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SUSTAINABLE PRODUCTION OF HIGH-PERFORMANCE CONCRETE (HPC) USING LOCALLY SOURCED MATERIAL FROM THE NIGER DELTA

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ABSTRACT

This paper explores the sustainable production of High-Performance Concrete (HPC) utilizing locally sourced materials from the Niger Delta region of Nigeria. We examined key factors of high-performance concrete (HPC) that are essential for the construction industry, including workability, durability, and strength. A total of 1350 concrete cubes were tested using various curing mediums such as fresh water, chlorine, and sulfur to explore the impact of chikoko as an admixture on concrete's strength and durability, particularly when combined with uniformly or well-graded sand. By applying multiple regression analysis, we optimized the calcination temperature and admixture concentration of pulverized chikoko in M25-grade concrete, using uniformly graded Abraka sand as the fine aggregate. The results showed that the control (NS) concrete had an average compressive strength of 32.59 N/mm² at 28 days, while PS (with pulverized sand) recorded a significantly lower value of 21.78 N/mm², a 49.84% reduction in strength due to pulverization. A quadratic relationship between admixture concentrations (0-20%) was observed, with 10% CPC proving to be optimal for enhancing PS concrete strength. The strength advantages of NS concrete were nullified *at 10% CPC calcined at 600°C. The optimized CPC-NS concrete met HPC standards for both strength and durability, offering promising results for areas with limited access to well-graded sand. This study underscores the effectiveness of chikoko-based admixtures in improving concrete properties, contributing to the development of more sustainable and durable construction materials.*

Keywords: High-performance concrete (HPC), Chikoko admixture, Concrete strength, Fine aggregates, Admixture concentration.

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1.0. Introduction

The construction industry is a major source of global greenhouse gas emissions and is under growing pressure to adopt more sustainable practices. Concrete, one of the most widely used construction materials, is particularly responsible for a significant share of these emissions, primarily due to the energy-intensive production of Portland cement (Orumu & Overo, 2020; Zhang et al., 2017). Despite the environmental impact, the need for high-strength, durable concrete is essential for the development of infrastructure like highways, bridges, and skyscrapers.

High-Performance Concrete (HPC) is highly sought after due to its exceptional strength, durability, and workability. However, HPC often requires costly and energy-consuming materials. This paper explores the potential of producing HPC using locally sourced materials from the Niger Delta, focusing on chikoko as a supplementary cementitious material (SCM) to reduce costs and energy consumption.

Thermally activated clays, especially those in the kaolinite group, are gaining attention in the construction world for their strong reactivity with calcium hydroxide in cement hydration. This reactivity, boosted by the thermal activation process, enhances concrete strength and durability while also cutting down on CO2 emissions, making them a sustainable choice for construction. (Cabrera et al., 2018).

There is limited research on the potential of locally available supplementary cementitious materials (SCMs), especially in areas with few SCM options. Chikoko, a commonly found but weak soil in the Deltaic regions of Nigeria, presents an opportunity for this. When heated (calcined), chikoko transforms into a highly reactive pozzolanic material, making it a valuable but underused resource in construction. While some studies have looked into using chikoko as a partial replacement for cement, its potential as an admixture in concrete has not been widely explored.

This study aims to optimize and model the compressive strength of Chikoko-blended concrete, focusing on high performance concrete. Chikoko has gained attention as a viable alternative due to the growing demand for locally available materials that can reduce both environmental impact and concrete production costs (Otoko,(2014;Onwuka & Sule,2017). Previous studies suggest that calcining Chikoko at different temperatures can significantly enhance its pozzolanic properties, leading to improvements in the mechanical strength of concrete (Orumu & Overo 2020; Slade & Jones, 1992; Shah et al., 2020; Malhotra, 2000).

2.0. Literature Review

Supplementary cementitious materials (SCMs), through hydraulic or pozzolanic activity, influence the properties of cured concrete. Some common examples of supplementary cementitious materials (SCMs) are fly ash, slag cement (ground, granulated blast-furnace slag), and silica fume. These materials can be used on their own or in various combinations with Portland or blended cement. The addition of supplementary cementing materials is a common practice in concrete to enhance its cost-effectiveness, environmentally friendly, reduce permeability, boost strength, or alter other qualities (Mehta & Monteiro, 2006;Kumar & Reddy, 2018). Figure 1 is a representation of the different conventional supplementary cementitious materials.

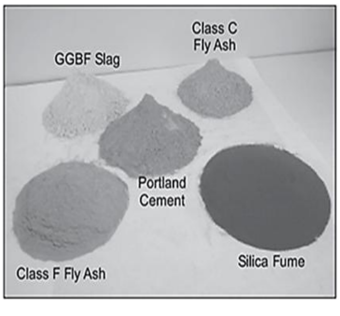

Figure 1: Portland cement and conventional supplementary cementitious materials (NRM,2021)

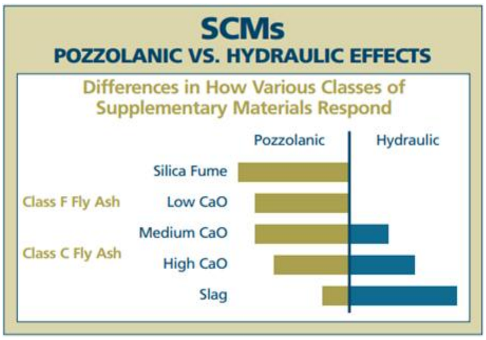

Figure 2: Pozzolanic and hydraulic supplementary cementitious materials (Walker and Pavia, 2011)

The use of supplementary cementitious materials (SCMs) and natural pozzolans, like the one shown in Figure 2, has been extensively researched for its ability to reduce the environmental impact of concrete production. Chikoko, a clay-based material found in the Niger Delta, has shown potential in other applications such as ceramics and construction. Research by Yao et al. (2019) highlighted that incorporating natural materials into concrete can improve its workability, strength, and durability. Similarly, studies have found that using clay and other natural pozzolans in concrete can enhance compressive strength and lower permeability, making the material more resistant to environmental damage (Ayo et al., 2015; Orumu & Overo, 2020).

In the Niger Delta region, the use of chikoko in concrete production has not been widely studied. This research seeks to address this gap by exploring the potential of chikoko as a sustainable and cost-effective supplementary cementitious material (SCM) for high-performance concrete (HPC), taking advantage of its local availability. Additionally, chikoko offers the potential to reduce the amount of cement used in concrete mixes without compromising performance, making it a promising alternative for promoting more sustainable construction practices (Zhang et al., 2020).

3. Methodology

3.1. Materials

The materials used in this study include chikoko, a locally sourced clay-based material from the Niger Delta region, which was ground and sieved to the desired fineness to serve as a supplementary cementitious material (SCM). It meets the specifications of ASTM C618 for pozzolanic materials. Ordinary Portland Cement (OPC) was used as the control material, conforming to the standards outlined in BS 12:2011. The river sand and gravel, sourced locally, were selected to meet the grading requirements of BS EN 12620:2002 for aggregates. Clean, potable water, which complies with BS 3148:1980 standards, was used. Additionally, a superplasticizer admixture was included to improve the workability of the mix, adhering to the guidelines of ASTM C494 for chemical admixtures in concrete. Additionally, a furnace with a capacity of 1500°C was utilized to calcine the chikoko clay at varying temperatures to activate its pozzolanic properties.

3.2 Experimental methods

3.2.1 Sample Preparation

Chikoko clay, sourced from Okrika, was subjected to a seven-day sun-drying process to remove any residual moisture. Following this, the clay underwent calcination under controlled conditions, using adjustable air inlet valves and a digital infrared thermometer for precise monitoring. The temperature was gradually increased at a rate of 10°C per minute, with a 30-minute holding period at the target temperature to ensure uniform heat treatment. The calcination was performed at temperatures of 25°C (ambient), 200°C, 400°C, 600°C, and 800°C. After calcination, the material was pulverized into fine particles and sieved through a 75-micron mesh to prepare it for incorporation into concrete production.

3.2.2 Specimen Production, Curing and Testing

In accordance with the guidelines outlined in BS 1881-113:2011, each batch of concrete produced included three standard cubes, each measuring 150 x 150 x 150 mm, using M25 grade concrete and a water-to-binder ratio of 0.55. Calcined and pulverized chikoko (CPC) was added as an admixture at varying concentrations of 0%, 5%, 10%, 15%, and 20%. The concrete cubes were cured for different periods, including 7, 14, 28, 56, and 90 days. Various tests were performed to measure compressive strength, water absorption, and strength loss due to chloride and sulphate exposure. Compression tests were conducted on each cube, and the maximum compressive strength for each set of cubes was averaged. The mix design for the concrete cubes is detailed in Table 1.

Table 1 Concrete cube production mixture configuration

Specimen details	Cement (kg)	Sand (kg)	Chippings (kg)	Chikoko (%)	Chikoko (kg)	W/Cem. Ratio	Water (kg)	No of cubes
0% CPC	3.75	7.5	15	0	0	0.55	2.06	3
5% CPC	3.75	7.5	15	0.05	0.1875	0.55	2.17	3
10% CPC	3.75	7.5	15	0.1	0.375	0.55	2.27	3
15% CPC	3.75	7.5	15	0.15	0.5625	0.55	2.37	3
20% CPC	3.75	7.5	15	0.2	0.75	0.55	2.48	3

3.2.3 Particle Size Distribution

Particle size distribution and Atterberg limits are important tests used to classify soil types, which directly affect the soil's bearing capacity, stability, and drainage properties. The AASHTO Soil Classification System and the ASTM Unified Soil Classification System (USCS) are typically used for this classification. For fine aggregates, sieve analysis is conducted following ASTM D422 standards, using equipment such as an analytical balance, sieves, a wire brush, and a sieve shaker to ensure accurate measurement and classification.

3.2.4 Compression Test

For the compression testing, the concrete cube specimens, each measuring 150mm x 150mm x 150mm, were first submerged in fresh water for 24 hours to cure, following standard procedures. The compressive strength (CS) was then determined by dividing the crushing load at failure by the area of the cube's surface that was subjected to the load. This testing method aligns with the guidelines outlined in ASTM C39.

3.2.5 Durability Test:

Durability tests included water absorption, chloride attack, and sulphate attack. Water absorption, following BS 1881-122 (2011), was tested at 28, 56, and 90 days by measuring weight changes before and after immersion in water. Chloride attack was evaluated using a

10% sodium chloride solution, with strength loss calculated using the Chloride Induced Strength Loss Index (CISLI). Sulphate attack was tested with a 2.5% sodium sulphate solution, and the Sulphate Induced Strength Loss Index (SISLI) was calculated to assess weight and strength loss during immersion to assess the durability of the HPC mixes.

Results and Discussion

3.1 Sieve Analysis

The particle size distribution of the natural sand (NS) obtained from Abraka and pulverized sand (PS) used in the study are as shown .The gradation variables for coarse aggregate are as follows

Coefficient of Uniformity (Cu) = $\frac{D60}{D10} = \frac{15.5}{9.0} = 1.72$

Coefficient of Curvature (Cc) = $\frac{D30^2}{D10 \times D60} = 1.03$

The coarse aggregate is poorly graded as the coefficient of uniformity of 1.72.

3.2 Compressive Strength results

The results for the strength of concrete blended with chikoko is as shown in Figure 3 to 5

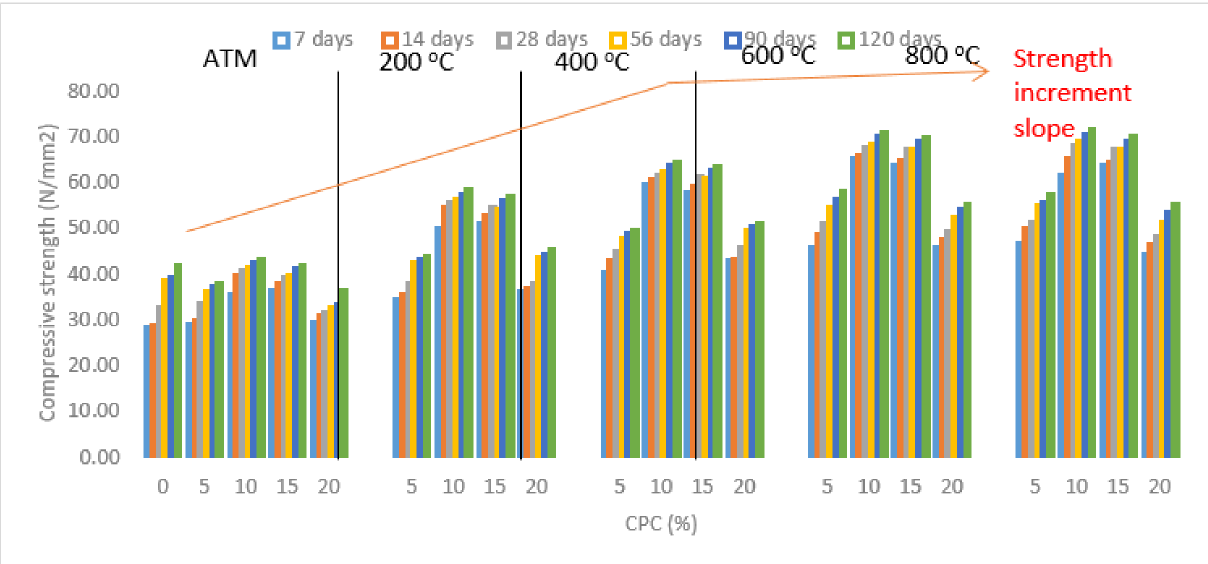

Figure 3: Compressive strength of concrete samples soaked with fresh water

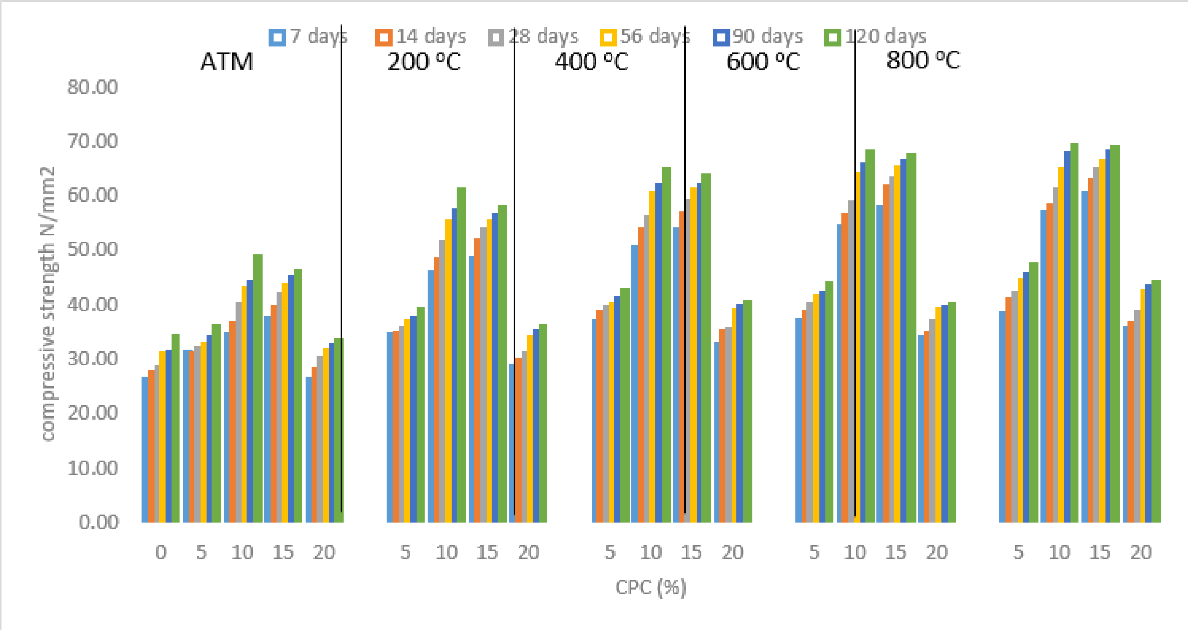

Figure 4: Compressive strength of concrete samples soaked with chloride solution

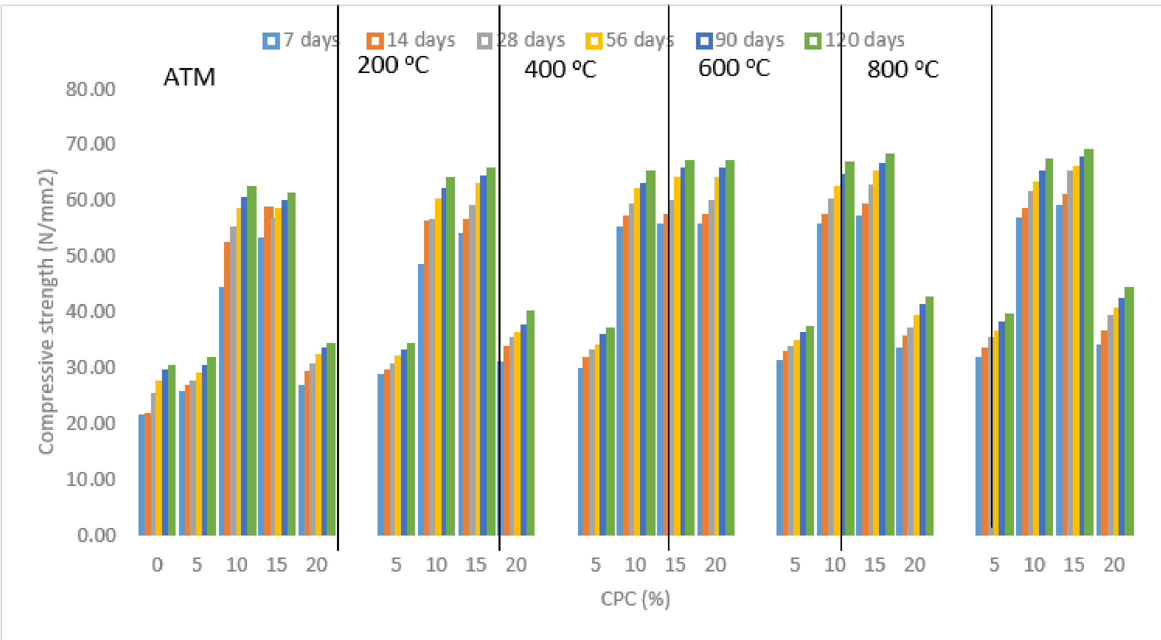

Figure 5: Compressive strength of concrete samples soaked with sulphate solution

Figures 3, 4, and 5 highlight the significant role of chikoko admixture concentration, calcination temperature, and curing age in improving the compressive strength (CS) and durability of concrete. The optimal chikoko concentration was found to be between 10% and

15%, with a peak CS observed at 10%. This is consistent with previous research that suggests supplementary cementitious materials (SCMs) like calcined clays, including chikoko, can improve concrete strength and resistance to environmental attacks (Slade & Jones, 1992; Malhotra, 2000). At 28 days, concrete with 10% chikoko admixture achieved a CS of approximately 35 N/mm², which was slightly higher than the control specimens (NS 28), which reached 30 N/mm². This finding supports previous studies that found improvements in concrete strength with the incorporation of pozzolanic materials (Mehta & Monteiro, 2014).

In Figures 4 and 5, the effect of calcination temperature on concrete strength was examined. Higher calcination temperatures, especially at 600°C and 800°C, resulted in significantly improved CS, particularly when combined with 10% chikoko admixture. The highest CS was observed for samples cured at 800°C, consistent with findings by Shah et al. (2020), who reported that higher calcination temperatures enhance the pozzolanic properties of materials like chikoko, leading to greater concrete strength. These results indicate that calcination temperatures between 600°C and 800°C maximize the potential of chikoko as a pozzolanic material, improving both strength and durability.

The study also found that longer curing times (90–120 days) allowed the concrete to reach its maximum potential strength, as observed in Figure 5, where CS continued to increase with curing age. This is in line with the work of Taha (2009), who emphasized the importance of curing in the development of concrete's long-term strength. Additionally, the stabilization of CS values over time suggests that the concrete's performance improves as it matures, which aligns with findings from Neville (1995), who indicated that longer curing times enhance concrete durability and strength.

Furthermore, the results in both sulfate and chloride environments demonstrate that chikoko admixture enhances concrete’s resistance to these aggressive exposures, which is crucial for infrastructure durability. These findings are consistent with Malhotra (2000), who emphasized the role of supplementary cementing materials in mitigating the effects of environmental exposure, particularly sulfate and chloride attacks. The results suggest that optimizing chikoko concentration and calcination temperature can significantly improve concrete's performance in aggressive conditions, which is supported by the findings of several researchers in the field of sustainable construction materials (Onwuka & Sule, 2017; Orumu & Overo, 2020).

3.3 Model Development for Chikoko Blended Concrete

The data analysis and model development for chikoko-blended concrete were derived from laboratory results, which took into account the effects of chikoko calcination temperature, admixture concentration, and the curing age of the concrete.

Table 2: Design of Experiment

Run	F 1 Chikoko %	F 2 Temperature °C	F 3 Curing Age Days	Resp 1 Comp. strength
1	0	800	28	21.78
2	10	400	90	36.15
3	10	30	7	18.74
4	5	30	90	30.21
5	10	400	56	34.22
6	0	800	7	13.4
7	0	400	7	13.4
8	5	600	120	38.34
9	10	400	7	25.93
10	20	400	7	20.58
11	15	30	90	27.77
12	20	30	28	16.22
13	10	800	56	36.59
14	15	600	28	32.22
15	15	200	120	26.88
16	10	800	7	34.0
17	5	200	28	26.2
18	20	800	120	33.91
19	0	200	56	24.04
20	15	800	90	38.13
21	15	200	120	26.88
22	15	600	28	32.22
23	0	30	120	26.48
24	20	200	56	23.76
25	10	800	56	36.59
26	0	400	90	25.43
27	5	200	28	26.2
28	5	600	120	38.34

The models developed are presented in equations 1 to 5, which were derived following the application of Design of Experiments (DOE) to the laboratory data shown in Table 2. The data was analyzed to create the model, with a multiple polynomial approach being chosen for this study due to its common use in real-world scenarios where multiple independent variables affect the dependent variable. Furthermore, Design Expert software version 13.0 was employed, as it is a vital tool in DOE for modeling and optimizing complex interactions between factors and responses. Consequently, the model is considered statistically robust and is suitable for exploring the design space.

$$fcu^{7} = 8.33 + 1.94CK + 0.01T + 0.0009CKT - 0.09CK^{2} - 2.58 \times 10^{-6}T^{2} \quad (1)$$

$$fcu_{28} = 18.98 + 1.63CK + 0.005\,T + 0.0009CKT - 0.09CK^{2} - 2.58 \times 10^{-6}T^{2} \quad (2)$$

$$fcu^{56} = 24.17 + 1.65CK - 0.0005\,T + 0.0009CKT - 0.09CK^{2} - 2.58 \times 10^{-6}T^{2} \quad (3)$$

$$fcu_{90} = 24.86 + 1.55CK + 0.003\,T + 0.0009CKT - 0.09CK^{2} - 2.58 \times 10^{-6}T^{2} \quad (4)$$

$$fcu^{120} = 25.99 + 1.11CK + 0.012\,T + 0.0009CKT - 0.09CK^{2} - 2.58 \times 10^{-6}T^{2} \quad (5)$$

Where:

fcu7 = Compressive strength of chikoko-blended concrete at 7 days (N/mm²)

fcu28 = Compressive strength of chikoko-blended concrete at 28 days (N/mm²)

fcu56 = Compressive strength of chikoko-blended concrete at 56 days (N/mm²)

fcu90 = Compressive strength of chikoko-blended concrete at 90 days (N/mm²)

fcu120 = Compressive strength of chikoko-blended concrete at 120 days (N/mm²)

CK = Percentage of chikoko admixture used in the cement mix (%)

T = Calcination temperature of the chikoko material

Table 3: Model Fit Summary for the CS of chikoko blended concrete

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Mean vs Total	21986.17	1	21986.17			
Linear vs Mean	886.38	6	147.73	5.22	0.0020	
2FI vs Linear	283.33	9	31.48	1.21	0.3691	
Quadratic vs 2FI	**301.12**	**2**	**150.56**	**147.52**	**< 0.0001**	**Suggested**
Cubic vs Quadratic	10.21	5	2.04			Aliased
Residual	0.0000	5	0.0000			
Total	23467.21	28	838.11			

Table 4: Analysis of Variance (ANOVA) for the CS of chikoko blended concrete

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	1470.83	17	86.52	84.77	< 0.0001	significant
A-Chikoko	29.69	1	29.69	29.09	0.0003	
B-Temperature	323.46	1	323.46	316.94	< 0.0001	
C-Curing Age	389.88	4	97.47	95.50	< 0.0001	
AB	59.81	1	59.81	58.61	< 0.0001	
AC	93.34	4	23.33	22.86	< 0.0001	
BC	40.88	4	10.22	10.01	0.0016	
A^2	258.84	1	258.84	253.62	< 0.0001	
B^2	0.4791	1	0.4791	0.4694	0.5088	
Residual	10.21	10	1.02			
Lack of Fit	10.21	5	2.04			
Pure Error	0.0000	5	0.0000			
Cor Total	1481.03	27				

Table 5: Coefficient of Regression for the CS of chikoko blended concrete

Std. Dev.	1.01	R^2	0.9931
Mean	28.02	Adjusted R^2	0.9814
C.V. %	3.61	Predicted R^2	0.8485
		Adeq Precision	32.4761

In Tables 3 and 5, several models were proposed, with the best one selected based on the P-value. A P-value of 0.05 or lower is considered acceptable at a 95% confidence level. The Quadratic vs. 2FI model, which has an F-value of 84.77, is deemed statistically significant, with only a 0.01% likelihood that the results are due to random noise. Key model variables include A, B, C, AB, AC, BC, and A2, while B2 is found to be statistically insignificant with a value of 0.5088.

The regression coefficients for the model R^2, adjusted R^2, and predicted R^2 are 0.9931, 0.9814, and 0.8485, respectively, as shown in Table 8. The mean value of 28.02 was multiplied by 1.01 to determine the standard deviation, and the resulting coefficient of variation was 3.61%, which is below the 30% threshold, indicating that the model is statistically adequate. The Adeq Precision value of 32.476, well above the threshold of 4, indicates a satisfactory signal-to-noise ratio.

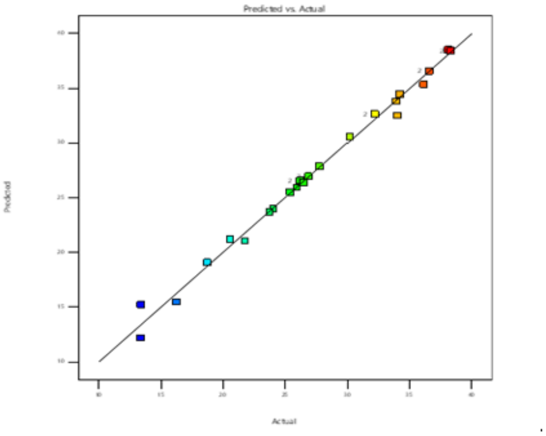

Figure 6: Model interactions for the Compressive strength of chikoko blended concrete

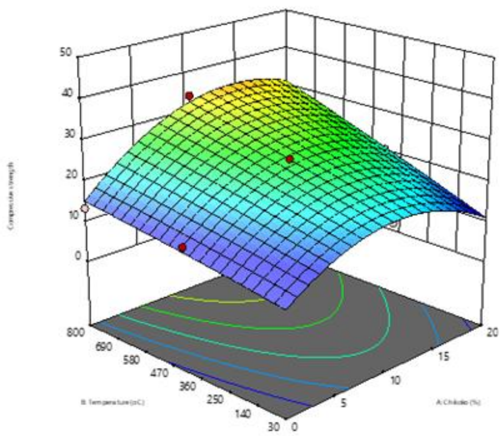

Figure 7: Model interaction for 7day CS of chikoko blended concrete

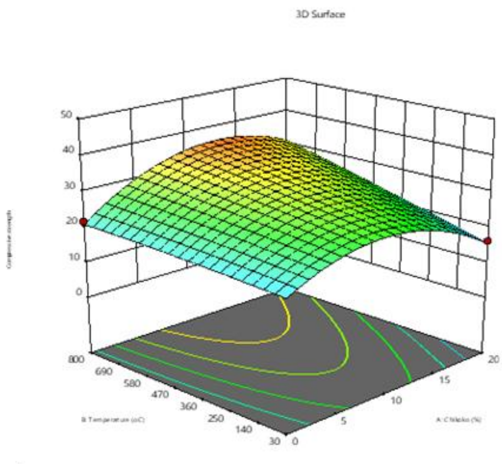

Figure 8: Model interactions for 28day CS of chikoko blended concrete

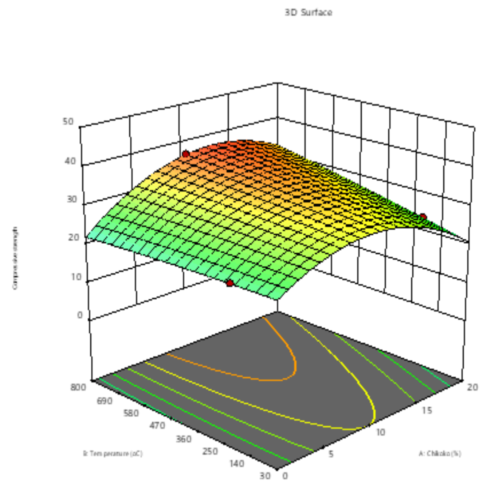

Figure 9: Model interactions for 56day CS of chikoko blended concrete

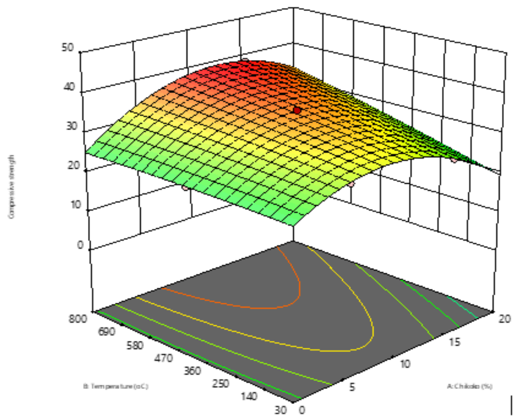

Figure 10: Model interactions for 90-day CS of chikoko blended concrete

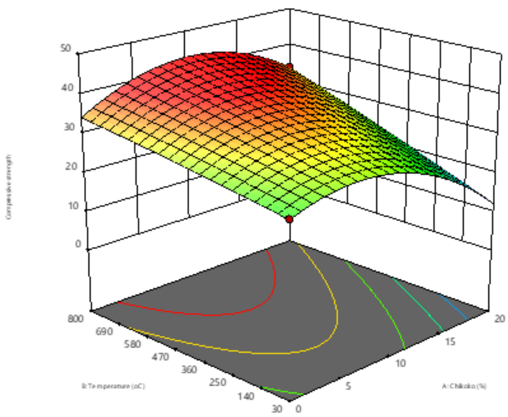

Figure 11: Model interactions for 120-day CS of chikoko blended concrete

3.3 Discussion

This study compared experimental data and model predictions, showing a strong correlation with an average of 99.6% at 28 days, exceeding the 95% threshold for accuracy. The compressive strength (CS) test results indicated that concrete with a 10% chikoko admixture had a CS of 24.25 N/mm², which was 16.92% greater than the PS control specimens (20.74 N/mm²) but 13.93% lower than the NS control (33.78 N/mm²). These findings suggest that chikoko admixture can enhance concrete strength while mitigating the effects of sulfate attack, particularly when used with uniformly graded fine aggregates. This aligns with previous research on pozzolanic materials in concrete (Slade & Jones, 1992; Mehta & Monteiro, 2014).

The study also investigated the impact of chikoko on sulfate resistance. The CS values of specimens cured in a sulfate medium with 0, 5, 10, 15, and 20% admixture concentrations at a calcination temperature of 200°C were 20.74 N/mm², 36.78 N/mm², 37.22 N/mm², 34.89 N/mm², and 26.33 N/mm², respectively. These results showed a quadratic increase in CS with the admixture concentrations, with the peak strength observed between 5% and 15% for all curing ages, consistent with studies by Shah et al. (2020) and Malhotra (2000), who highlighted the role of calcined pozzolanic materials in improving concrete properties.

After 28 days, the concrete with 10% chikoko additive had a CS of 37.22 N/mm², which was 54.12% higher than the ATM concrete, 79.37% higher than the PS control, and 10.28% higher than the NS concrete control. This significant increase in both strength and sulfate resistance indicates that chikoko, when calcined at 200°C, performs better than the ATM concrete specimens. The study also highlighted the importance of optimizing the calcination temperature of chikoko for use as an admixture in concrete. It was found that the CS decreased with calcination temperatures above 400°C, likely due to the interaction between high temperatures and the sulfate environment.

Further tests at a calcination temperature of 600°C, with 10% chikoko admixture, revealed a CS of 39.7 N/mm², which was 91.42% higher than the PS control, 17.53% higher than the NS control, and 64.39% higher than the ATM specimens. This shows that higher calcination temperatures result in greater compressive strength, but with diminishing returns after 400°C. The study also found that the CS values at 600°C were 6.66% higher than those at 200°C, 1.86% lower than at 400°C, and 0.38% higher than at 600°C.

Figures 7 to 11 depict the relationship between calcination temperature, admixture concentration, and compressive strength (CS) of concrete, showing that the influence of chikoko admixture on CS follows a quadratic trend, with peak strength observed at admixture concentrations of 10–15%. This suggests that an optimal concentration exists for chikoko, beyond which the strength begins to decrease slightly. Similarly, the effect of calcination temperature on CS is linear, with higher calcination temperatures leading to increased compressive strength. These findings are consistent with Thienel and Beuntner (2015), who reported that clay samples calcined at varying temperatures (both at laboratory scale (LCT) and industrial scale (GCT)) exhibited a quadratic relationship between the solubility of aluminium and silicon ions and calcination temperature, as well as a linear increase in activity index with higher temperatures. This study highlights chikoko as an effective admixture that not only enhances compressive strength but also improves sulfate resistance in concrete. The results underscore the importance of optimizing calcination temperature to achieve significant improvements in concrete performance, confirming that higher calcination temperatures lead to enhanced strength and durability, particularly in sulfate-rich environments.

4.0. Conclusion

This study successfully demonstrated the significant impact of calcination temperature and chikoko admixture concentration on the mechanical and durability properties of concrete, particularly in sulfate- and chloride-rich environments. The results revealed that compressive strength increased quadratically with calcination temperature, peaking at temperatures over 600°C, and with chikoko admixture concentrations between 10% and 15%. The study also found that the presence of chikoko admixture (5–15%) and optimal calcination temperatures between 200–600°C notably improved concrete performance. Concrete specimens produced at 400°C demonstrated a 40.78% improvement in compressive strength over those made at ATM and 200°C, with a 10% admixture concentration. Additionally, both sulfate and chloride attacks were reduced in CPC concrete blends, with well-graded fine aggregates showing more pronounced resistance to sulfate attack. The models developed in this study, with low variance inflation factors (VIFs), indicated reliable coefficients, offering a robust tool for simulating and optimizing concrete mixes for improved strength and durability. This research introduces an innovative approach to enhancing concrete performance, even with lower-quality aggregates, by integrating optimally calcined chikoko as a supplementary admixture.

Conflict of Interest Statement

The author(s) declare(s) that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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