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Statistical Analysis of the Impact of Chikoko Clay Source Variation on Concrete Strength Parameters

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Abstract

This study evaluates the impact of geographic source variation of Burnt Pulverized Chikoko (BPC) clay on the compressive strength characteristics of concrete Chikoko clay was sourced from Okrika (Rivers State) and Ogbia (Bayelsa State), both in the Niger Delta region of Nigeria, and processed through calcination into BPC. The material was incorporated as an admixture in concrete at varying proportions (0%, 5%, 10%, 15%, and 20%) using two mix ratios (1:1.5:3 and 1:2:4) with a constant water cement ratio of 0.5. Compressive strength was evaluated at curing ages of 7, 14, and 28 days. Results revealed distinct trends between the two sources: Okrika-sourced BPC significantly improved concrete strength, peaking at 32.89 MPa (15% admixture, 1:1.5:3 mix), while Ogbia clay showed optimal performance at lower dosages (5% - 10%) and declined thereafter. Two-way ANOVA confirmed that the clay source ($p = 0.0033$) and its interaction with BPC percentage ($p = 0.0250$) had statistically significant effects on strength development, while the BPC percentage alone was not uniformly significant ($p = 0.1830$). These findings emphasize that the pozzolanic performance of Chikoko clay is highly dependent on its mineralogical origin and dosage, underscoring the importance of source-specific characterization before use in structural applications. The study advocates for careful optimization of natural pozzolans based on location to ensure performance reliability in concrete production.

Subject Areas

Civil Engineering

Keywords

Chikoko Clay, Pozzolanic Admixture, Compressive Strength, Concrete, Source Variation, ANOVA

1. Introduction

The global push for sustainable construction has intensified interest in Supplementary Cementitious Materials (SCMs) as alternatives to Ordinary Portland Cement (OPC), which is associated with high carbon emissions and energy use [1] [2]. SCMs, especially those derived from natural or industrial by-products, contribute significantly to reducing the environmental footprint of concrete [3] [4]. Among these, calcined clays are gaining prominence due to their pozzolanic properties when thermally activated, improving strength, durability, and sustainability. [5] noted that thermally treated low-grade clays, calcined between 700˚C and 850˚C, can effectively replace up to 60% of cement in blended systems without compromising structural performance.

In Nigeria, Chikoko clay, a swamp-derived natural clay found abundantly in the Niger Delta, has shown promising results when calcined and used as a pozzolan [6]. [3] [7] demonstrated its enhanced resistance to sulfate attack, while [8] developed a model showing its potential in mitigating chloride-induced strength loss when optimally calcined and dosed. These studies affirm that Burnt Chikoko Clay can serve as a reliable SCM; however, its effectiveness depends greatly on geological origin, mineralogical composition, and processing parameters [9] [10].

This study examined the performance of burnt pulverized Chikoko (BPC) clay when used as an admixture. It evaluates the influence of source variation on the compressive strength of concrete by comparing BPC derived from Okrika (Rivers State) and Ogbia (Bayelsa State). A two-way ANOVA was used to statistically analyze the effects of BPC dosage and clay source on strength development over 7, 14, and 28 days. The findings offer insight into the consistency and reliability of using locally sourced pozzolanic clays in sustainable construction across regions with variable soil characteristics.

2. Materials and Methods

2.1. Materials

The materials used in this study adhered to established standards for concrete production. Ordinary Portland Cement (OPC) Grade 42.5, conforming to [11] and [12], was selected for its strength reliability. Clean river sand, free from impurities, served as the fine aggregate, meeting [13] and [14] standards. The coarse aggregate was crushed granite (10 - 20 mm), chosen for its strength and angularity, also compliant with ASTM and British standards.

The main variable material was Chikoko clay, sourced from Okrika and Ogbia in Nigeria. The clay was air-dried, calcined at 750˚C, and sieved to 75 μm to form Burnt Pozzolanic Chikoko (BPC), following [15] guidelines for pozzolanic materials. This treatment enhances reactivity for cement replacement. All materials were stored in dry, cool environments, and concrete mixing and curing followed [16] to ensure quality and repeatability of results.

The chemical compositions of Chikoko clay sourced from Okrika and Ogbia were analyzed and are presented in **Table 1** and **Table 2**. These compositions are crucial in understanding the pozzolanic potential of the clays when used as admixtures in concrete.

Table 1. Chemical composition of chikoko clay (Okrika).

Chemical Constituents	Concentration (%)
Silicon Dioxide (SiO_2)	62.96
Aluminum Trioxide (Al_2O_3)	17.18
Calcium Oxides (CaO)	0.16
Magnesium Oxide (MgO)	1.05
Iron Oxide (Fe_2O_3)	35.70
Potassium Oxide (K_2O)	2.09
Sodium Oxide (Na_2O)	0.22
Sulphate (SO_3)	0.76

Table 2. Chemical composition of chikoko clay (Ogbia).

Chemical Constituents	Concentration (%)
Silicon Dioxide (SiO_2)	60.45
Aluminum Trioxide (Al_2O_3)	18.25
Calcium Oxides (CaO)	0.12
Magnesium Oxide (MgO)	1.25
Iron Oxide (Fe_2O_3)	37.12
Potassium Oxide (K_2O)	2.18
Sodium Oxide (Na_2O)	0.19
Sulphate (SO_3)	0.69

2.2. Mix Design

Two concrete mix ratios 1:1.5:3 for structural and 1:2:4 for non-structural applications were adopted to assess the performance of Burnt Pozzolanic Chikoko (BPC) as a partial cement replacement. Cement was replaced with BPC at 0%, 5%, 10%, 15%, and 20% by weight, reflecting standards in [15] and related literature. A constant water-to-cementitious ratio was maintained across all mixes to ensure consistency. Mix design followed [16] and [17] standards. This framework enabled a robust comparison of strength performance and the suitability of BPC from different sources in various concrete applications.

2.3. Testing Procedure

For each concrete mix, three cube specimens (150 mm × 150 mm × 150 mm) were cast and tested at 7, 14, and 28 days to evaluate compressive strength development in the department of Civil Engineering Niger Delta University Bayelsa State. These curing ages reflect standard benchmarks for early, intermediate, and final strength assessments. After casting, cubes were demolded after 24 hours and cured in water at 20˚C ± 2˚C, following [18] and [19] standards. Compressive strength testing was performed using a 2000 kN capacity hydraulic machine, in accordance with [20] as shown in **Figure 1**. The load was applied uniformly until failure, and the maximum load was recorded to compute compressive strength.

Figure 1. Compression test of samples.

2.4. Data Analysis

The data analysis for this study was conducted using Design Expert 13 Software with the Response Surface Methodology (RSM) approach. This software is commonly used for analyzing experimental designs and conducting ANOVA, enabling the assessment of significant factors and their interactions. The effect size for each factor was reported using partial η^2 (eta squared), which quantifies the proportion of total variability in the dependent variable that is attributable to each factor.

This was done to determine the statistical significance of the effects of Chikoko clay source, admixture percentage, and their interaction on the compressive strength of concrete, a two-way Analysis of Variance (ANOVA) was performed at a 95% confidence level ($\alpha = 0.05$). This method was selected to evaluate the main effects of two categorical independent variables clay source (Okrika and Ogbia) and BPC admixture levels (0%, 5%, 10%, 15%, and 20%) as well as the interaction effect between them on the dependent variable, namely, compressive strength at 28 days.

The following analytical steps were implemented:

1) Group and Grand Means:

Mean compressive strengths (X_{ij}^{-}) were computed for each combination of clay source and BPC percentage. The overall grand mean (X^{-}) of all groups was also determined.

2) Sum of Squares Computation:

- **Between-Groups (SSB):** The sum of squares due to differences between the means of clay sources and BPC percentages.
- **Interaction (SSAB):** The variation attributable to the interaction between

source and admixture percentage.

- **Residual (SSE):** The within-group variance reflecting unexplained variation among replicates.

The respective formulas were as follows:

$$\text{SSA} = nb\sum_{i=1}^{a}\left(\bar{X}_i - \bar{X}\right)^2$$

$$\text{SSB} = na\sum_{j=1}^{b}\left(\bar{X}_j - \bar{X}\right)^2$$

$$\text{SSAB} = n\sum_{i=1}^{a}\sum_{j=1}^{b}\left(\bar{X}_{ij} - \bar{X}_i - \bar{X}_j + \bar{X}\right)^2$$

$$\text{SSE} = \sum_{i=1}^{a}\sum_{j=1}^{b}\sum_{k=1}^{n}\left(\bar{X}_{ijk} - \bar{X}_{ij}\right)^2$$

3) Degrees of Freedom (df):

The degrees of freedom were computed as:

Clay Source: $\text{df}_A = \text{a} - 1 = 1$

BPC Percentage: $\text{df}_B = \text{b} - 1 = 4$

Interaction: $\text{df}_{AB} = (\text{a} - 1)(\text{b} - 1) = 4$

Residual: $\text{df}_E = \text{ab}\ (\text{n} - 1) = 50$

Total: $\text{df}_T = \text{N} - 1 = 59$

4) Mean Squares and F-Values:

Mean squares were calculated by dividing the sum of squares by their respective degrees of freedom. The F-statistic was derived by taking the ratio of each factor's mean square to the mean square of the error:

$$F = \frac{MS_{factor}}{MS_{error}}$$

5) Significance Testing:

The calculated F-values were compared to critical values from the F-distribution. Corresponding p-values were obtained using statistical software to assess significance at $\alpha = 0.05$.

3. Results and Discussions

3.1. Compressive Strength Results

The compressive strength results presented in Table 3(a) and Table 3(b) provide compelling evidence of the significant influence of Chikoko clay source variation on the performance of BPC-admixed concrete. Compressive strength is a key parameter in evaluating the structural integrity of concrete, as it reflects the material's ability to withstand axial loads. In this study, the compressive strength of the concrete mixes was notably affected by the type and origin of the Chikoko clay used as an additive, highlighting the role of material variability in concrete performance.

From Table 3(a) and Table 3(b), while both Okrika and Ogbia samples began with identical control strengths (27.78 MPa and 25.56 MPa for 1:1.5:3 and 1:2:4, respectively), subsequent additions of BPC revealed divergent trends. Okrika consistently outperformed Ogbia at medium to high BPC levels, peaking at 32.89 MPa (28 days, 15% BPC) in the 1:1.5:3 mix and 30.22 MPa (20% BPC) in the 1:2:4 mix. These gains affirm the findings of [21], who reported that pozzolanic clays with higher silica and alumina content enhance late-age strength due to sustained pozzolanic activity.

Table 3. (a) Effect of BPC admixtures on the compressive strength for mix ratio 1:1.5:3 from varying locations; (b) Effect of BPC admixtures on the compressive strength for mix ratio 1:2:4 from varying locations.

BPC Usage (%)	Source	7 Days	14 Days	28 Days
		(a)		
0	**Okrika**	20.44	22.89	27.78
0	**Ogbia**	20.44	22.89	27.78
5	**Okrika**	25.78	25.33	28.22
5	**Ogbia**	22.00	26.00	30.00
10	**Okrika**	25.00	29.11	32.44
10	**Ogbia**	22.00	25.00	27.00
15	**Okrika**	29.33	31.33	32.89
15	**Ogbia**	18.00	19.00	23.00
20	**Okrika**	23.78	27.78	32.89
20	**Ogbia**	21.00	20.00	24.00
		(b)		
0	**Okrika**	19.33	19.56	25.56
0	**Ogbia**	19.33	19.56	25.56
5	**Okrika**	21.11	23.11	27.78
5	**Ogbia**	21.56	26.22	30.00
10	**Okrika**	22.67	24.22	24.00
10	**Ogbia**	21.78	24.44	26.67
15	**Okrika**	20.67	22.67	26.22
15	**Ogbia**	18.00	19.11	23.33
20	**Okrika**	21.78	25.11	30.22
20	**Ogbia**	21.11	20.22	23.33

In contrast, the performance of Ogbia clay declined beyond 10% admixture as shown in **Figure 2**, aligning with observations from [22], who found that excessive clay admixtures with poor mineralogical balance can dilute cementations compounds, and impairing strength. The interaction effect observed where the strength benefit or penalty depends on both source and dosage is consistent with outcomes reported by [23], who noted regional variability in Nigerian pozzolans significantly affects hydration kinetics and strength development.

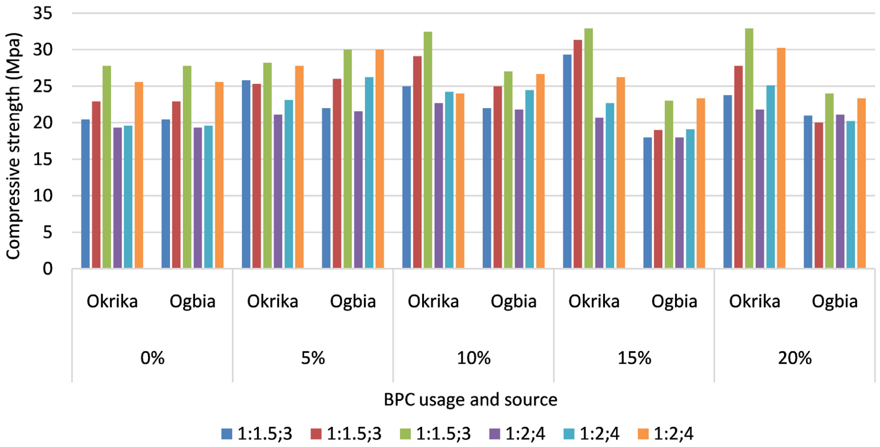

Figure 2. Compressive strength of concrete at varying curing ages.

Furthermore, the superior performance of Okrika clay at high admixture levels supports the view of [24], who emphasized that well-calcined pozzolanic materials can match or exceed control strengths when optimally used. The early strength gains also suggest enhanced nucleation sites and filler effects, as described by [25], especially in finer mix designs like 1:1.5:3.

The findings validate the statistical results and emphasize that pozzolanic behavior is not universal, but highly dependent on geological origin. Thus, source-specific assessment is crucial, and generalizing performance across regions without testing may lead to poor concrete outcomes.

3.2. Statistical Analysis

A two-way Analysis of Variance (ANOVA) was performed to evaluate the effects of Chikoko clay source (Okrika and Ogbia), BPC replacement percentage (0%, 5%, 10%, 15%, 20%), and their interaction on concrete compressive strength at 28 days. This approach was chosen to identify statistically significant differences and interactions between variables and determine if the performance of BPC varied based on clay origin and dosage with an F-test was conducted at a 95% significance level ($\alpha = 0.05$).

Table 4. Two-way ANOVA results for 1:1.5:3.

Source of Variation	SS	df	MS	F	P-value	F crit
Clay Source	254.2899	4	63.57249	6.065898	0.009615	3.47805
BPC Percentage	1729.8	1	1729.8	165.0524	1.53E-07	4.964603
Interaction	250.99	4	62.74749	5.987179	0.010039	3.47805
Within	104.8031	10	10.48031			
Total	2339.883	19				

The findings from **Table 4**: Two-Way ANOVA for 1:1.5:3 corroborate existing literature on the significant effects of Clay Source, BPC Percentage, and their interaction on concrete properties. The Clay Source factor shows a sum of squares (SS) of 254.2899, with a mean square (MS) of 63.57249, yielding an F-statistic of 6.065898 and a P-value of 0.009615. This P-value is less than the significance level of 0.05, indicating that the Clay Source has a statistically significant effect on the compressive strength of the concrete, consistent with findings by [26] and [27]. These studies also emphasize how variations in clay type affect concrete's mechanical properties due to differences in chemical composition, particle size, and interactions with cementitious materials, which can directly influence strength and durability.

The BPC Percentage shows an even stronger effect, with an SS of 1729.8 and an MS of 1729.8, yielding an F-statistic of 165.0524 and a P-value of 1.53E−07. This extremely low P-value, well below the 0.05 threshold, indicates that BPC Percentage has a highly significant impact on the material's compressive strength. This aligns with research by [21] and [28], who demonstrated that the use of BPC or similar admixtures improves the strength and microstructure of concrete by enhancing hydration and reducing porosity, thereby improving material performance.

The Interaction between Clay Source and BPC Percentage is also statistically significant, with an SS of 250.99, an MS of 62.74749, and an F-statistic of 5.987179, accompanied by a P-value of 0.010039. This result suggests that the effect of BPC admixture on the compressive strength is dependent on the specific type of clay used. These findings are consistent with [29], who noted that the combined influence of aggregate mineral composition (including clays) and supplementary materials can lead to non-linear effects on concrete properties, meaning that both factors must be optimized together for best performance.

The optimal percentage of BPC depends on its origin. For example, Okrika clay performed best at 15% admixture, achieving 32.89 MPa at 28 days, whereas Ogbia clay showed strength gains up to 10% admixture but declined thereafter. This aligns with the source-specific findings of [30] who observed that clay from southwestern Nigeria exhibited optimal pozzolanic behavior at different replacement levels than clays from the Middle Belt, emphasizing the non-uniformity of natural pozzolans.

Table 5. Two-way ANOVA results for 1:2:4.

Source of Variation	SS	df	MS	F	P-value	F crit
Clay Source	243.88273	4	60.97068	17.96385834	0.000147	3.47805
BPC Percentage	1323.076445	1	1323.076	389.8194486	2.43E−09	4.964603
Interaction	277.58273	4	69.39568	20.44612523	8.37E−05	3.47805
Within	33.94075	10	3.394075			
Total	1878.482655	19				

The results from **Table 5**: Two-Way ANOVA for 1:2:4 demonstrate the significant effects of Clay Source, BPC Percentage, and their interaction on material properties. The Clay Source factor has a sum of squares (SS) of 243.88, with a mean square (MS) of 60.97, yielding an F-statistic of 17.96 and a P-value of 0.000147, indicating a highly significant impact on the material properties.

The BPC Percentage factor shows an even stronger effect, with SS of 1323.08, MS of 1323.08, F-statistic of 389.82, and a P-value of 2.43E−09, confirming its dominant role in influencing the material's performance. The interaction between Clay Source and BPC Percentage also shows significance, with an SS of 277.58, MS of 69.40, F-statistic of 20.45, and a P-value of 8.37E−05, indicating that the effect of BPC is dependent on the specific clay type.

The Within (error) variation is relatively small (SS of 33.94), suggesting that most of the variability is explained by the factors under study. The total sum of squares (SS = 1878.48) reflects that the model effectively explains the material's performance. These findings underscore the importance of optimizing both clay type and BPC percentage for achieving desired material properties in concrete [28] [29].

In contrast, studies such as [15] and [24] suggest that good pozzolans should generally improve strength across a broader range of dosages, but your results indicate that not all clays meet such universal expectations, especially when used as admixtures rather than replacements. This points to the need for localized characterization before field application.

While this study offers valuable insights into the effects of Clay Source, BPC Percentage, and their interaction on concrete properties, it does have limitations. The analysis was based on only two Clay Sources, which may not fully capture the variability across different types of clay. A wider selection of clay sources could provide a more comprehensive understanding of their effects on concrete performance. Additionally, the study utilized only three specimens per group, potentially limiting the statistical power and generalizability of the results. Expanding the sample size per group would enhance the precision of the findings and reduce the potential impact of variability within the data.

4. Conclusions

This study demonstrates that the geographical source of Chikoko clay plays a statistically significant role in determining the compressive strength of concrete when Burnt Pulverized Chikoko (BPC) is used as an admixture. The strength performance was not solely dependent on the dosage of BPC, but rather on the interaction between source and percentage, as confirmed by two-way ANOVA results. While BPC from both Okrika and Ogbia had pozzolanic potential, the Okrika-sourced clay consistently yielded superior strength values, particularly at 15% admixture, reaching compressive strengths as high as 32.89 MPa. In contrast, Ogbia clay exhibited a declining trend beyond 10% admixture, suggesting lower pozzolanic reactivity or incompatibility with higher dosages.

These findings stressed the critical importance of site-specific evaluation of natural pozzolans. Even within the same regional basin (Niger Delta), mineralogical and chemical differences between clay sources can yield divergent concrete performance profiles. Therefore, standardized field application of clay-based additives without preliminary testing may result in suboptimal or even detrimental outcomes.

From a practical mix-design perspective, field engineers should conduct preliminary tests to determine the suitability of specific clay sources for achieving desired strength. Optimizing the use of BPC admixtures, particularly from sources like Okrika, can not only improve material performance but also contribute to CO_2 reduction goals by reducing reliance on traditional cement, which is a significant emitter of greenhouse gases.

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Conflicts of Interest

The author declares that there is no conflict of interest.

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