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COMPRESSIVE STRENGTH AND FLEXURAL STRENGTH OF ALKALI-ACTIVATED SLAG CONCRETE DESIGNED BY TAGUCHI METHOD

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ABSTRACT

Alkali Activated Slag (AAS) concrete is a combination of blast furnace slag and alkaline solution that is used as a binder. In this paper, Taguchi method was used to design of AAS mixtures. By considering four affecting factors including concentration of sodium hydroxide (NaOH) solution, sodium hydroxide to sodium silicate ratio, alkaline solution to slag ratio, and aggregate content, the optimal mixture design that provides the maximum compressive strength and flexural strength was identified. To verify the results, the optimal mixture was produced and tested. The mixture resulted in more compressive strength and flexural strength than other mixes.

Keywords: Alkali activated slag; compressive strength; flexural strength; taguchi method.

1. INTRODUCTION

Today, concrete is one of the most widely used construction materials. Concrete enjoys several advantages over wood and steel and other construction materials such as flexibility in shaping, fire resistance, durability and ease of production and finally, more economy. It is estimated that 2.2 billion tons of cement would be produced in the coming years throughout the world [1,2]. The vast applications of Ordinary Portland Cement (OPC) concrete and the growing demand of OPC in the future will create some environmental issues including the availability of the raw material, CO_2 emissions and the need for a large input of energy during the manufacture of OPC. The production of one ton of OPC emits approximately one ton of CO_2 into the atmosphere [1-6]. The cement industry responsible for about 7% of all the CO_2 emission into the atmosphere [3] and it is estimated that by the year 2020, the CO_2 emissions will rise by about 50% from the current levels [7]. The cement production account about 5% of worldwide industrial energy consumption and producing each ton of OPC of

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which about 1.5 tons of raw material is needed [4,5]. The problems of OPC concrete mentioned above have motivated researchers to consider alternative materials for OPC that provide environmentally friendly materials and achieve sustainable development in concrete production.

One possible alternative is the application of Alkali Activated Slag (AAS) concrete that is a combination of blast furnace slag and alkaline solution that is used as a binder. These binders have been found to have higher strength and good performance in chemical attack, frost–thaw cycles and high temperatures, in comparison with OPC mortars [8,9]. The appropriate rate of strength development and the final strengths, the reduction of energy and natural resources consumption and low environmental effects due to the low volume of emitted CO_2 have encouraged researchers to consider this kind of concrete as a proper alternative for OPC concretes [9]. Slags have a variable composition depending on the raw materials and the industrial process; hence, the effect that an activator can have on strength development may be different for slags of different origins and each slag responses differently to the activation. Therefore, it is necessary to determine the most suitable and optimum composition for each case [8,10].

In this research work, compressive strength and flexural strength of AAS concrete has been designed by Taguchi method. This study proposes a method for selecting the mix proportions of AAS concrete. By using blast furnace slag from Isfahan steel plant and activating it by alkaline solution containing sodium hydroxide and sodium silicate, and considering the effective and salient factors in producing this concrete, including the concentration of sodium hydroxide solution, sodium hydroxide to sodium silicate ratio, alkaline solution to slag ratio, and aggregate content, the optimal mixture design was obtained and the effect of each factor on the compressive strength and flexural strength of AAS specimens were evaluated.

2. MATERIALS AND METHODOLOGY

2.1 Materials

Blast furnace slag with the specific gravity of 2.85 was from Isfahan steel plant. The chemical compositions of slag are shown in Table 1. The alkaline activator used in this study was a combination of sodium hydroxide (NaOH) and sodium silicate (water glass) with a SiO_2/Na_2O ratio of 2.6 (Na_2O=15%, SiO_2=39%, and water=46%). Sodium hydroxide with 98% purity was dissolved in water to make a solution with the required concentration. Fine aggregates were crushed sand, with a fineness modulus of 2.94, saturated surface dry specific gravity of 2.64, water absorption of 0.8% and a maximum size of 4.75 mm. Crushed stone, with a maximum nominal size of 12 mm, saturated surface dry specific gravity of 2.68 and water absorption of 0.5%, was used as coarse aggregates. The combined aggregates were selected to meet the requirements of ASTM: C-33.

Table 1: Chemical compositions (mass%) of GGBFS

Na_2O	K_2O	SO_3	MgO	Fe_2O_3	Al_2O_3	SiO_2	CaO
0.38	0.90	2.49	8.60	0.51	6.40	37.50	34.80

2.2 Experiment design

Taguchi method is one widely used design of experiment (DOE) method to investigate the effects of several parameters simultaneously by the minimum experiments. In this study, in order to determine the optimal mix with maximum compressive strength and flexural strength, design of experiments based on Taguchi method was used. Concentration of sodium hydroxide solution (in terms of molar), the alkaline liquid to slag ratio by mass, the ratio of sodium silicate solution to sodium hydroxide solution by mass and aggregate content were considered as the most important factors. Several primary tests showed that NaOH concentration between 4 and 8 molar provided suitable compressive strength values. Besides, working with high concentrations of NaOH in laboratory was not safe and easy. Moreover, alkaline liquid to slag ratio less than 0.4 did not provide appropriate workability and values more than 0.5 did not yield the necessary strength and were not economically acceptable because it is known that the most costly ingredient in an alkali activated slag concrete mix is the alkaline liquid. The same results were observed for NaOH to sodium silicate ratio, with less than 1 and more than 5, respectively. In addition, the aggregate content was chosen to be between 75-80 %. The design method proposed in this research was based on the concrete density of 2400 kg/m^3. Table 2 shows the factors and levels of each factor were considered in this study.

Orthogonal arrays, i.e. OA_9 (3^4), developed by Taguchi method were used [11]. The components of each mixture and the compositions of concrete mixes are shown in Tables 3 and 4, respectively. For the trial mixtures, the water/solid ratio by mass was kept constant at 0.4 to obtain the desirable workability and strength. The water in the mix was the sum of water contained in the sodium silicate, sodium hydroxide and the added water. The solid was the sum of GGBFS and the solid in the alkaline solution.

Table 2: Factors and levels of each factor used in Taguchi method

Factor	Description	Level 1	Level 2	Level 3
1	Concentration of NaOH (M)	4	6	8
2	Alkaline liquid to slag ratio	0.4	0.45	0.5
3	NaOH to sodium silicate solution ratio	1	3	5
4	Aggregate content (kg/m^3)	1800	1848	1896

Table 3: The component variables of the mixture trials

NO.	concentration of NaOH	alkaline liquid /slag ratio	NaOH/ sodium silicate solution ratio	aggregate content (kg/m^3)
T1	4	0.4	1	1800
T2	4	0.45	3	1848
T3	4	0.5	5	1896
T4	6	0.4	3	1896
T5	6	0.45	5	1800
T6	6	0.5	1	1848
T7	8	0.4	5	1848
T8	8	0.45	1	1896
T9	8	0.5	3	1800

Table 4: Alkali activated slag concrete mixtures used for Taguchi optimization

mix	Slag (kg/m^3)	NaOH solution (kg/m^3)	Sodium silicate (kg/m^3)	Aggregates (kg/m^3)	Added water (kg/m^3)
1	428.6	85.7	85.7	1800	83.3
2	380.7	128.5	42.8	1848	41.2
3	336.0	140.0	28.0	1896	17.6
4	360.0	108.0	36.0	1896	58.8
5	413.8	155.2	31.0	1800	47.0
6	368.0	92.0	92.0	1848	58.8
7	394.3	131.4	26.3	1848	67.6
8	347.6	78.2	78.2	1896	70.6
9	400.0	150.0	50.0	1800	52.9

2.3 Mixing, moulding, and curing specimens

The mixing was done in laboratory room condition at approximately 25°C. At first, slag and the aggregates were mixed together in the dry state for about 3 minutes. Next, the alkaline activator (sodium silicate, NaOH, and additional water) was added to the blend and mixed for further 4 minutes. The mixing was performed using a 50-litre mixer. The mix was then poured into the moulds and vibrated for 1 minute. All specimens were demoulded after 24 hours and then left at an environmental control room (50% RH, 20°C) prior to testing. The specimens were wrapped with plastic to prevent the extra evaporation (Fig. 1).

Figure 1. Wrapping concrete specimens

3. RESULTS AND DISCUSSIONS

Compressive strength and flexural strength tests were performed for the trial mixes according to BS 1881 part 116 [12] and ASTM: C-78, respectively. Three specimens were

tested and the average of the three tests was reported. The results for 9 suggested experiments by Taguchi method are shown in Table 5 and Figs. 2 and 3.

Table 5: Compressive strength and modulus of rapture results for the trial mixes

No.	Compressive strength (7-days) (MPa)	Compressive strength (28-days) (MPa)	Modulus of rupture (MPa)
T1	46.03	57.40	4.61
T2	43.71	50.26	4.45
T3	45.63	56.67	4.89
T4	41.35	53.80	4.52
T5	47.02	58.11	4.88
T6	54.70	57.18	4.83
T7	27.40	38.10	3.28
T8	53.11	65.02	4.92
T9	48.83	60.80	4.85

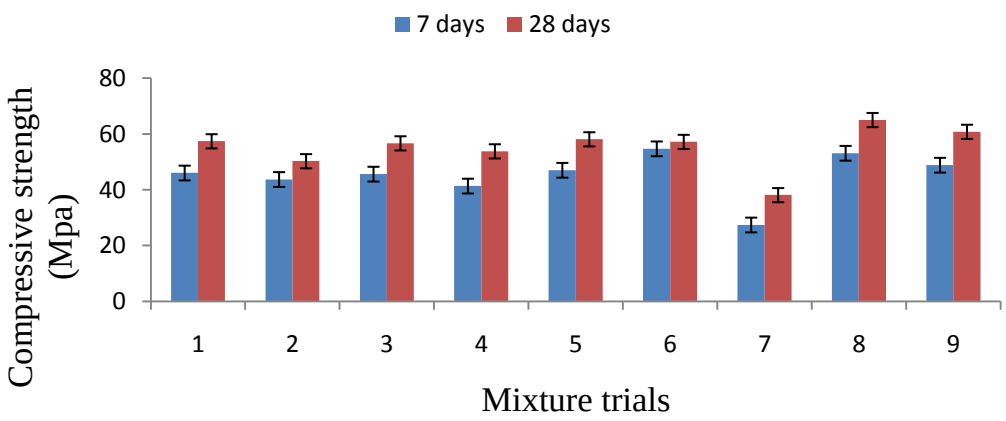

Figure 2. Comparison of compressive strength results in 7 and 28 days for trial mixes

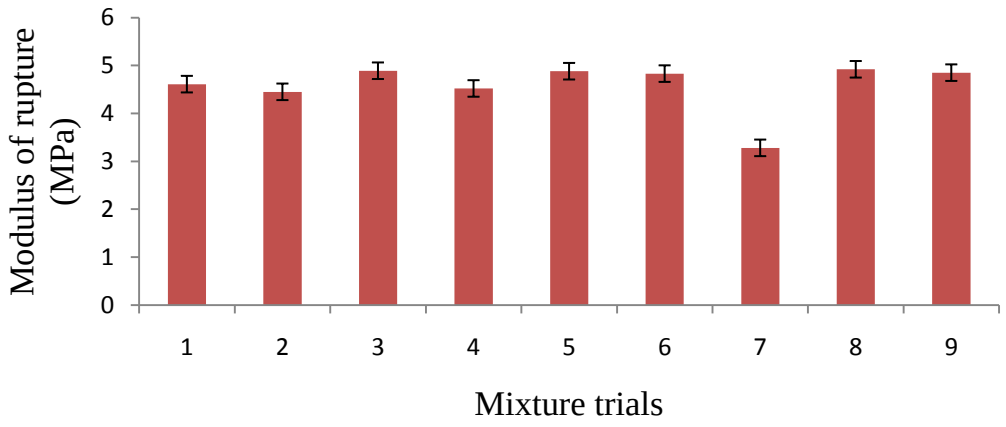

Figure 3. Comparison of modulus of rupture results for trial mixes

Mix T6 resulted in the highest compressive strength after 7 days (54.70 MPa) with NaOH concentration of 6 M, alkaline liquid to slag ratio of 0.5, NaOH to sodium silicate ratio of 1 and the aggregate content of 1848 kg/m^3. However, the highest compressive strength after 28 days (65.02) and also the highest modulus of rupture was related to the mix T8 with NaOH concentration of 8 M, alkaline liquid to slag ratio of 0.45, NaOH to sodium silicate ratio of 1 and the aggregate content of 1896 kg/m^3. Similar to a previous study, the high compressive strength of mix T8 could be due to the high percentage of the aggregate content [13]. Moreover, based on these results, the mix with NaOH concentration of 8 M, alkaline liquid to slag ratio of 0.4, NaOH to sodium silicate ratio of 5 and the aggregate content of 1848 kg/m^3 (T7) gave the lowest compressive strength and modulus of rupture.

The response index for each factor was calculated by summing the strengths for each trial mix that contained that factor dividing by the sum by the number of measurements [11,13]. For example, NaOH concentration of 4 M was tested in trial mixes T1–T3 (Table 3). The response index for this factor was, therefore, the average of the compressive strengths or modulus of rupture for trials T1–T3 (Figs. 4 and 5). NaOH concentration of 6M gave a greater compressive strength and flexural strength than other NaOH concentrations and was, therefore, the optimal value for this factor. Optimal values were obtained in the same way for other factors (Table 6).

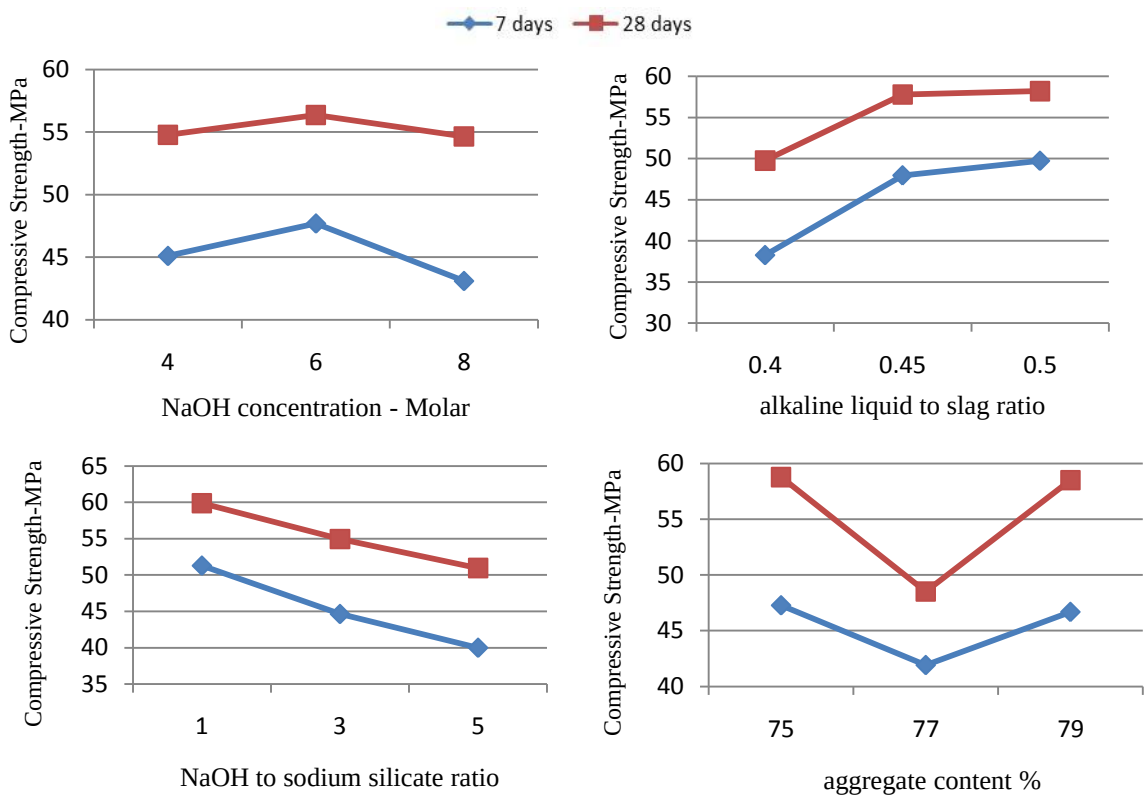

Figure 4. Compressive strength results against the four influential factors and their values

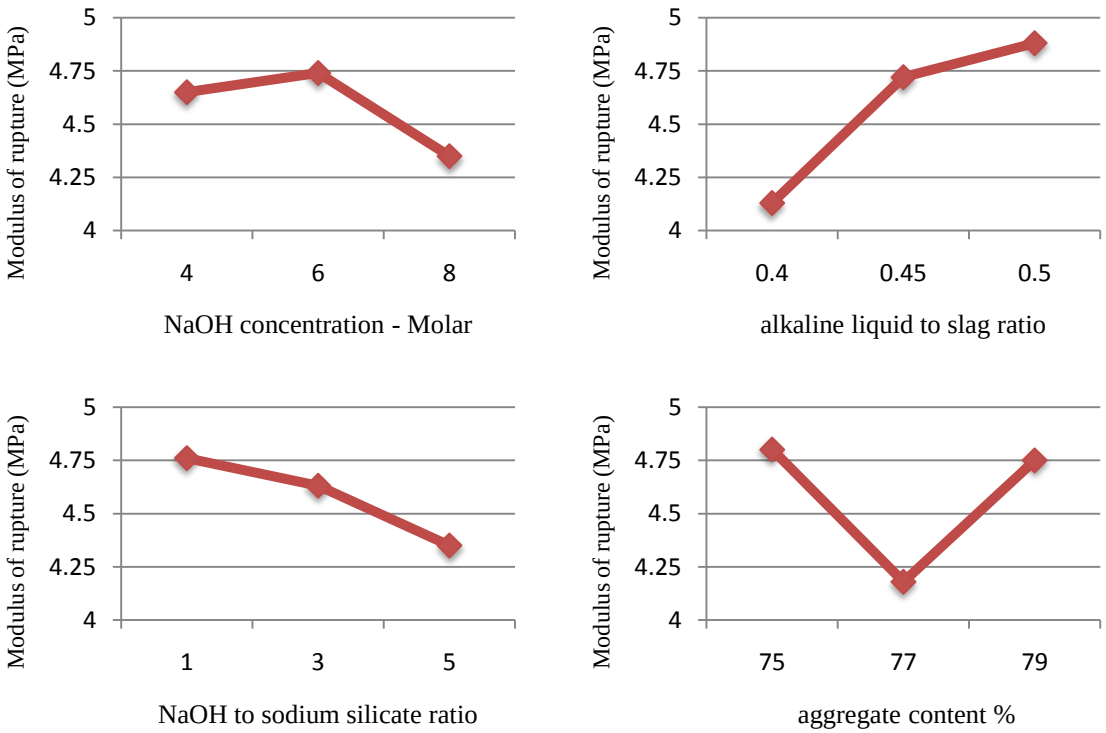

Figure 5. Modulus of rupture results against the four influential factors and their values

Table 6: Optimum values of factors affecting the compressive strength and modulus of rupture

Factor	NaOH concentration (M)	alkaline liquid to slag ratio	NaOH to sodium silicate ratio	aggregate content (kg/m^3)
Optimum value	6	0.5	1	1800

As shown in Fig. 4, NaOH concentration did not have a significant effect on the compressive strength development of AAS concrete specimens, especially in 28 days. This may be due to the similarity of microstructure in AAS specimens activated by NaOH regardless of the concentration, as reported by Song, et al [14]. Increasing the alkaline liquid to slag ratio also improved strength over 28 days due to the introduction of more alkaline components and the maximum strength was obtained with alkaline liquid to slag ratio of 0.5. However, as reported by Wang, et al [15], the higher liquid/slag ratio caused the increase of pore volume in the hardened concrete due to the introduction of more water. Therefore, there was a little difference in the strength developed for mixtures with alkaline liquid to slag ratios of 0.45 and 0.5. In addition, the higher amounts of sodium silicate caused the increase in the compressive strength of AAS concrete specimens. Similar results were found in some previous studies [8,9,15]. The mixture containing 1800 kg/m^3 aggregate developed the greatest strength. It appears that the development of the flexural strength of the AAS concretes was a result of the same process that produced their compressive strength.

To verify these results, the optimal mixture according to the condition brought in Table 6 was made. Table 7 shows compressive strength and flexural strength results for this optimal

mixture. As observed, the optimal mixture resulted in more compressive strength and flexural strength than other mixes. The results also indicated that Taguchi method could be effective and suitable for optimizing AAS concrete parameters to obtain the maximum strength.

Table 7: Compressive strength and modulus of rupture results for the optimal mixture

Mix	Compressive strength (7-days) (MPa)	Compressive strength (28-days) (MPa)	Modulus of rupture (MPa)
optimal	56.80	65.80	4.96

4. CONCLUSIONS

Based on the experimental work reported in this study, the following conclusions could be drawn:

1- Sodium hydroxide (NaOH) solution with the concentration of 6 M provided the highest compressive strength and flexural strength. Nevertheless, NaOH concentration was not an effective factor on strength development of AAS concrete specimens, especially during a period of 28 days.

2- The optimum ratio of alkaline solution to slag and also, NaOH to sodium silicate ratio by mass were obtained to be equal to 0.5 and 1, respectively. In addition, it was observed that the aggregate content of 1800 kg/m^3 resulted in the highest compressive strength and flexural strength.

It can be concluded that this environmentally friendly concrete could be a proper alternative for ordinary Portland cement concretes.

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