. For each property, triplicate samples per mix were tested to obtain an average.

2.3. Optimization methodology

A total of sixteen CWP-BFS blended geopolymer concrete mixes were designed based on Taguchi's method to concurrently consider different factors (Table 1). Each factor was characterized by four levels, i.e., binder content (400, 450, 500, 550 kg/m^3), BFS replacement percentage (20, 40, 60, 80%), AAS/B (0.50, 0.55, 0.60, and 0.65), SS/SH (1.0, 1.5, 2.0, and 2.5) and SH solution molarity (8, 10, 12, and 14 M). BWM-based Taguchi method was employed to simultaneously consider the identified mechanical and durability properties into a single performance criterion. Its detailed procedure can be found elsewhere [23]. Yet, it should be noted that mixes B12 and B14 could not be cast due to their excessively low workability.

Two quality criteria, i.e., Q1-Q2, were assigned to f'c and water absorption. The quality criteria were given equal weights in the analysis. The signal-to-noise (S/N) ratio was analyzed, as it is commonly carried out through three responses, responses, namely, the nominal-the-better, the smaller-the-better, and the larger-the-better. In this work, the smaller-the-better and the larger-the-better were used based on the targeted performance response. For instance, compressive strength strength was to be maximized, while the water absorption was to be minimized.

Table 1: Mixture proportions of the geopolymer mixes for the L_{16} Taguchi array.

Mix ID	Binder content (kg/m^3)	BFS (%)	AAS/B	SS/SH	SH (M)
B1	400	20	0.50	1.0	8
B2	400	40	0.55	1.5	10
B3	400	60	0.60	2.0	12
B4	400	80	0.65	2.5	14
B5	450	20	0.55	2.0	14
B6	450	40	0.50	2.5	12
B7	450	60	0.65	1.0	10
B8	450	80	0.60	1.5	8
B9	500	20	0.60	2.5	10
B10	500	40	0.65	2.0	8
B11	500	60	0.50	1.5	14
B12	500	80	0.55	1.0	12
B13	550	20	0.65	1.5	12
B14	550	40	0.60	1.0	14
B15	550	60	0.55	2.5	8
B16	550	80	0.50	2.0	10

3. Results

The compressive strength and water absorption of CWP-BFS geopolymer concrete mixes are considered key hardened properties that assess the mechanical and durability performance (Fig. 1). Referring to 20, 40, 60, and 80% BFS replacement categories, mixes B5, B2, B11, and B16 yielded the highest f'c responses of 34.8, 38.5, 56.6, and 40.9 MPa, respectively. These mixes share a binder content of 400-500 kg/m3, BFS replacement percentage of 20-80%, AAS/B of 0.50-0.55, SS/SH of 1.5-2.0, and SH molarity of 10-14 M. Hence, the binder content and SH molarity seemed to be less significant in obtaining high compressive strength response. Also, higher BFS replacement percentages led to higher f'c responses. This could be attributed to the granular structure and hydraulic activity reaction of BFS, which, in turn, led to the production of additional calcium silicate hydrate and aluminosilicate hydrate gels [8, 9].

From the durability perspective, the results of the water absorption corroborated well with those of f'c, as per BFS replacement percentage categories. For instance, mixes B5, B2, B11, and B16 yielded the lowest water absorption responses, ranging from 4.15 to 4.73%. Hence, Equation 1 was established to predict the Wabs having a correlation coefficient (R^2) of 0.88.

$$W_{abs} = -0.075\text{f}'\text{c} + 7.67 \quad (1)$$

ANOVA was carried out to identify the most significant factors, as shown in Fig. 2. It can be noticed that SS/SH, AAS/B, SH solution molarity, and BFS replacement were the most influencing factors with respective contributions of 42.1, 27.1, 14.9, and 12.1%. Conversely, the binder content showed the lowest contribution to the combined performance criteria of 3.4%. These results are well-aligned with those of f'c and water absorption.

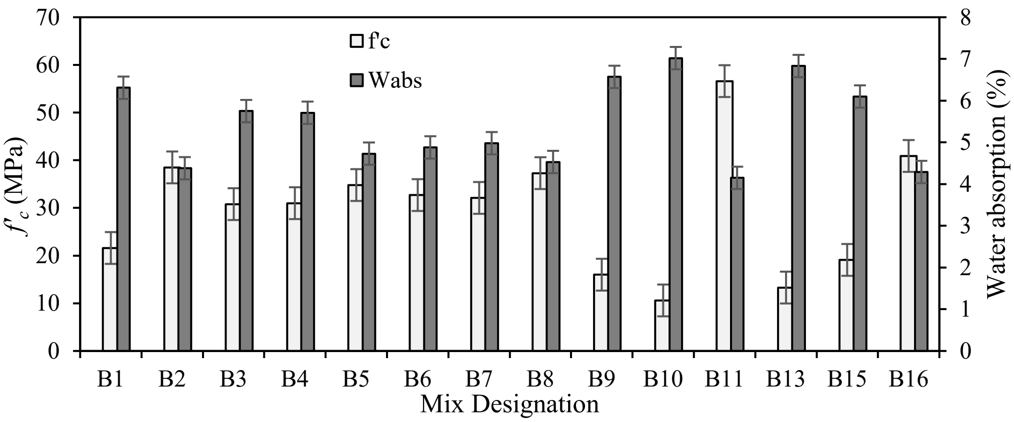

Fig. 1: Compressive strength and water absorption of CWP-BFS geopolymer concrete mixes.

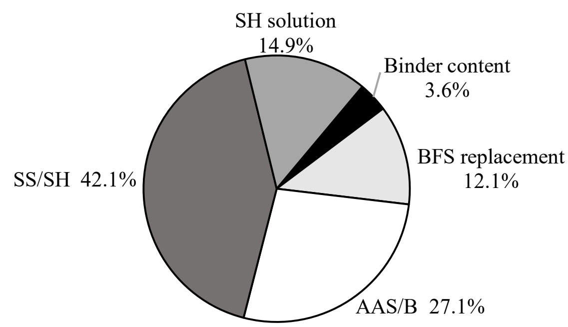

Fig. 2: ANOVA contribution factors for Q1-Q2 quality criteria.

Fig. 3 shows the S/N ratios to assess the variation in the levels of factors. The target response for geopolymer mixes using the BWM method was to obtain superior mechanical and durability properties. Hence, the "larger-the-better" or "smaller-the-better" statistic performance was adopted for evaluating f'c and water absorption, respectively. Results showed that the maximum f'c and Wabs responses were characterized by a binder content, BFS replacement percentage, AAS/B, SS/SH, and SH solution molarity of 450 kg/m^3, 60%, 0.5, 1.5, and 10 M, respectively. Further experiments were carried out to validate the optimization process. The corresponding results showed that the f'c was indeed maximized with a value of 56.6 MPa, while water absorption was minimized to a value of 3.45%.

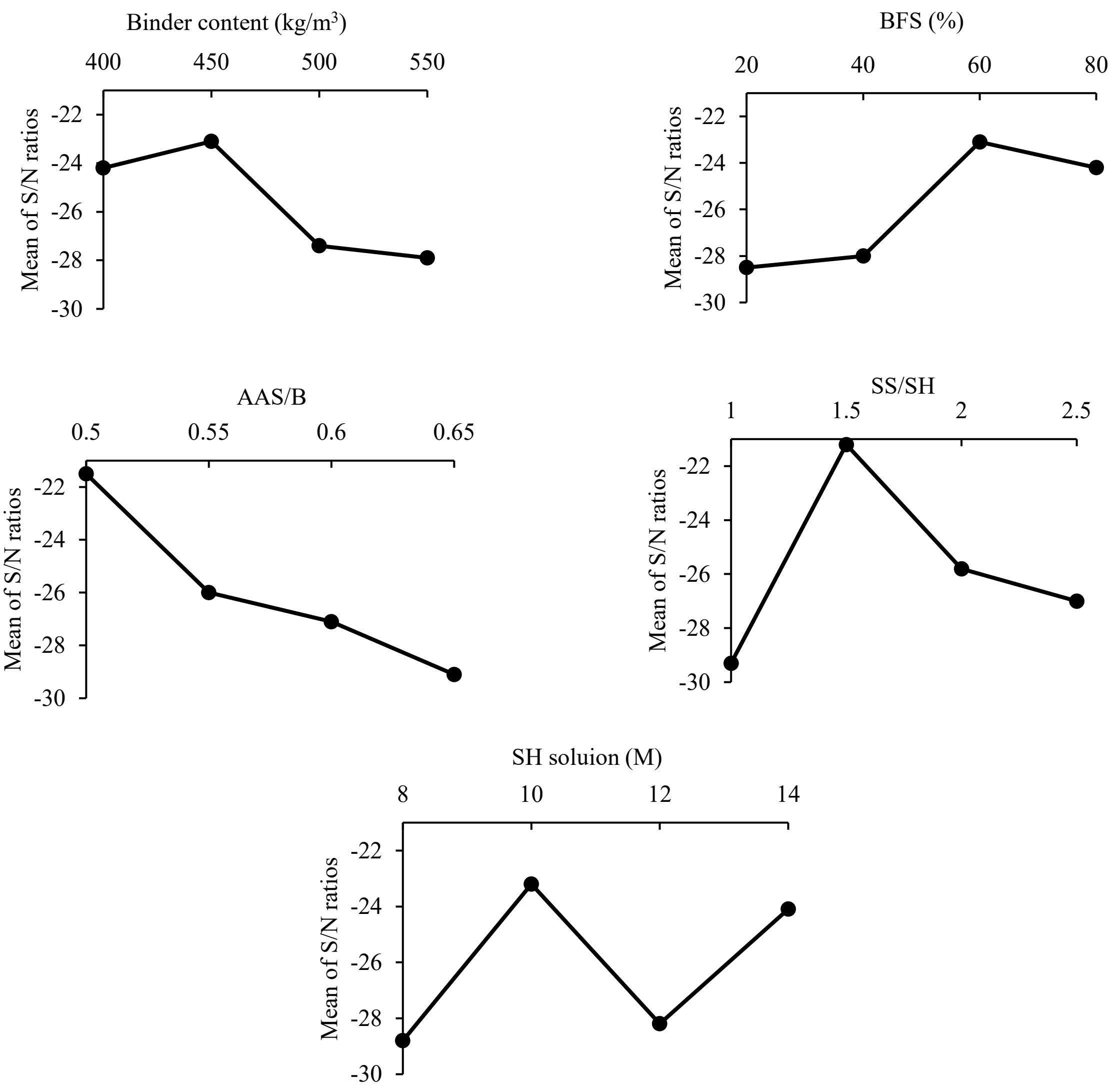

Fig. 3: Mean of S/N ratios of the two quality criteria.

4. Conclusion

The best-worst method (BWM) was adopted as a multi-response optimization approach to optimize the mixture proportions of geopolymer concrete incorporating ceramic waste powder (CWP) and granulated blast furnace slag (BFS). The compressive strength and water absorption were the respective mechanical and durability characteristics. They were combined into a single performance criterion using the BWM approach. A total of five different factors, including the binder content, BFS replacement percentage, alkali-activator solution-to-binder ratio (AAS/B), sodium silicate-to-sodium hydroxide ratio (SS/SH), and sodium hydroxide solution molarity were considered in the design of experiments by adopting an L_{16} orthogonal array. Results showed that mix B11 incorporating 40% CWP and 60% BFS yielded superior mechanical and durability properties. The ANOVA revealed that AAS/B, SS/SH, and SH solution concentration were key factors affecting the mechanical and durability characteristics of CWP-BFS geopolymer concrete. The BWM approach showed that the optimum geopolymer mix consisted of a binder content of 450 kg/m^3, AAS/B of 0.5, SS/SH of 1.5, and SH molarity of 10 M.

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