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MECHANICAL PROPERTIES OF FLY ASH-BASED ALKALI-ACTIVATED CEMENT USING A STATISTICAL ANALYSIS TECHNIQUE

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This paper presents the mechanical properties of fly ash-based alkali-activated cement (AAC). A statistical analysis method was used to determine the effect of mix proportion parameters on the dry density and compressive strength of fly ash-based AAC pastes and mortars. For that purpose, sample mixtures were designed according to Taguchi's experimental design method, i.e., in a L9 orthogonal array. Four factors were selected: "silica fume content" (SF), "sand to solid ratio" (s/c), "liquid to solid ratio" (l/s), and "superplasticiser content" (SP). The experimental results were analysed by using signal to noise for quality control of each mixture, and analysis of variance (ANOVA) was used to determine the significant effect on the compressive strength of fly ash-based AAC. Furthermore, a regression-analysis method was used to predict the compressive strength according to the variation of the four factors. Results indicated that silica fume is the most influencing parameter on compressive strength, which could be decreased by superplasticiser and l/s ratio. There is no significant effect of sand-to-cementitious ratio on compressive strength of fly ash-based AAC. The dry density decreases as the sand-to-cementitious ratio is decreased. The increasing l/s ratio and superplasticiser dosage could further decrease the dry density of fly ash-based AAC.

Keywords: Cementitious, AAC, ANOVA, Taguchi, DOE, Sustainable.

1 INTRODUCTION

Cement companies produce approximately 5-8% of total CO_2 emission that will reach 3.5 billion tonnes per year by 2055 (Van den Heede and De Belie 2012). Alkali-activated cement (AAC) is a generic term for mixtures made of Pozzolan, such as blast-furnace slag or coal fly ash, which reacts with alkali-activator to produce binders. Thus AAC is a sustainable and potential cementitious system that can be used as alternative or supplementary cement, reducing the environmental impact of cement production (Shi et al. 2006, Shi et al. 2011). AAC can have superior properties ordinary Portland cement (OPC), such as mechanical, chemical, and thermal (Duxson et al. 2007). Specializations of AAC include geopolymer and lime-pozzolan cement. In geopolymer, aluminium is a main source of material and is not present as carbonate; therefore, it does not release vast quantities of CO_2. Properties of AAC superior to those in OPC are (Xu and Van Deventer 2000, Kong and Sanjayan 2010, Demirel and Keleştemur 2010):

- Less drying shrinkage than that in OPC
- Higher early age strength

- High chemical durability
- Resistance of high temperatures

This research investigates the effect of mix proportion parameters on the dry density and compressive strength of fly ash-based AAC pastes and mortars. It uses Taguchi's design experimental method, which determines the parameters affecting the mechanical properties of fly ash-based AAC mixtures.

2 TAGUCHI'S DESIGN EXPERIMENT AND STATISCAL ANALYSYS

Taguchi's method was developed by Gen'ichi Taguchi during the 1950s (Roy 1990). Taguchi's experimental method approach to parameter design provides the engineer with a systematic and efficient method for investigating optimum design parameters for performance and cost. Taguchi's experimental method should be discussed in terms of "signal to noise" (S/N) factors. Noise factors are anything that cause a measureable product or process characteristic to deviate from its target value (Ozbay et al. 2009). The target values are described below:

When smaller is better: select when the goal is to minimize the response. The S/N ratio can be determined from Eq. (1):

$$S/N = -10 \times \log_{10}\left(\frac{1}{n}\sum_{i=1}^{n} Y_i^2\right) \tag{1}$$

When larger is better: select when the goal is to maximize the response. The S/N ratio is as given in Eq. (2):

$$S/N = -10 \times \log_{10}\left(\frac{1}{n}\sum_{i=1}^{n} \frac{1}{Y_i^2}\right) \tag{2}$$

When nominal is better: select when the goal is to target the response, and when the S/N ratio must be based on standard deviations only. The S/N ratio can be determined from Eq. (3):

$$S/N = -10 \times \log_{10}\left(\frac{1}{n}\sum_{i=1}^{n} (Y_i - Y_0)^2\right) \tag{3}$$

In these equations, Y is the measured value of each response.

3 EXPERIMENTAL PROGRAM

In this experiment, commercial cementitious material from Australasia, Class F (low calcium) fly, silica fume, sand were used to prepare fly ash-based AAC mixtures. ASTM C305 was adapted for mixing the admixtures (ASTM International 2011). Specimens were cast in a cubic mold 50 mm × 50 mm ×50 mm. The specimens were cured in a steam chamber at 60ºC for 24 hours, then placed in a curing room at 23ºC until testing. The compressive strength and dry density of fly ash-based AAC were measured at the age of 28 days. The selection of mix proportions was the process of choosing suitable parameters of fly ash-based AAC and determining relative quantities.

Table 1 shows variation factors and their three levels. The detail of variables used in the experiment with a standard L_9 orthogonal array is shown in Table 2.

Table 1. Factors and levels.

Levels	**Factors**			
	Silica Fume (SF)	**Sand to Cementitious ratio (s/c)**	**Liquid to solid ratio (l/s)**	**Superplasticiser (SP)**
1	0 %	0	0.6	0 %
2	2 %	0.25	0.65	2 %
3	4 %	0.5	0.7	4 %

Table 2 Standard L9 orthogonal array.

EXP NO.	**SF**	**s/c**	**l/s**	**SP**
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

4 RESULTS AND DISCUSSION

The compressive strength and dry density of fly ash-based AAC is presented in Table 3. The minimum and maximum compressive strength at the age of 28 days are 25.3 and 6.8 MPa. It can be seen that the minimum and maximum dry density at the age of 28 days are 1509.4 and 1717.9 kg/m^3, respectively. The effects of each level of the mix proportions were investigated with Taguchi's design experimental method for maximization of compressive strength and minimization of dry density. The statistical performances were evaluated based on the "the larger the better" S/N ratio for compressive strength, and "the smaller the better" S/N ratio for dry density, as seen in Figure 1 and Figure 2. A statistical analysis was performed to investigate the significant factors and analysis of variance as presented in Table 4.

The results indicate that increasing silica fume and superplasticiser level decrease the compressive strength. Silica fume has the major effect on the compressive strength of fly ash-based AAC with 55.48% contribution. It can be seen that there was a minor effect of the sand-to-cementitious ratio on compressive strength, with a 2.38% contribution. The second-most influencing factor is superplasticiser content, with a 29.15% contribution to the compressive strength of fly ash-based AAC.

The dry density of AAC should be minimized in order to reduce the self-weight. The decreasing density was affected by the increase in l/s ratio and superplasticiser.

The sand-to-cementitious ratio was the most influencing factor on the dry density of fly ash-based AAC, with a 79.90% contribution. The second-most influencing factor was the superplasticiser and l/s ratio, with 8.96% and 8.97% respectively. It is observed that the silica fume effect had a minor influence on dry density of fly ash-based AAC.

A multiple linear regression equation was modelled to predict the dry density and compressive strength of fly ash-based AAC, as expressed in the following equation:

$$\rho = 1836.97 + 4.88\chi_1 + 278.293\chi_2 - 447.467\chi_3 - 12.28\chi_4 \tag{4}$$

$$f_{c28} = -4.124 + 0.779\chi_1 + 8.816\chi_2 + 14.966\chi_3 - 0.227\chi_4 \tag{5}$$

where ρ is dry density (kg/m^3) and f_{c28} is compressive strength (MPa) at age of 28 days, x_1 is silica fume (%), x_2 is the sand-to-cementitious ratio, x_3 is the l/s ratio, and x_4 is superplasticiser (%). Correction coefficient (R) of these proposed relations in dry density and compressive strength is 98.36% and 93.37% respectively.

Table 3. Compressive strength at 28 days and dry density.

EXP NO.	f_{c28} (MPa)	Dry Density (kg/m^3)
1	25.3	1570.1
2	15.8	1598.4
3	12.5	1615.4
4	6.8	1509.4
5	10.4	1586.7
6	9.8	1685.6
7	8.8	1521.9
8	9.9	1602.6
9	13.3	1717.9

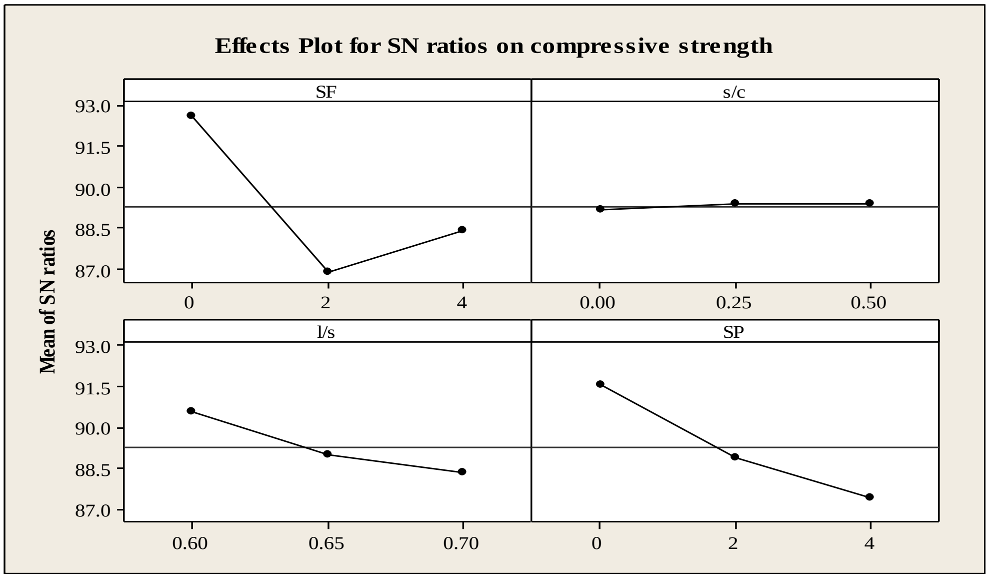

Figure 1. The effect plot for S/N ratio on compressive strength.

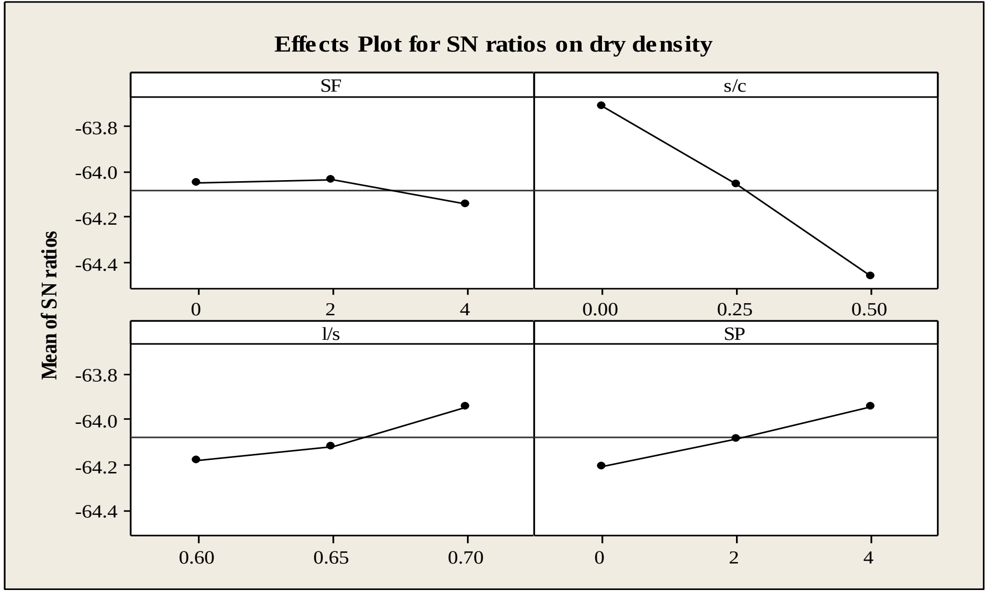

Figure 2. The effect plot for S/N ratio on dry density.

Table 4. Analysis of variance of fly ash-based AAC.

	Source	SF	s/c	l/s	SP
Compressive load (kN)	**DF**	2	2	2	2
	SS	834	36	195	438
	MS	417	18	98	219
	Contribution (%)	55.48	2.38	12.99	29.15

Density (kg/m3)	**DF**	2	2	2	2
	SS	790	29115	3270	3264
	MS	395	14577	1635	1812
	Contribution (%)	2.17	79.90	8.97	8.96

5 CONCLUSION

The findings obtained from this investigation are based on Taguchi’s experimental method and the statistical analysis of the results. The results were then used to determine the effect of each factor on the compressive strength and dry density of fly ash-based AAC. The following conclusions can be drawn:

(1) Silica fume was the most influencing parameter on the compressive strength. Superplasticiser and l/s ratio could decrease the compressive strength. There was no significant effect of sand-to-cementitious ratio on the compressive strength of fly ash-based AAC.

(2) The dry density decreased as the sand-to-cementitious ratio decreased. The increasing l/s ratio and superplasticiser dosage could further decrease the dry density of fly ash-based AAC.

(3) Linear regression results were used to predict the compressive strength and the dry density of the mixtures. The correction coefficients (R) indicate significant corrections.

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