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Response Surface Analysis of the Compressive Strength of Self-Compacting Concrete Incorporating Metakaolin

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ABSTRACT

This research developed a mathematical model and optimization of materials for the development of metakaolin self-compacting concrete. This is in a bid to reduce the overall material quantity and cost towards sustainable infrastructural construction. To achieve the aim of this research, Response Surface Analysis (RSM) was used. Kaolinitic clay was De-hydroxylated at 750°C to form metakaolin. This was used as a partial replacement for cement at 0%, 5%, 10%, 15%, 20% and 25% weight of Portland limestone cement. Both strength and rheology properties of the developed metakaolin self-compacting concrete were assessed. To this end, slump flow, L-Box test and V-funnel test were carried out alongside the compressive strength using relevant standard. The result of the research revealed that at 15% addition of metakaolin the slump flow, passing ability and filling ability was unsatisfactory according to EFNARC standard. From the numerical optimization of the compressive strength, the maximum predicted compressive strength of 44.35 N/mm^2 was obtained. At a low value of metakaolin addition (5–15%), the compressive strength increased as the age of the concrete increased from 3–150 days. The age with the optimum mechanical strength formation was 110 days with metakaolin addition of 52.73 kg. The result of this research provide a database for Engineers, Researchers and Construction workers on the optimum metakaolin required to achieve satisfactory mechanical strength in metakaolin self-compacting concrete.

Keywords. response surface analysis, metakaolin, self-compacting concrete, sustainable infrastructure.

INTRODUCTION

Cement is one of the most commonly used construction materials in the world and its price has risen at an alarming rate over the last few years. This high increase in the cost of cement has led to a reduction in concrete construction in underdeveloped and developing countries. This calls for the incorporation of natural non-expensive material as a substitute for cement. Metakaolin is a naturally occurring material with pozzolanic properties, capable of replacing a certain percentage of cement when used in production of self-compacting concrete (SCC). Self-compacting concrete is a recent development in the concrete construction industry. It is asserted as being the way forward in concrete production based on its numerous advantages [Ouchi and Hibino 2000]. Focus on sustainability in line with the application of self-compacting concrete was done by [Tarun and Naik 2012; Grdić et al. 2008; Navid et al. 2016; Hesami et al., 2016; Aggarwal et al., 2008; Okamura and Ouchi 2003] to mention a few. The use of cement alone as a binder in self-compacting concrete leads to thermal crack. In an attempt to reduce the incidence of the crack and reduce the cost of SCC production, the use of metakaolin as a supplementary material was adopted based on its unique properties.

Metakaolin is obtained when Kaolinitic clay is heated to a temperature of 650–900 °C. At this temperature, an endothermic reaction takes place to form metakoalin, according to Justice et al. (2005). The reaction of this material with modified cement paste micro structure is similar to the pozollanic properties of silica fumes, rice husk ash, fly ash etc. [Shivram and Nagesh 2007]. In line with the use of other cementitious material, the use of metakaolin was found to form a good combination in concrete production [Kamaruddin 1991, Sabir et al. 2001, Nabil 2006, Jiping and Albinas 2009, Jian-Tong and Zongjin 2002, Hemant 2011, Vejmelková et al. 2010, Badogiannis et al. 2004 and Arikan et al. 2001].

The use of this mineral material was found to improve the durability, strength and cohesion of concrete structures [Justice et al. 2005, Kong and Orbison 1987]. Studies showed that the introduction of 20% of metakaolin improves the strength of concrete (Shepur 2014). However, there is a need to assess the optimum quantity of this material needed in self-compacting concrete. To this end, Response Surface Analysis Method (RSM) was adopted in this study.

Response Surface Methodology (RSM) is a collection of mathematical and statistical techniques useful for the modelling and analysis of problems in which a response of interest is influenced by several variables [Myers and Montgomery, 1995; Akinoso et al., 2011]. It is a powerful tool used for the optimization of chemical reactions or engineering processes.

This unique tool was used to assess the effect of metakaolin and Self-Compacting Concrete in concrete technology.

The aim of making concrete affordable and improving green construction motivated this research. RSM was used to provide a data base on the optimum strength achievable using metakaolin in self-compacting concrete for engineers, researchers and construction workers.

MATERIAL AND METHODS

Locally available Portland limestone cement (rapid hardening cement) conforming to NIS (2003) was used in the study. The metakaolin used as a supplementary material was sourced from south western Nigeria. The kaolin used for this research was sourced from the same geographic location as in the study of Ogundiran and Ikotun (2016) and Labiran (2016). Scanning Electron Microscopy was used in assessing the chemical composition, surface structure and particleometry of the metakaolin. The chemical composition of the metakaolin and the cement used is as shown in Table 1. Coarse and fine aggregate of size 4.5 mm and 19.5 mm were used in the research. A polycarboxylate-based high-range water reducing admixture (HRWRA), super-plasticizer was used in this research according to EFNARC (2002).

Metakaolin was used as a replacement for the Portland limestone cement at 0%, 5%, 10%, 15%, 20% percentage of the dry weight of the cement. The total paste volume was kept constant for all SCC mixtures. The flowing ability, passing ability and the slump flow were assessed using the L-Box, V-funnel and the slump flow apparatus. The results obtained were compared with the standards of EFNARC. The strength properties were assessed using the compressive strength and split tensile, this was done according to ASTM C192 specifications.

Response surface methodology (RSM) was adopted in the design of experimental combinations. It also used to quantify the relationship between the controllable input parameters and the obtained response surfaces.

Analysis of variance (ANOVA) was performed for the data obtained in this experiment for different replacement as the age increased. The interaction between the input variables (cement, age and metakaolin) and the response of different regression models developed for compressive strength was investigated.

RESULTS AND DISCUSSION

Rheological properties of the fresh concrete

The segregation resistance of the self-compacting concrete was determined by using the V-funnel

test. According to EFNARC (2002) specification the acceptable criteria for the V-funnel result is between 6 and 12 seconds. On the basis of these criteria, the SCC mix with metakaolin addition from 15% and more did not satisfy this criterion (Figure 1). This may be due to the fact that the incorporation of high metakaolin content affected the viscosity of the mix.

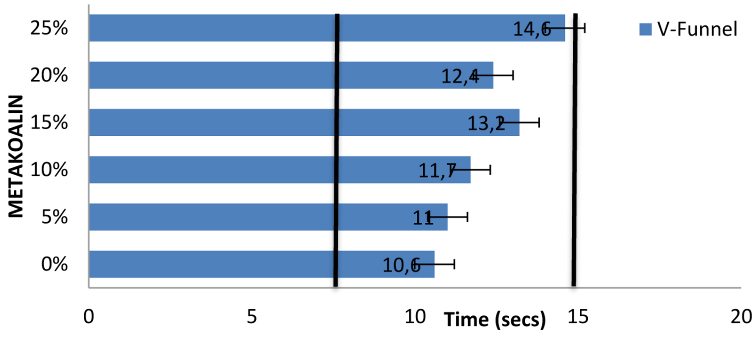

Figure 1. V-Funnel

L-box height ratios were measured and the corresponding outcomes were presented in Table 1. The result followed a similar trend with the slump flow test. At 15% percentages and greater addition of metakaolin, the L-box result became unsatisfactory too, as seen in Figure 2.

The slump flow test was used to determine the ability of the SCC to flow in a non-restricted condition. The factors affecting the results of the T_{50} time are the amount, shape and size distribution of aggregates and also the viscosity and amount of paste, in accordance with Uygunoglu and Topçu [2005]. The mix with the lowest T_{50} time is the SCC with no metakaolin addition (Table 1). On the basis of the result, a direct relationship was established with metakaolin quantity and T_{50} time based on the EFNARC (2002) specification.

Strength properties

The result of the analysis showed that the addition of metakaolin to concrete resulted in an improved strength till 10% replacement. Upon further addition, the compressive strength began to reduce. The highest strength across all ages was recorded at 10% addition of metakaolin. However, at 15% and 20% (Figure 3) the strength was still higher than the control. However, a decrease in the compressive strength was noticed when compared with 0% metakaolin at the percentages higher than 20%.

Table 1. Slump flow

Metakaolin percentage replacement	T_{50}(Sec) Slump flow
0% (control mix)	3.5
5% replacement	4.0
10% replacement	4.4
15% replacement	5.6
20% replacement	7.3
25% replacement	8.1

The predicted R-Squared of 0.766 is in reasonable agreement with the "Adjusted R-Squared" of 0.809 as shown in Table 2. "Adeq Precision" measures the signal to noise ratio. A ratio greater than 4 is desirable. The model ratio of 15.712 indicates an adequate signal. This model can be used to predict the effect of metakaolin, cement and age on the compressive strength of metakaolin concrete.

The model equation in terms of actual factor is given in equation 1 as follows;

$$\begin{aligned} Compressive\ Strength &= -184.70 + 1.60\,A - \\ &- 0.14\,B + 813.61\,C - 1.61\,A^2 + 1.77\,B^2 - \\ &-768.30\,C^2 + 4.08\,A{\cdot}B - 3.19\,A{\cdot}C - 0.35\,B{\cdot}C \end{aligned} \quad (1)$$

where: A – age,
B – metakaolin,
C – cement.

The results indicate that the addition of cement and metakaolin had a positive effect on the strength properties of the developed self-compacting concrete, as seen in equation 1.

The normal plot of residuals on the experimental run shows a close fit with the predicted values. Figure 4 shows no outlier in the experimental runs.

The predictability plot of the model to account for future occurences is as shown in Figure 4. The predicted data points scatter round the actual data points showing less overfitting and gave a predicted R-squared value of 0.767.

Synergetic effect of input parameters on compressive strength

The Figures 5 and 6 show the contour plots and 3D for determining the effects of Age and Metakaolin against the compressive strength. At low value of Metakaolin, the compressive

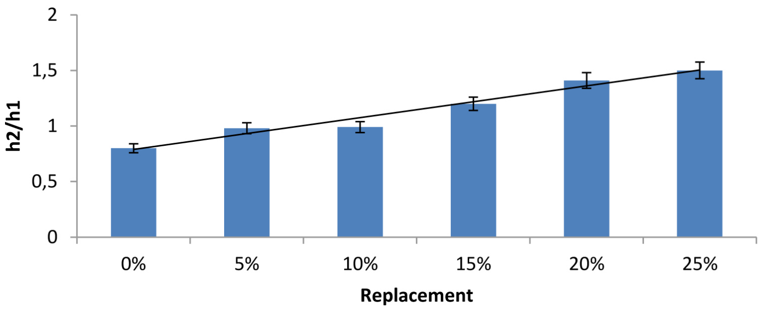

Figure 2. L-Box result

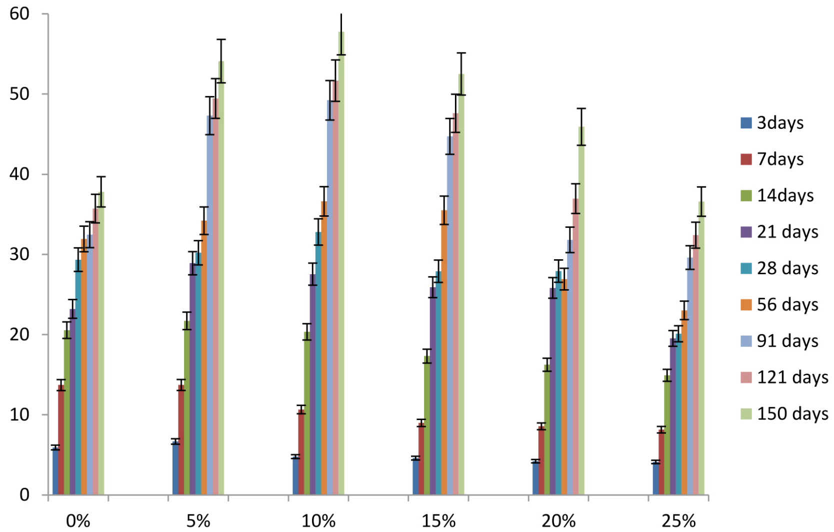

Figure 3. Compressive strength of dehydroxylated Kaolinitic clay versus age

Table 2. ANOVA for response surface quadratic model

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F	
Model	2074.283	9	230.4759	26.00548	<0.0001	significant
A	623.8372	1	623.8372	70.38995	<0.0001	
B	0.449426	1	0.449426	0.05071	0.8229	
C	0.750283	1	0.750283	0.084657	0.7724	
A^2	472.1313	1	472.1313	53.27239	<0.0001	
B^2	0.008533	1	0.008533	0.000963	0.9754	
C^2	0.006395	1	0.006395	0.000722	0.9787	
AB	38.7879	1	38.7879	4.376588	0.0422	
AC	46.28101	1	46.28101	5.222064	0.0272	
BC	0.000165	1	0.000165	1.86E-05	0.9966	
Residual	389.9539	44	8.862589			
Cor Total	2464.237	53				

strength increases as the Age of the concrete grows from 3 to 150 days. This is in agreement with the experimental results, as seen in Figure 2.

From the numerical optimization obtained as shown in the Figure 3, the maximum predicted compressive strength of 44.35 N/mm^2 was achieved under the optimum concrete formation of 110 days, Metakaolin of 52.73 kg. The desirability of 1.00 was achieved with the numerical optimization performed, showing best accuracy of the developed model.

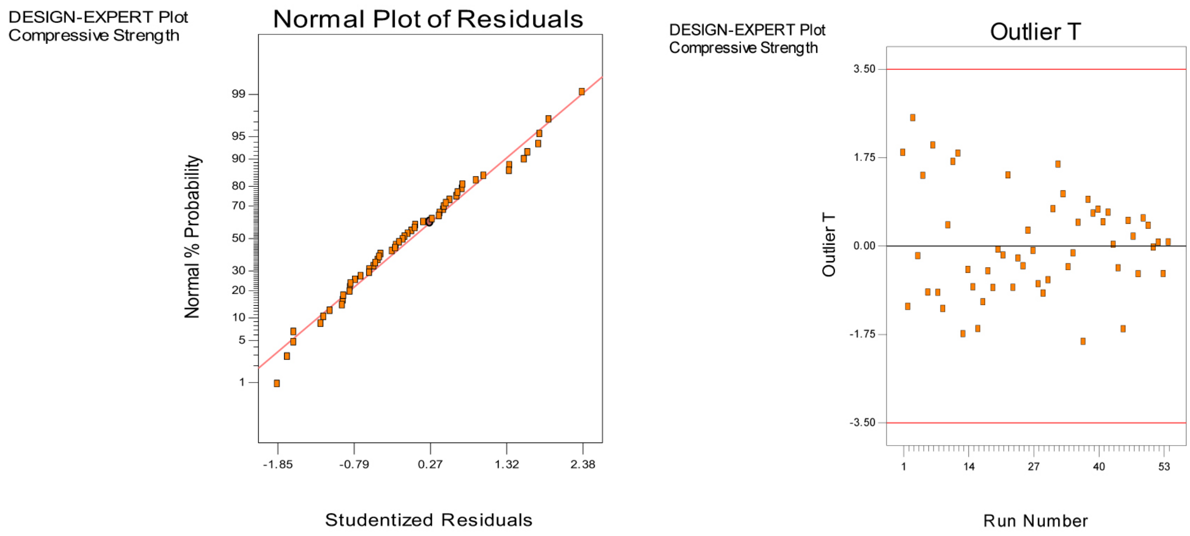

Figure 4. Diagnostic plots of residuals and outlier against experimental runs

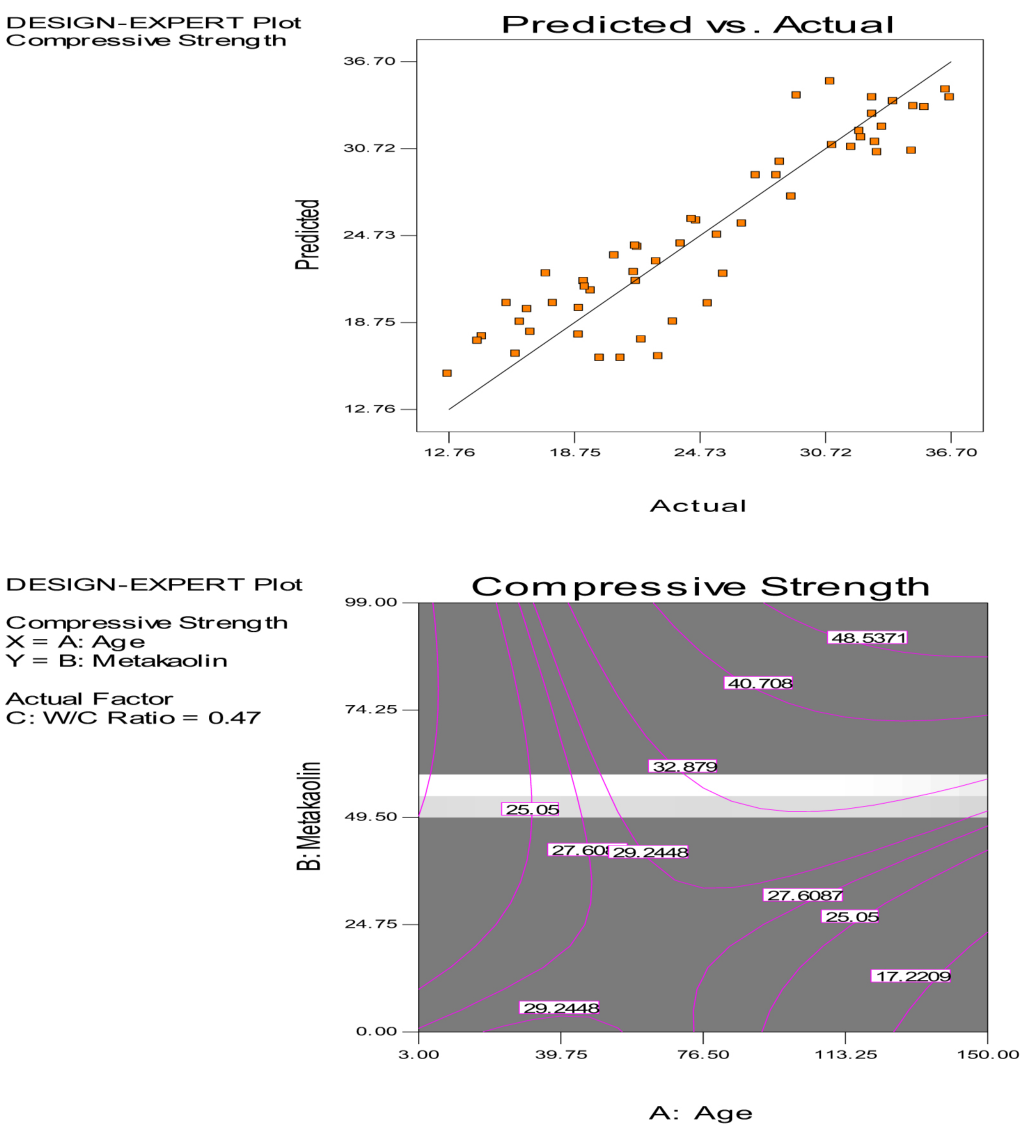

Figure 5. Contour Plots of the Response Surface

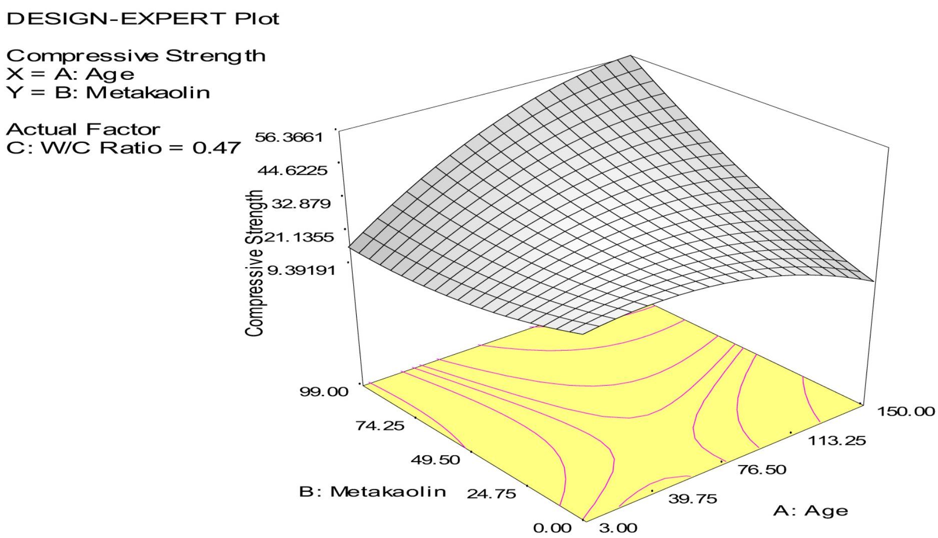

Figure 6. Response surface plots of Age and Metakaolin against the compressive strength

CONCLUSIONS

This research optimized the strength properties of metakaolin self-compacting concrete using response surface methodology. This was achieved using six concrete mixes by varying the proportion of metakaolin at 0%, 5%, 10%, 15%, 20% and 25% respectively. The rheology and strength properties of the developed concrete were assessed at the fresh state and hardened state respectively. The result of the experimental analysis showed that the mix with the lowest T50 time is the SCC with no metakaolin addition. Additionally, from the numerical optimization obtained, the maximum predicted compressive strength of 44.35 N/mm^2 was obtained under the optimum concrete formation of 110 days, Metakaolin of 52.73 kg. The age with the optimum concrete strength formation is 110 days with metakaolin addition of 52.73 kg.

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