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Application of Two-Factorial Design for Optimizing the Degree of CO_2 Concentration and Compressive Strength in Sandcrete-Talc Composite

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ABSTRACT

Global interest in carbon dioxide (CO_2) emission reduction has triggered alternative cement formulation using non-classical raw materials. This research work is aimed at applying a 2-factorial design for optimizing the degree of CO_2 sequestered and compressive strength of the sandcrete-talc (S-T) composite at ambient conditions. The statistical analysis (ANOVA) showed that Age and Talc had the greatest effect on the degree of CO_2 sequestered from the atmosphere at ambient conditions, while Sand, Talc and Age had the most significant effect on the compressive strength of the S-T composite. The result also showed that as curing age increases with an increase in talc content, the concentration of carbon dioxide increased. Also, the compressive strength increased as the age, talc and sand components increased at constant cement composition. The developed predicted mathematical models showed that the optimal concentration of CO_2 (CC) and compressive strength (CS) obtained were 0.2083 mol/dm^3 and 2.3925 N/mm^2 after 7-day, and 0.4528 mol/dm^3 and 7.315 N/mm^2 after 28-day curing at ambient condition respectively. The quality of the sandcrete-talc composite at the optimum predicted conditions satisfied the Nigeria Industrial Standard (NIS) of 2007. The developed predicted equations could be used in the design of an S-T mix composite for structural buildings and to minimize the effect of greenhouse gas.

1. INTRODUCTION

The rapid growth in any country's economy and population requires additional physical infrastructures to enhance the Gross National Product (GNP) (Anosike. and Oyebade, 2012; DePersio, 2019). These physical infrastructures which include residential and commercial buildings require the integration of engineering, project, and production management techniques (Ko, 2011). A sandcrete block is an important engineering material in building construction and widely used in Nigeria and other African countries. The main drawback of the utilization of this engineering material is its low carbon sink and mechanical properties (Odigure, 2002; Anosike and Oyebade, 2012).

Researchers in the building industry have shown that cement is one of the largest contributors to CO_2 emission around the globe (IPCC, 2007). Diverse technologies have been developed for capturing atmospheric CO_2 (Sunho *et al.* 2009). However, the utilization of mineral talc as an admixture could be the best short-to-long term mitigation strategy for CO_2 sequestration and to improve the mechanical strength of sandcrete composite (Abdullahi *et al.,* 2016b).

Talc is a hydrated magnesium silicate ($Mg_3Si_4O_{10}(OH)_2$) mineral. It is an important raw material in cement formulation and sealing of borehole due to its blend and disperse characteristic in a polymeric phase (Pusch *et al.* 2013; Ngally Sabouang *et al.* 2014; 2015).

The desire by researchers to improve the degree of predictability of CO_2 sequestered and compressive strength using statistical methodology by cement and cement related materials cannot be overemphasized. Ramezanianpour *et al.* (2000) used a normal distribution tool to determine the depth of carbonation in concrete. Applying the principle of stochastic and deterministic modeling, the researchers found out that the carbonation depth after 20 years was 29.13 mm. Kharazi *et al.* (2013) designed and optimized concrete mix proportion using a statistical mixture design approach to determine concrete performance at 3-, 7-, 28-, 56- and 91-day compressive strengths. Barbuta and Lepadatu (2008) and Muthukumar and Mohan (2004) used a statistical technique to optimize polymer concrete mixtures, while Bedi *et al.* (2016) used statistical dispersion (logarithmic-normal distribution function) to study flexural fatigue of plain and glass fibre reinforced polymer concrete composites. By consciously controlling composite constituents and the interactions between them, cement-based composite such as sandcrete utilizing mineral silicates (talc) without sacrificing the key material properties has not been fully investigated by the authors. Hence, this research work, therefore looks at the possibility of optimizing and determining the CO_2 concentration and compressive strength of sandcrete-talc composite using the design of experiment.

This research work focused on the application of full factorial design (FFD) using two level-four factors (2^4) to determine the effect of sand (A), Talc (B), Cement (C) and Age (D) and their interaction on CO_2 concentrations and compressive strengths after 7- and 28-day. A factorial design was employed to ensure high reliability of the inferences at a high standard (Vairis and Perousis, 2009).

2. MATERIALS AND METHODS

2.1. Materials

Talc from Kagara in Rafi Local Government Area of Niger State (10°11'04''N, 6°15'12''E), Nigeria was used as a supplementary cementitious admixture with the fineness of 700 – 900 m^2/kg. The fine aggregate was locally sourced river sand conforming to ASTM C33 and; passing through 4.75 mm IS sieve with a specific gravity of 2.65. The cement used for the investigation is an Ordinary Portland Cement (OPC) with ISO 9001:2008 obtained from Dangote Cement Company conforming to NIS 444-1:2003-cem 11/B-L 42.5R (NIS, 2007).

2.2. Sandcrete Production Procedure

Table 1 shows the range of statistical mix design proportion for sandcrete-talc (S-T) composite generated by Design-Expert version 11. The preparation procedure was based on the method of sandcrete production according to Abdullahi *et al.* (2016a). All samples produced were made up of $1.25x10^{-4}$ m^3 in volume with a fixed cement-to-aggregate ratio of 1:6 and water-to-cement ratio (W/C) of 0.5 (Anosike and Oyebade, 2012). All the experimental processes were conducted at ambient conditions. The casted cubes were allowed to sequestrate atmospheric carbon dioxide and demoulded after 24 hours and tested for compressive strength at 7- and 28- day respectively using hydraulic powered press machine Model No. 526, Ogawa Seiki Co., Ltd., Tokyo, Japan.

2.3. Design of Experiment

A two level-four factor (2^4) experimental design was carried out to study the degree of CO_2 sequestration and compressive strength (f'_c) of S-T composite for 7- and 28-day. The mass proportion of each component and its experimental range and intensities are presented in Table 1, while the statistically factorial design combination of components is shown in Table 2. The effect of interactions between components gives a quantitative estimate of the response in terms of CO_2 concentrations and compressive strengths. The two statistical levels are called high (h) and low (l) or, +1 and -1.

Table 1: Range of mix design proportion for S-T composite

Component	Symbol	Minimum (-1)	Maximum (+1)
Sand(g)	A	171.95	202.29
Talc (g)	B	10.12 (5%)	30.34 (15%)
Age (Day)	C	7	28

Table 2: Factorial design showing combination of factors (per m^3 of sandcrete)

Run order	A= Sand (g)	B=Talc (%)	C=Age (day)
1	171.95	10.12	28
2	171.95	30.34	28
3	202.29	10.12	28
4	202.29	30.34	7
5	202.29	10.12	7
6	171.95	10.12	7
7	171.95	30.34	7
8	202.29	30.34	28

3. RESULTS AND DISCUSSION

3.1. Mathematical Model and Verification

The experimental results of 7- and 28- day CO_2 concentrations and compressive strengths for all 8 experiments are depicted in Table 3. The effect of water, cement and water-cement ratio could not be established as a result of the constant quantity of these materials used throughout the experiments. The result shows increased CO_2 concentration and compressive strength (0.923 mol/dm^3 and 7.59 N/mm^2) after 28-day curing at ambient conditions. The result was analyzed using Design-Expert version 11.

Table 3: Experimental CO_2 concentration and compressive strength at varying age

Run	Day	CO_2 Concentration (mol/dm^3)	Compressive strength (N/mm^2)
1	28	0.447	6.43
2	28	0.923	7.43
3	28	0.456	7.31
4	7	0.278	3.21
5	7	0.205	2.43
6	7	0.209	2.12
7	7	0.298	2.31
8	28	0.768	7.59

Figures 1 and 2 showed the Pareto chart for CO_2 concentration and compressive strength respectively. The results depict the effect of the main components and their interaction matrices on CO_2 concentration and compressive strength of sandcrete-talc composite. The analysis of the results showed that Talc (B), Age (C) and their interaction (BC) are the most important components that have a great effect on the concentration of CO_2 sequestered (Figure 1), while Sand (A), Talc (B) and Age (C) and their interactions (ABC) have a significant effect on the compressive strength (Figure 2) (Equations 1 and 2).

$$CC = 0.4480 - 0.0213*A + 0.1187*B + 0.2005*C - 0.0225*AB + 0.0783*BC \quad (1)$$

$$CS = 4.85 + 0.2812*A + 0.2812*B + 2.34*C + 0.0388*BC - 0.1638*ABC \quad (2)$$

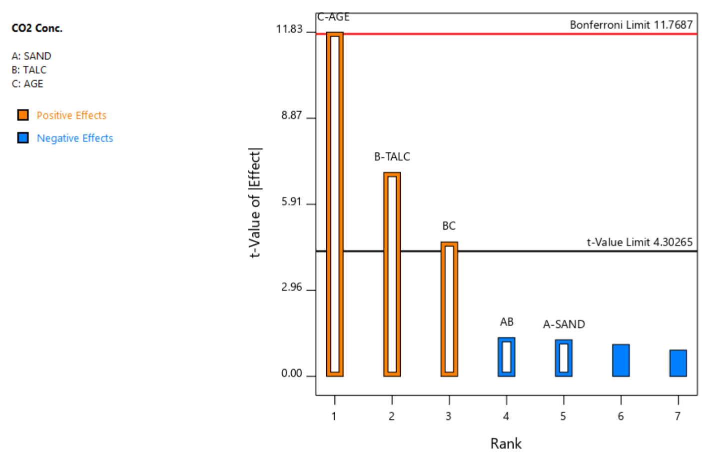

Figure 1: Pareto chart showing the effect of mixture components on CO_2 concentration

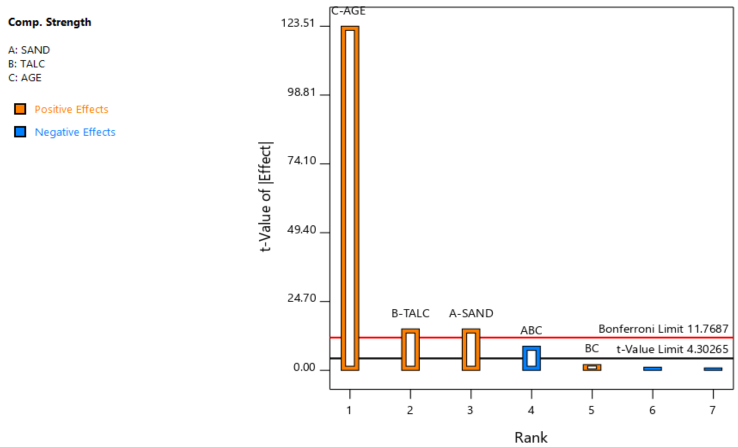

Figure 2: Pareto chart showing the effect of mixture components on compressive strength

The predictive models were validated by checking the analysis of variance (ANOVA) and the model terms were accepted or rejected based on p-values with a 95% confidence level as shown in Tables 4 and 5 respectively. The developed model was used in confirming the effect of the various components and the degree of significance on the measured CO_2 concentration and compressive strength of sandcrete-talc composite. The model is significant given the acceptable p-and F-values coupled with high correlation coefficients (R^2, adjusted R^2 and predicted R^2).

Table 4: Analysis of variance for CO_2 concentration

Source	Sum of squares	df	Mean square	F-value	p-value	
Model	0.4911	5	0.0982	42.71	0.0230	significant
A-SAND	0.0036	1	0.0036	1.57	0.3367	
B-TALC	0.1128	1	0.1128	49.06	0.0198	
C-AGE	0.3216	1	0.3216	139.87	0.0071	
AB	0.0040	1	0.0040	1.76	0.3157	
BC	0.0490	1	0.0490	21.30	0.0439	
Residual	0.0046	2	0.0023			
Cor Total	0.4957	7				

Table 5: Analysis of variance for compressive strength

Source	Sum of squares	df	Mean square	F-value	p-value	
Model	45.16	5	9.03	3155.05	0.0003	significant
A-SAND	0.6328	1	0.6328	221.07	0.0045	
B-TALC	0.6328	1	0.6328	221.07	0.0045	
C-AGE	43.66	1	43.66	15253.98	< 0.0001	
BC	0.0120	1	0.0120	4.20	0.1771	
ABC	0.2145	1	0.2145	74.94	0.0131	
Residual	0.0057	2	0.0029			
Cor Total	45.16	7				

The statistical analysis (ANOVA) presented in Tables 4 and 5 revealed that the empirical results for CO_2 concentration and compressive strength are best fitted into quadratic and cubic models respectively at 95%

degree of confidence. With p-value less than 0.05, components B-talc, C-age and its interaction matrix BC had a great effect on the degree of CO_2 sequestration, while components A-sand, B-talc, and C-age had a significant effect on the compressive strength of S-T composite. This finding is corroborated by Abdullahi *et al.* (2016b). Furthermore, the presence of talc and sand enhance the degree of CO_2 adsorbed and the compressive strength.

The comparative analyses of experimental and simulated results for CO_2 concentrations and compressive strengths are shown in Tables 6 and 7 respectively. The statistical analysis of goodness of fit carried out showed highly positive correlations coefficients (R^2 and $Adj\ R^2$) for CO_2 concentration (0.9907 and 0.9675) and compressive strengths (0.9999 and 0.9996) at 95% confidence level.

Table 6: Comparative analysis of actual and predictive CO_2 concentration of sandcrete-talc composite

Run Order	Actual value (mol/dm^3)	Predicted value (mol/dm^3)	Residual (mol/dm^3)	Standard order (mol/dm^3)
1	0.4470	0.4503	-0.0033	5
2	0.9230	0.8893	0.0337	7
3	0.4560	0.4527	0.0033	6
4	0.2780	0.2443	0.0337	4
5	0.2050	0.2083	-0.0033	2
6	0.2090	0.2058	0.0032	1
7	0.2980	0.3318	-0.0338	3
8	0.7680	0.8018	-0.0338	8

Table 7: Comparative analysis of actual and predictive compressive strength of sandcrete-talc composite

Run order	Actual value (N/mm^2)	Predicted value (N/mm^2)	Residual (N/mm^2)	Standard order (N/mm^2)
1	6.43	6.43	0.0050	5
2	7.43	7.39	0.0375	7
3	7.31	7.32	-0.0050	6
4	3.21	3.20	0.0050	4
5	2.43	2.39	0.0375	2
6	2.12	2.16	-0.0375	1
7	2.31	2.32	-0.0050	3
8	7.59	7.63	-0.0375	8

Figure 3 showed the effect of varying talc content with age on carbon dioxide sequestration. It is evident from the result that an increase in the mass of talc with a simultaneous increase in curing age of 7- to 28-day at ambient conditions resulted in increase in carbon dioxide concentration in the sandcrete composite matrix. Also, the result presented in Figure 4 showed an increase in compressive strength as mineral talc and age increases at constant cement and water-cement ratio. These results confirmed the fact that mineral talc, sand in conjunction with increased curing age from 7- to 28-day plays a significant role in the quantity of CO_2 sequestered and compressive strength of the sandcrete-talc composite. This is corroborated by Vasburd *et al.* (1997) and Abdullahi *et al.* (2016b).

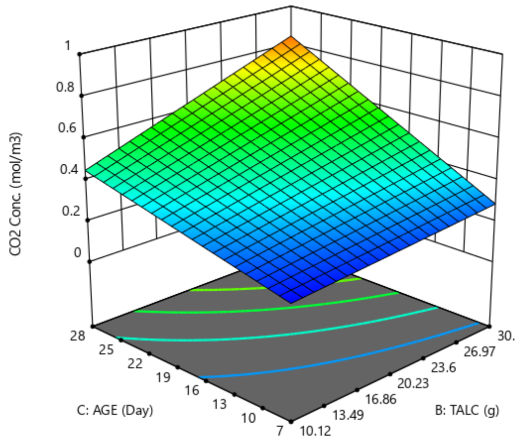

Figure 3: Effect of sand, talc and age on CO_2 concentration

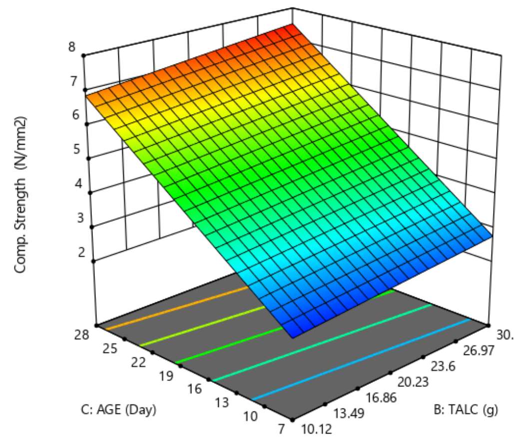

Figure 4: Effect of talc and age on compressive strength

3.2. Numerical Optimization of Sandcrete Components

The numerical optimization method employing desirability function used by Kharazi *et al.* (2013) was adopted. The method involves the transformation of individual responses into desirability function that ranged from $0 \ll d_i \ll 1$. Equations 1 and 2 were solved to obtain the optimum values of sandcrete components (variables) and the desired maximal values of the output responses (CO_2 concentration and compressive strength) as shown in Figures 5 and 6 respectively. The results showed that the sandcrete-talc mixture found to maximize desirability in 7- and 28-day has the following mass proportion: Sand = 202.29 g, Talc = 10.12 g at constant cement and water content. The optimal CO_2 concentration and compressive strength obtained using the predicted mixture generated by Design Expert for 7- and 28-day are: 0.20825 mol/dm^3 and 2.3925 N/mm^2; and 0.45275 mol/m^3 and 7.315 N/mm^2 respectively.

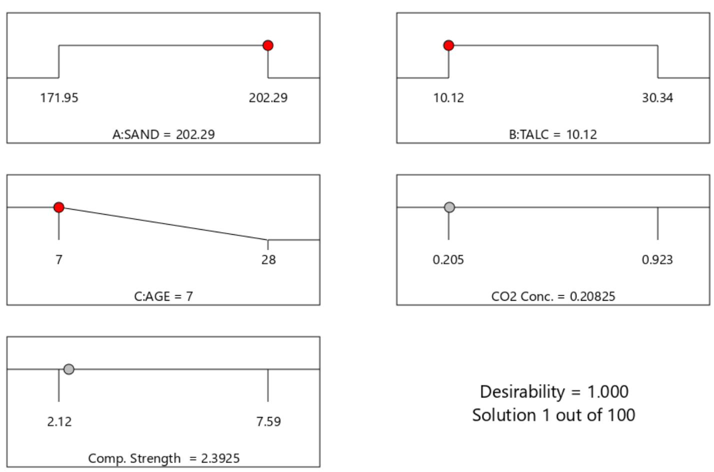

Figure 5: Desirability optimization of sandcrete components for 7-day

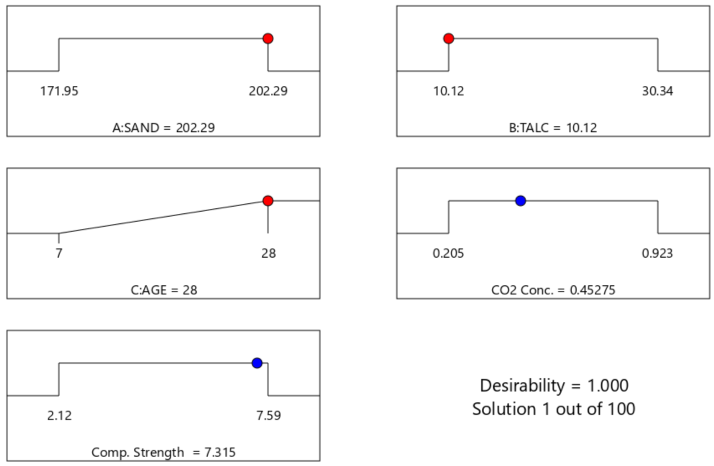

Figure 6: Desirability optimization of sandcrete components for 28-day

The fundamental aim in sandcrete and sandcrete carbonation is to find the best possible mixture combination that will enhance the degree of CO_2 sequestration and improve the mechanical properties.

In order to validate the optimized predictive results obtained using Equations 1 and 2, an additional experimental work was conducted using the results in Figures 5 and 6 to determine the concentrations of carbon dioxide sequestered and compressive strengths after 7- and 28-day curing in an ambient conditions almost similar to the initial experimental run conducted. The results obtained for CO_2 concentration for 7- and 28-day curing were 0.212 and 0.431 mol/dm^3, while the compressive strengths at the same curing age were 2.51 and 7.36 N/mm^2 respectively. These results are close to the optimized statistical CC and CS results and satisfied NIS of 2007 (minimum compressive strength specified in NIS 87:2007 is between 2.5 N/mm^2 to 3.45 N/mm^2). These results fall within the predicted intervals coupled with desirability equal to 1, hence validating the developed model models and could be effectively used in determining the degree of CO_2 sequestration and compressive strength in sandcrete-talc composite. The comparative analysis of the confirmatory experimental and predictive CC and CS showed highly positive correlations with slight variations attributed to temperature and humidity variation during the curing stage.

Largely, the dissolution of mineral talc in sandcrete is associated with microstructural densification with an increased carbonation with hydrated cement products ($Ca(OH)_2$, C-S-H and C-A-H) (Odigure, 2002; Shah, 2005; Vasburd *et al*., 1997; Abdullahi *et al.,* 2016a). These morphological changes could be responsible for the increase CO_2 sequestration and compressive strength as corroborated by Pusch *et al.* (2013), gally Sabouang *et al.* (2014), Ngally Sabouang *et al.* (2015) and Abdullahi *et al.* (2016b).

4. CONCLUSION

The mathematical models for the determination of CO_2 concentration and compressive strength sandcrete-talc (S-T) composite were developed and optimized using 2-level factorial design. The interactive effects of Sand, Age and Talc with constant cement and w/c ratio of 0.5 were investigated. The statistical analysis (ANOVA) showed that Age and talc have a greater effect on the degree of CO_2 sequestered from the atmosphere at ambient condition, while sand, talc, and age have the most significant effect on the compressive strength of the sandcrete-talc composite. The result showed that an increase in age and talc content, the concentration of carbon dioxide increases. Also, the compressive strength increased as the age, talc and sand components increase at constant cement composition. The quality of the sandcrete-talc composite at the optimum predicated conditions satisfying NIS of 2007. The developed predicted equations could be used in the design of S-T mix composite for structural buildings and to minimize the effect of greenhouse gas.

5. ACKNOWLEDGMENT

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6. CONFLICT OF INTEREST

There is no conflict of interest associated with this work.

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