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Use of Taguchi Method to Optimize the Mix Design of Pervious Geopolymer Concrete

Faiz Habib Anwar[1], Abdulkader El-Mir[1,2], Hilal El-Hassan[1], Mohamed Hamouda[1], Kim Hung Mo[3]
[1] Department of Civil and Environmental Engineering, UAE University, Al Ain P.O. Box 15551, United Arab Emirates
[2] Department of Civil Engineering, University of Balamand, El-Kourah, Lebanon
[3] Department of Civil Engineering, Universiti Malaya, Kuala Lumpur, Malaysia
202090162@uaeu.ac.ae; abdulkader.e@uaeu.ac.ae; helhassan@uaeu.ac.ae; m.hamouda@uaeu.ac.ae; khmo@um.edu.my

Abstract **-** The challenges related to the impervious pavement, including tire-pavement noise, urban heat island effect, and skid resistance, can be mitigated using pervious pavements. Instead of cement, Pervious geopolymer concrete (PGC) utilizes industrial wastes that would otherwise end up in landfills to produce an alkali-activated binder. This paper aims to optimize the mix design of PGC for superior mechanical performance using the Taguchi method. The binder consisted of a 3:1 blend of ground granulated blast furnace slag and fly ash. A total of nine PGC mixtures were designed, considering four factors, each at three levels, namely the binder content (400, 450, 500 kg/m^3), dune sand addition (0, 10, 20%), alkaline activator solution-to-binder ratio (AAS/B, 0.55, 0.60, 0.65), and sodium hydroxide (SH) molarity (8, 10, 12). The signal-to-noise (S/N) ratios were determined to optimize the mixture proportions for superior mechanical performance, with compressive strength being the response criterion. Results showed that the optimum mix was made with a binder content of 500 kg/m^3, dune sand addition of 20%, AAS/B of 0.60, and SH molarity of 12 M. Experimental research findings serve as a guide for optimizing the production of PGC with superior compressive strength while minimizing the number of experiments.

Keywords**:** pervious concrete, sustainability, geopolymer, compressive strength, Taguchi method.

1. Introduction

The need to develop new infrastructure for the economic and global population growth has necessitated high demand for cement for concrete production, with an estimated 23% by 2050, which will consequently adversely affect both environmental and economic perspectives [1, 2]. Greenhouse gas emissions (GHG) is one of the greatest environmental concern as about 8-10% of the total CO_2 is liberated during cement production leading to global climate change, heat waves, and storms [3]. Another adverse concern is the rapid utilization of natural resources, as 1 ton of cement consumes approximately 1.6 tons of natural resources [4]. Approximately 3% of the world's surface is imperviously paved due to rapid urbanization, thus preventing water and air passage [5]. Such impervious surfaces have led to non-skid-resistant surfaces with low friction to promote surface runoff [5]. Other environmental concerns involve the disposal of industrial wastes in landfills, significantly affecting environmental processes [6].

Indeed, for effective and sustainable infrastructure to meet the rapid global urbanization, environmental challenges caused by cement production, impervious pavements, and disposal of industrial by-products should be addressed and mitigated. Utilization of industrial by-products as supplementary cementitious materials (SCMs) in concrete production to replace cement is one of the effective techniques in handling some of the challenges. This technique has a dual effect as it reduces the cement consumption in concrete production and the disposal of industrial by-products leading to a more friendly environment. Furthermore, an engineered solution for impervious pavement surfaces is pervious concrete (PC). PC is an open-graded pavement material that consists of coarse aggregates, and little or no fine aggregates [7] and whose permeable network of voids offers a sustainable solution to stormwater management and flood control challenges [8]. Thus, the combined effect of SCM and PC will help produce sustainable pervious infrastructure, reduce the CO_2 footprint of the construction industry, and conserve natural resources. This system is expected to alleviate the mentioned environmental challenges by mitigating CO_2 emissions and consumption of natural resources, beneficially recycling industrial wastes, reducing noise from tire-surface interaction, and improving skid resistance [3, 8–10]. However, the mechanical performance of PC is inferior to conventional concrete, with compressive strength ranging between 2 and 28 MPa. It is mainly suitable for low-to-medium traffic pavement, owing to its porous nature [11].

Geopolymers are produced by fully replacing cement with such SCMs. The resultant is a cement-free concrete that promises a reduced CO_2 footprint compared to conventional concrete. This mechanism is achieved by activating the aluminosilicate precursors, such as fly ash (FA), granulated blast furnace slag (GBFS), or other materials with alkaline solutions, leading to the precipitation of three-dimensional polymeric structures consisting of Si-O-Al rigid bonds [12, 13]. PC made with geopolymers, known as pervious geopolymer concrete (PGC), showed high early strength, reduced shrinkage, good resistance to sulfate attack, and superior strength and durability responses compared to cement-based counterparts [14–17].

Accordingly, PGC is considered a promising material for use in concrete pavement. Yet, further studies are needed to explore the effect of mixture design factors on the strength response of PGC. This study aims to evaluate the influence of mix design parameters on the 7-day compressive strength of PGC while also optimizing the mixture proportions for superior mechanical performance. Taguchi method for the design of experiments was utilized to proportion the PGC mixes and to optimize the mix considering various factors, including binder content, dune sand addition, alkaline-activator solution-to-binder ratio (AAS/B), and sodium hydroxide (SH) molarity. Such data can be of particular interest to engineers that seek to optimize the mix proportions of PGC for superior mechanical performance for use in sustainable concrete pavement. This underlines the importance of using the Taguchi method for designing the mixes while minimizing the experimental work.

2. Materials and Methods

2.1. Materials

Granulated blast furnace slag (GBFS) and Class F fly ash (FA) [18] were the SCMs used as binders sourced locally from Al Ain, UAE. The coarse aggregate used was crushed dolomitic limestone with a nominal maximum size of 10 mm and gradation of 4 to 10 mm. The dry rodded density, surface area, specific gravity, and fineness modulus of crushed limestone were 1663 kg/m^3, 2.49 cm^2/g, 2.82, and 6.82, respectively. The fine aggregate used was a single-sized desert dune with a gradation of 0.3 to 0.6 mm, a dry rodded density of 1660 kg/m^3, surface area of 141.5 cm^2/g, a specific gravity of 2.77, and fineness modulus of 1.45. Both coarse and fine aggregates used conform to ASTM C33 requirements [18]. SH flakes were dissolved in measured tap water producing SH solutions with different molarities of 8, 10, and 12 M. Finally, an Alkaline activator solution (AAS) was made by blending sodium silicate (SS) and sodium hydroxide (SH).

2.2. Development of Pervious Concrete Mixes

Taguchi method for designing the experiments was used to produce PGC mixtures using three levels and four factors, producing an L9 orthogonal array, as shown in Table 1. Based on previous studies, a ratio of 3:1 for GBFS and FA was considered, providing superior mechanical performance [19, 20]. A range of between 400 and 500 kg/m^3 was chosen for binder content (i.e., GBFS and FA), 0 and 20% by mass of the total aggregate for dune sand addition, and the quantity of alkaline activator solution ranged from 0.5 to 0.6, while the SH solution molarity ranged from 8 to 12 M.

Table 1. Mix design of pervious geopolymer concrete

Mix No.	Binder Content (kg/m^3)	Dune Sand Addition (%)	AAS/B	SH Molarity (M)
1	400	0	0.50	8
2	400	10	0.55	10
3	400	20	0.60	12
4	450	0	0.55	12
5	450	10	0.60	8
6	450	20	0.50	10
7	500	0	0.60	10
8	500	10	0.50	12
9	500	20	0.55	8

2.3. Sample Preparation and Test Method

All processes were conducted in the laboratory at an ambient temperature of 24±2°C and relative humidity of 50±5%. SH solutions were first prepared using SH flakes and measured tap water. AAS solutions were prepared using SS and SH solutions and left for 24 hours for the proper chemical reaction between the solutions. Furthermore, the binder and aggregates were blended for four minutes in a pan mixer, followed by the gradual addition of the AAS solutions. The specimens were cast into two layers in 100-mm cubic mould, compacted manually, and cured in the laboratory prior to testing. The 7-day compressive strength (f_{cu}) was determined as per BS EN-12390-3 [21] using three samples for each mix to compute the average f_{cu} value. The analysis was carried out on 7-day samples only based on the fact that previous test results showed a slight change in the strength between 7 and 28 days for geopolymer concrete.

2.4. Taguchi Analysis

Taguchi method considers factors and levels using a signal-to-noise ratio (S/N) to evaluate the desired property [22]. The response values are calculated using one of three functions, namely "larger is better," "smaller is better," and "nominal is better." "Larger is better" means maximum response is required for the target value, while "smaller is better" means minimum response is needed for the target value. However, in the "nominal is better," the target value is calculated from the standard deviation [23]. The present study aimed to maximize the compressive strength, i.e., the response criteria. As such, the S/N ratio of "larger is better" was adopted and calculated using Equation 1. The detailed methodology for the Taguchi approach can be found elsewhere [24-25].

$$S/N = -10 \times \log_{10}\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{Y_i^2}\right) \rightarrow \text{(Larger is better)} \quad (1)$$

S/N denotes the signal-to-noise ratio, n represents the number of experiments, and Y_i is the optimized response.

3. Results and Discussion

3.1. Mechanical Performance

The compressive strength of PGC reached a maximum of 40.7 MPa for mix 6 having binder content of 450 kg/m^3, dune sand addition of 20%, AAS/B of 0.50, and SH solution molarity of 10 M, as shown in Table 2 below signifying that geopolymer can produce a PC with satisfactory performance. Alternatively, mix 1 with a binder content of 400 kg/m^3, dune sand addition of 0%, AAS/B of 0.50, and SH solution molarity of 8 M produced PGC with the lowest compressive strength. It signifies that binder content and dune sand are the main factors influencing the mechanical performance of PFC. It can be observed that mixes with 20% dune sand addition exhibited the highest compressive strength which can be seen evident from the deviation values where positive values were obtained. In contrast, mixes with 0% dune sand addition exhibited the lowest compressive strength where negative values were obtained for the deviation signifying its inferior performance from the mean value. Furthermore, all the PGC produced met the standard requirement of between 2 to 28 MPa according to [26] for the compressive strength of PC. Thus, PGC can be used for pavement construction considering its satisfactory mechanical performance, especially with high binder content and dune sand addition.

Table 2. Compressive strength of PGC mixes

Mix No.	Binder Content (kg/m^3)	Dune Sand Addition (wt.%)	AAS/B Ratio	SH Molarity (M)	Compressive Strength (MPa)
1	400	0	0.50	8	12.7 ± 0.6
2	400	10	0.55	10	16.5 ± 0.4
3	400	20	0.60	12	26.4 ± 1.1
4	450	0	0.55	12	22.1 ± 1.0
5	450	10	0.60	8	22.8 ± 0.8
6	450	20	0.50	10	40.7 ± 2.1

7	500	0	0.60	10	21.4 ± 1.2
8	500	10	0.50	12	32.2 ± 1.6
9	500	20	0.55	8	38.6 ± 1.8

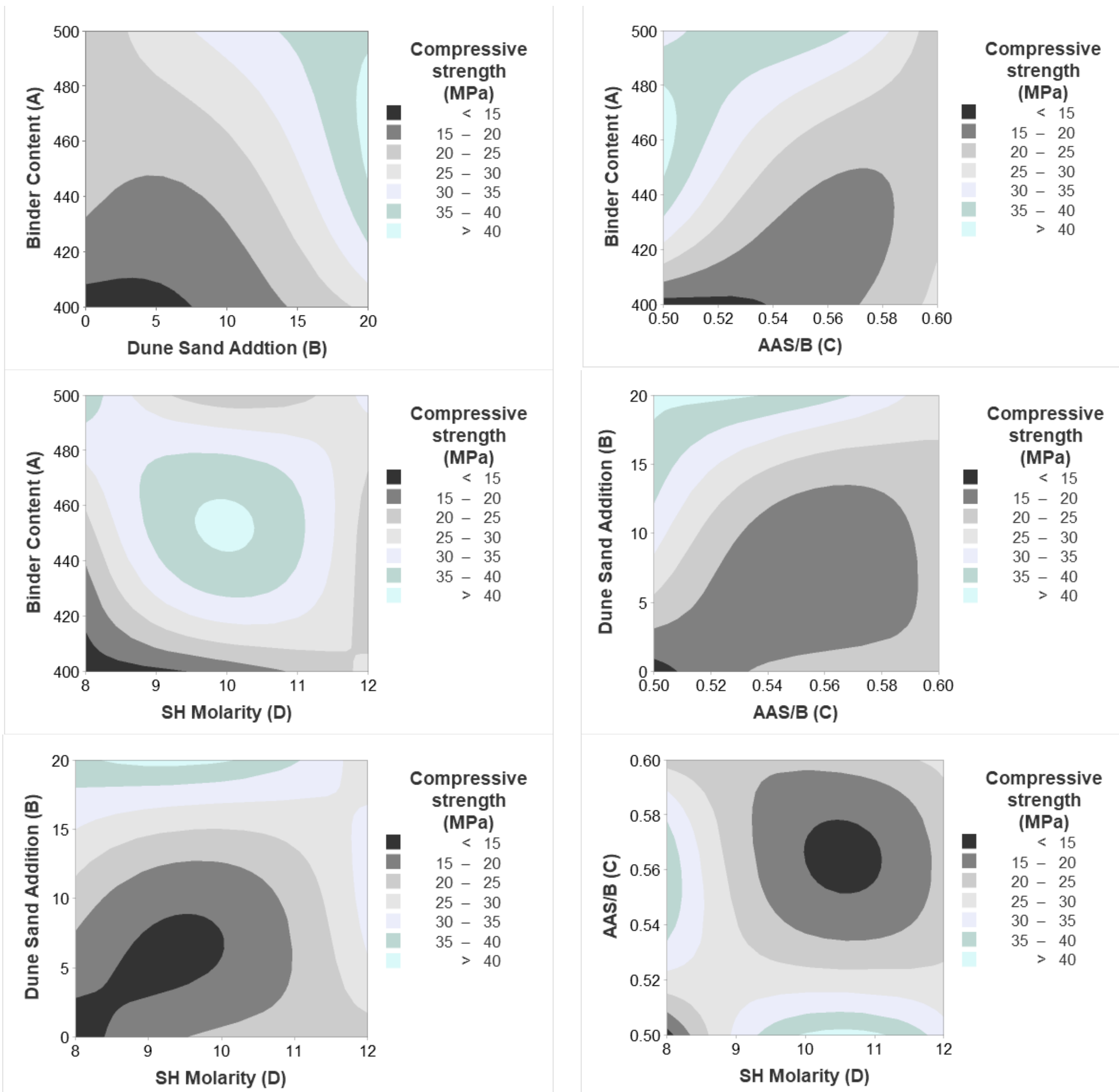

Figure 1. Bivariate relationships between mix design factors and compressive strength.

The influence of the individual mix design factor on the strength of PGC is illustrated in Figure 1 below using contour plots. The effect of binder content and dune sand addition was further validated being responsible for high compressive strength. For instance, higher compressive strength was attained with a binder content of ≥ 450 kg/m^3 and dune sand addition of between 10-20% coupled with low AAS/B of 0.5-0.55 and low SH molarity of 8M. Increased compressive strength due to high binder content may be attributed to higher hydraulic reaction capacity with the presence of more Ca^{2+} ions in the binding matrix [27], while dune sand addition increased the strength due to the improved particle packing density, reduced void content and fineness [28, 29]. It can be observed that compressive strength can be enhanced with higher binder content and dune sand addition, filling all the voids and thus producing a denser and homogenous PGC [30, 31]. Alternatively, high or low contents of SH molarity and AAS/B have less impact on strength response [13]. Thus, the strength performance of PGC cannot be evaluated without incorporating all factors under consideration.

3.2. Taguchi Analysis

A signal-to-noise ratio (S/N) illustrates how the relationship between the desired factor (signal) and the background factors (noise) affects the response target. For instance, low S/N indicates that the desired factor is outweighed by the noise factor, which has a significant impact on the overall response target [7]. The optimum mixture proportion of PGC for satisfactory strength was obtained using the S/N, as illustrated in Figure 2. The optimum mix was attained with a binder content of 500 kg/m^3, dune sand addition of 20%, AAS/B of 0.50, and SH molarity of 12 M, producing PGC with compressive strength greater than 30 MPa. Figure 2(a) also shows a rapid increase in S/N ratio from 18.53 to 28.53 at 400 kg/m^3 to 450 kg/m^3. The rapid increase may be attributed to the fact that noise factors (dune sand addition, AAS/B, and SH Molarity) have a significant impact on the strength performance of the PGC at low binder content. However, as binder content increases, the strength is not influenced by the noise factors, as enough binder is present in the mix to overcome the impact of the other factors, as observed with binder levels ranging from 450 kg/m^3 to 500 kg/m^3. As such, decrease in the slope was observed, indicating that the noise factors have little impact on the strength performance compared to the desired factor. For Figure 2(b), the strength is greatly affected by the noise factors as dune sand addition is in the range of 10 to 20%. Conclusively, it can be seen that the Taguchi method for design can effectively produce PGC with a particular combination of levels and factors exhibiting superior mechanical performance for pervious pavement construction using a smaller number of experiments.

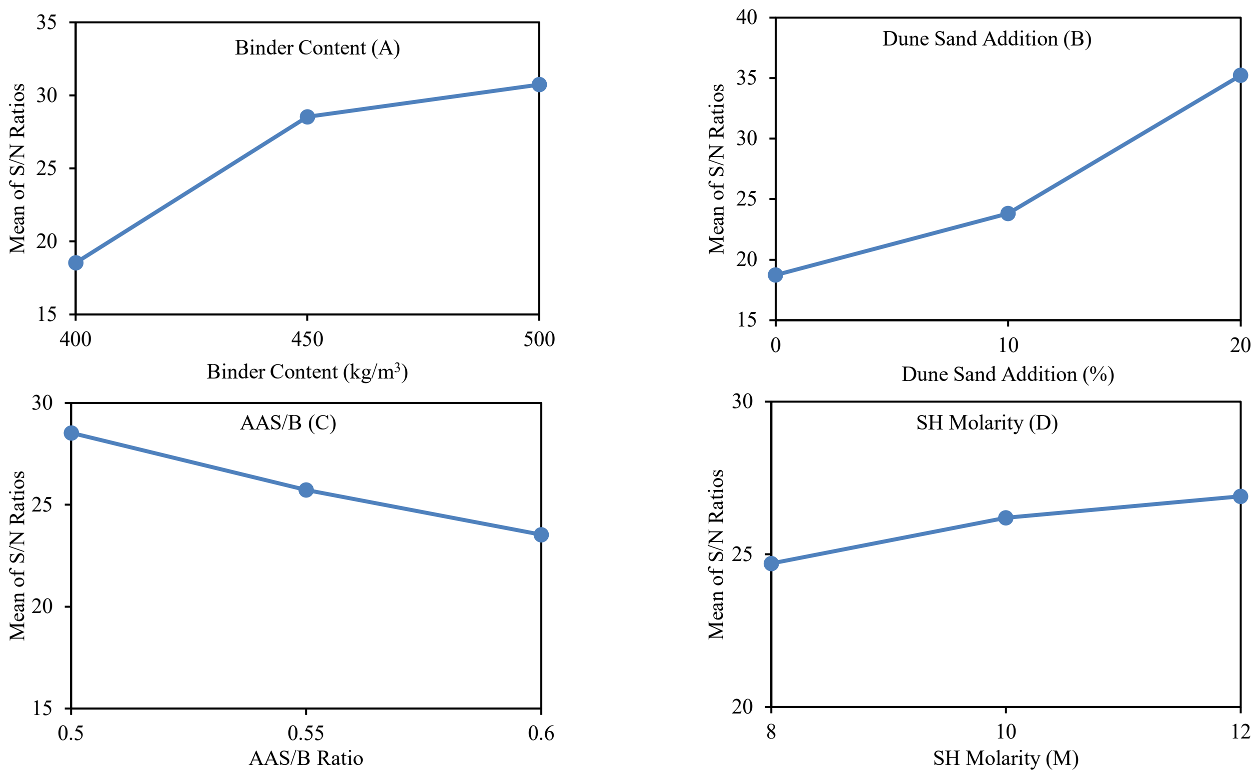

Figure 2. S/N ratios of Taguchi analysis for compressive strength

4. Conclusions

The influences of various parameters on the mechanical performance of pervious geopolymer concrete (PGC) for sustainable pavement were evaluated using compressive strength as the evaluation criterion. Taguchi design method used as the tool for optimization for superior performance. A compressive strength higher than 30 MPa could be achieved for PGC mixtures made with a binder content of 450-500 kg/m^3, dune sand addition of 10-20%, AAS/B ratio of 0.50- and SH molarity of 8-12 M. An optimum mix for superior compressive strength was made with binder content, dune addition, AAS/B, and SH molarity of 500 kg/m^3, 20%, 0.50, and 12 M. Such PGC could be used for normal to heavy while mitigating the problems related to impervious pavement for sustainable infrastructure development.

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