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Original Research Article

Screening the Effects of Design Parameters on the Indirect Tensile Strength of Rice Husk Ash–Based Geopolymer-Stabilized Deltaic Clay Soil; A Quarter Fractional Factorial Design Approach

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Abstract

This study evaluates the indirect tensile strength (ITS) of rice husk ash (RHA)-based geopolymer-stabilized deltaic clay soil, characterized by high plasticity (liquid limit 76.5%, plasticity index 35.3%) and low bearing capacity (CBR 3.99%). Using a quarter fractional factorial design with 32 runs, seven key mix parameters were screened: alkaline activator-to-RHA ratio (0.20–0.40), sodium silicate-to-sodium hydroxide ratio (1–3), sodium hydroxide concentration (8–14 M), curing period (4–72 hours), curing temperature (40–120°C), water-to-solid ratio (20–25%), and compaction delay (0–180 minutes). After 28 days curing, ITS ranged from 0.49 to 0.66 MPa, indicating substantial improvement over untreated soil. Effect analysis revealed compaction delay had a significant negative impact on ITS (effect = –0.0869, t = –9.379), while sodium silicate-to-sodium hydroxide ratio (effect = 0.0220, t = 2.381) and sodium hydroxide concentration (effect = 0.0210, t = 2.237) positively influenced strength. Among interactions, only the alkaline activator-to-RHA ratio combined with sodium silicate-to-sodium hydroxide ratio was significant (effect = 0.0230, t = 2.453), highlighting the critical synergy between precursor content and activator composition. These findings underscore the importance of optimizing compaction delay, activator composition, and precursor ratio to enhance geopolymerization and tensile strength through sodium aluminosilicate hydrate (N-A-S-H) gel formation. This research addresses a crucial gap in tensile strength characterization of geopolymer-treated deltaic clays and supports sustainable agro-industrial waste valorization for geotechnical applications.

Keywords: Screening Design, Rice Husk Ash, Quarter Fractional Factorial Design, Deltaic Clay, Indirect Tensile Strength.

1. INTRODUCTION

The increasing demand for sustainable and eco-friendly soil stabilization methods has led to the growing use of agro-industrial wastes as alternatives to conventional binders. Among these, rice husk ash (RHA), a by-product of rice milling rich in amorphous silica, has shown promising potential as a precursor for geopolymer binders (Temuujin *et al.*, 2022). When combined with alkaline activators such as sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3), RHA can form geopolymeric gels composed primarily of sodium aluminosilicate hydrate (N-A-S-H), which improve the strength, stiffness, and durability of weak or expansive soils (Temuujin *et al.*, 2022; Lu *et al.*, 2025). The high silica content of RHA, often exceeding 85%, facilitates pozzolanic reactions and geopolymerization, resulting in strong chemical bonding within the soil matrix (Yip *et al.*, 2021). Several studies have confirmed the effectiveness of RHA-based geopolymers in increasing unconfined compressive strength, reducing swelling potential, and enhancing resistance to moisture-related degradation, especially in clayey or lateritic soils (Kumar & Dutta, 2023; Okoye *et al.*, 2020). Moreover, the use of RHA in soil stabilization aligns with global sustainability goals by diverting agricultural waste from landfills, reducing greenhouse gas emissions associated with cement production, and promoting circular economy practices in geotechnical engineering (Singh *et al.*, 2021; Mekonnen *et al.*, 2024).

Geopolymer technology, especially when derived from agricultural waste materials like rice husk ash (RHA), has been demonstrated to significantly enhance the strength, durability, and microstructural integrity of weak or problematic soils. For instance, Ayodele *et al*. (2024) documented a remarkable increase, up to 1500%, in the unconfined compressive strength (UCS) of tropical residual soils stabilized with RHA-based geopolymers, underscoring its potential as a sustainable soil treatment solution. Similarly, Khanday *et al*. (2021) reported that Indian peat soils treated with RHA geopolymers experienced over a hundred-fold strength improvement, effectively transforming highly compressible and organic soils into structurally reliable subgrade materials. These substantial improvements are primarily attributed to the geopolymerization process, wherein reactive aluminosilicate species in the RHA interact with alkaline activators (e.g., NaOH, Na_2SiO_3) to form cementitious gels, notably sodium aluminosilicate hydrate (N-A-S-H). This gel binds soil particles, fills voids, and significantly reduces porosity, resulting in a denser and more durable soil matrix (Yip *et al*., 2021; Kumar & Dutta, 2023). Furthermore, microstructural analyses using scanning electron microscopy (SEM) and X-ray diffraction (XRD) have confirmed the formation of compact gel phases and crystalline structures within the treated soils, corroborating the performance benefits of RHA-based geopolymers in geotechnical applications (Temuujin *et al*., 2022; Okoye *et al*., 2020).

While extensive literature exists on the compressive behavior of geopolymer-stabilized soils, studies focusing on tensile strength parameters, particularly indirect tensile strength (ITS), remain relatively limited. ITS is a vital mechanical indicator that reflects a material's resistance to cracking and deformation under tensile or lateral stress, conditions frequently encountered in pavement subgrades, embankments, and shallow foundation systems (Lu *et al*., 2025; Okoye *et al*., 2020). Unlike unconfined compressive strength (UCS), which primarily assesses axial load-bearing capacity, ITS provides insight into the soil's cohesion and interparticle bonding, key factors in long-term durability and structural integrity, particularly in cyclic or shrink–swell environments (Singh & Siddique, 2022). The lack of extensive data on ITS therefore represents a critical knowledge gap in fully understanding the mechanical performance of geopolymer-stabilized soils. This limitation is especially pertinent for infrastructure applications where tensile failure governs service life, such as roads exposed to dynamic loading or foundations built on expansive soils (Temuujin *et al*., 2022). A few recent studies have begun to address this, reporting that the development of geopolymeric gels like sodium aluminosilicate hydrate (N-A-S-H) not only contributes to compressive strength but also enhances tensile resistance through improved particle interlocking and reduced microcrack propagation (Kumar & Dutta, 2023; Rahman *et al*., 2021). Nevertheless, a more comprehensive evaluation of ITS behavior across different geopolymer formulations and curing regimes remains a pressing research priority.

Deltaic clay soils, commonly found in coastal and floodplain regions, are typically characterized by high plasticity, low shear strength, and poor bearing capacity. These geotechnical limitations severely restrict their direct use in infrastructure development without appropriate ground improvement techniques. The application of RHA-based geopolymers offers a promising eco-friendly and cost-effective method for enhancing the structural performance of such problematic soils. However, the efficiency of RHA-based geopolymer stabilization depends heavily on a range of mix design variables that influence the geopolymerization reaction and, by extension, the resulting mechanical properties of the treated soil (Temuujin *et al*., 2022; Lu *et al*., 2025). One critical parameter is the alkaline activator-to-RHA ratio (AA/RHA), which governs the dissolution of silica and alumina from the RHA. Optimal AA/RHA ratios (typically in the range of 0.6–1.0) have been shown to enhance gel formation and soil binding, while excessively high ratios may result in leaching and efflorescence (Joseph *et al*., 2021).

Additionally, the sodium silicate-to-sodium hydroxide ratio (SS/SH) plays a vital role in determining the availability of silicate ions, which influence the formation of sodium aluminosilicate hydrate (N-A-S-H) gel. Studies have indicated that SS/SH ratios between 1.5 and 2.5 tend to improve early strength and microstructural integrity of stabilized soils (Kumar & Dutta, 2023). Similarly, the sodium hydroxide concentration (SHc), usually expressed in molarity, affects the pH and dissolution rate of RHA. Concentrations between 8 M and 12 M have been reported as optimal for clayey soils, as higher concentrations may lead to gel over-saturation and microcrack development (Ali *et al*., 2021).

Equally important are curing conditions, particularly the curing period (Cp) and curing temperature (Ct). A longer curing period (e.g., ≥14 days) and elevated temperatures (typically between 40°C and 80°C) accelerate polycondensation reactions, increase the degree of geopolymerization, and lead to denser matrices with improved compressive and tensile strengths (Rahman *et al*., 2021; Mekonnen *et al*., 2024). Furthermore, the water-to-solid ratio (w/s) affects workability and porosity; optimal performance is generally achieved at w/s ratios between 0.3 and 0.5, balancing hydration needs with minimal void formation (Yip *et al*., 2021). Lastly, compaction delay (Dc), the time between mixing and field compaction—can influence the final microstructure. Delays exceeding 30 minutes may reduce strength development due to premature setting or uneven particle bonding (Ayodele *et al*., 2024). Therefore, for deltaic clays stabilized using RHA-based geopolymers, a comprehensive understanding of these design variables is essential to achieving targeted mechanical performance, minimizing environmental impact, and optimizing cost-efficiency in field applications.

Given the complex interactions among multiple design parameters in geopolymer soil stabilization, conducting comprehensive factorial experiments can be prohibitively costly and time-consuming. Such full-factorial designs involve testing every possible combination of variables, which rapidly increases the number of experimental runs as the number of factors grows, leading to significant resource consumption (Montgomery, 2017). To address this challenge, screening experimental designs, particularly quarter fractional factorial designs, offer a more efficient alternative. These designs strategically reduce the number of runs by only investigating a carefully selected subset of factor combinations, while still enabling reliable identification of the most influential parameters and their primary effects (Zhang & Jiang, 2017). The quarter fractional factorial design specifically reduces the experimental runs to one-quarter of those required for a full factorial design without substantially compromising the quality of information obtained about main effects and low-order interactions (Box *et al*., 2005). This approach is especially valuable during the preliminary stages of research, where it facilitates effective prioritization of variables before committing to more detailed and resource-intensive optimization studies such as response surface methodology or central composite designs (Montgomery, 2017; Myers *et al*., 2016). Moreover, fractional factorial designs have been successfully applied in the field of geopolymer and soil stabilization research to streamline experimental efforts and accelerate material development cycles (Singh *et al*., 2021; Rahman *et al*., 2021).

Therefore, this study aims to conduct a quarter fractional factorial screening analysis of selected design parameters affecting the ITS of RHA-based geopolymer-stabilized deltaic clay soils. The key objectives are to identify the most significant variables, quantify their effects on tensile strength, and lay the groundwork for further optimization. This work seeks to contribute to the limited body of knowledge on tensile strength behavior in geopolymer-treated clays, while promoting the valorization of agricultural waste in sustainable geotechnical engineering applications.

2. MATERIALS AND METHODS

2.1 Materials

Materials used in this study include the deltaic clay soil, geopolymer precursor (rice husk ash, RHA), and the activators; sodium hydroxide and sodium silicate.

Deltaic clay soil was obtained from a location on Eagle Island, Port Harcourt, Rivers State, at coordinates 4.7915° N, 6.9758° E. A semi-disturbed soil sample was retrieved using a hand auger from a depth of 1 to 3 meters and stored in nylon bags to maintain its moisture content. The extraction process is presented in Figure 1.

The natural moisture content was recorded at 30.28%, which is characteristic of deltaic clays commonly found in low-lying coastal areas of the Niger Delta. Such high moisture levels contribute to potential volumetric instability due to shrink-swell behavior during seasonal fluctuations, a trend observed in several coastal soil studies (LongJohn & Ayininuola, 2021; Amah, 2015).

The Atterberg limits analysis revealed a liquid limit of 76.5%, plastic limit of 41.2%, and a plasticity index of 35.3%, indicating high plasticity. These values suggest that the soil is highly susceptible to moisture-induced deformation and requires stabilization for engineering applications. This behavior aligns with earlier findings on deltaic marine clays in Nigeria, particularly in the Port Harcourt area, where high plasticity was also reported (Obianyo & Ezeokonkwo, 2021; Xu & Tan, 1987).

Particle size distribution showed 0% gravel, 33% medium-to-coarse sand, 5% fine sand, 52.3% silt, and 9.7% clay. The predominance of fine-grained silt indicates a low-energy depositional environment typical of deltaic zones. This composition implies low shear strength and high compressibility, both of which negatively impact foundation stability unless improved (LongJohn & Ayininuola, 2021; Xu & Tan, 1987).

The mineralogical composition, as determined by oxide content, showed a dominance of silicon oxide (48.80%) and aluminum oxide (42.15%), with minor iron and calcium oxides. These findings suggest the presence of silicate and clay minerals such as quartz and kaolinite, which govern the soil's cohesive and plastic behavior (Gao, Li, Zhang, & Zhou, 2018; Xu & Tan, 1987). Kaolinitic clays, in particular, are known for their high water absorption and moderate swelling characteristics.

The specific gravity of the sample was 2.06, which is relatively low compared to the general range of 2.27–2.72 for mineral soils in the region. This could indicate the presence of lightweight minerals or organic content common in marine or deltaic environments, which may contribute to lower compaction efficiency (Amah, 2015).

Compaction characteristics, including a maximum dry density (MDD) of 1.14 g/cm³ and optimum moisture content (OMC) of 49.25%, further confirm the fine-grained, moisture-retentive nature of the soil. These values are notably lower than typical lateritic or sandy soils, which tend to exhibit higher densities and lower OMCs (LongJohn & Ayininuola, 2021; Gao *et al*., 2018). The high OMC indicates a need for substantial moisture during compaction, while the low MDD limits

its suitability for load-bearing applications unless stabilized.

The California Bearing Ratio (CBR) value was determined to be 3.99%, significantly lower than the typical 5–20% range expected for suitable subgrade materials. This suggests that the soil, in its natural state, lacks adequate strength and would require stabilization to meet construction standards (Amah, 2015; Benedict & McCarthy, 2003).

a. Hand auger for soil extraction **b. Extracted deltaic clay soil**

Figure 1: Extraction of Deltaic Clay soil

Calcined rice husk ash (RHA) was sourced in powdered form from a reliable supplier in Benue State and delivered in 25 kg rice bags. The ash, produced at 450 °C, was sieved, and only particles finer than 75 µm were used for testing (see Figure 2). Chemical analysis revealed that the RHA contains 83.39% SiO_2, 2.13% Al_2O_3, 1.07% CaO, and 1.32% Fe_2O_3. The high silica content classifies RHA as a siliceous pozzolan, aligning with ASTM C618's Class N pozzolan standards. However, the low aluminum content suggests that RHA may require supplementation with an alumina-rich material, such as metakaolin (MK), to achieve an optimal Si/Al ratio for effective geopolymerization (Chindaprasirt & Rattanasak, 2017).

The combined oxide content ($SiO_2 + Al_2O_3 + Fe_2O_3$) was 86.84%, surpassing the ASTM C618 minimum of 70% required for pozzolanic classification. This confirms RHA's suitability for geopolymer applications. Additionally, its specific gravity of 2.07 indicates a low particle density, which can enhance workability and reduce the overall weight of geopolymer composites, beneficial for lightweight applications without significantly compromising strength (Kumar & Kumar, 2011).

Figure 2: Prepared Rice Husk Ash (RHA)

Commercial-grade sodium hydroxide flakes (3 mm, 98% purity, specific gravity 2.13) and sodium silicate powder (98% purity, specific gravity 1.27) were both procured from H-Chemicals Ltd, Port Harcourt. These were used to prepare alkaline activators for the RHA-based geopolymer. The sodium hydroxide solution was made by dissolving flakes in water, with concentration adjusted according to the experimental molarity. Sodium silicate solution was prepared by mixing silicate powder with water in a 70:30 ratio, yielding a final specific gravity of 1.6.

2.2 Methods

The methodology began with the development of a quarter fractional factorial design (QFFD) for screening key variables. Based on this design, RHA-based geopolymer-stabilized clay samples were prepared accordingly. The screening experiment assessed the indirect tensile strength (ITS) after 28 days of membrane curing. Subsequently, the main and interaction effects of the selected mix design parameters were evaluated through two approaches: manual effect and t-statistics computation, to determine their statistical significance.

2.2.1 Screening Design- Quarter Fractional Factorial Design

In constructing the quarter fractional factorial design (Q-FFD), seven key factors were identified as influencing the behavior of RHA-based geopolymer-treated deltaic clay soil. These factors included: the alkaline activator-to-RHA ratio (AA/RHA), sodium silicate-to-sodium hydroxide ratio (SS/SH), sodium hydroxide concentration (SHc), curing period (Cp), curing temperature (Ct), water-to-solid ratio (w/s), and compaction delay (Dc). Preliminary data such as the maximum dry density (MDD) and optimum moisture content (OMC) of untreated deltaic soil informed the design framework. The AA/RHA ratio was set within the range of 0.20–0.40, SS/SH between 1 and 3, and SHc from 8M to 14M. The curing period (Cp) varied from 4 to 72 hours, curing temperature (Ct) ranged from 40°C to 120°C, and compaction delay (Dc) was set between 0 and 180 minutes. The water-to-solid ratio (w/s) was based on the OMC of the untreated soil but adjusted to reflect the incorporation of additional binder materials, and thus ranged from 20% to 25%, approximately half of the initial OMC value. The Q-FFD for the seven factors, with a resolution IV design (2^{7-2}), resulted in 32 experimental runs, as outlined in Table 1 produced with the aid of Minitab software.

Table 1: Q-FFD of RHA Based Geopolymer stabilized Deltaic Soil for Screening Experiments

Experimental Run	AA/SM	SS/SH	SHc (M)	Cp (hrs)	Ct (^{O}C)	w/s	Dc (mins)
1	0.2	1	8	72	120	20	180
2	0.4	1	8	4	120	20	180
3	0.4	3	14	72	120	25	180
4	0.2	3	14	4	120	25	180
5	0.2	3	14	72	40	20	180
6	0.4	1	8	72	120	25	0
7	0.4	1	14	72	40	20	180
8	0.2	3	8	72	120	25	0
9	0.2	1	8	4	40	25	180
10	0.4	1	14	72	120	20	0
11	0.4	3	8	72	40	20	0
12	0.4	3	14	72	40	25	0
13	0.2	1	8	72	40	20	0
14	0.4	1	14	4	120	25	180
15	0.2	3	8	4	40	20	0
16	0.2	1	14	4	120	20	0
17	0.2	1	8	4	120	25	0
18	0.4	1	14	4	40	25	0
19	0.2	3	14	72	120	20	0
20	0.4	3	8	72	120	20	180
21	0.4	3	14	4	40	20	180
22	0.2	3	8	4	120	20	180
23	0.4	3	8	4	120	25	0
24	0.2	1	14	72	40	25	0
25	0.2	1	14	72	120	25	180
26	0.2	3	8	72	40	25	180
27	0.4	1	8	4	40	20	0
28	0.4	3	8	4	40	25	180
29	0.2	1	14	4	40	20	180
30	0.4	3	14	4	120	20	0
31	0.2	3	14	4	40	25	0
32	0.4	1	8	72	40	25	180

2.2.2 Preparation of RHA Based Geopolymer Stabilized Clay Soil Samples

To activate the geopolymer source materials, an alkaline solution was prepared by mixing sodium hydroxide (SH) and sodium silicate (SS) solutions. The SH solution was formulated by dissolving sodium hydroxide flakes in water, with the solid content adjusted according to the molarity specified in the Q-FFD. For instance, an 8M solution required 320 g of NaOH per liter, based on its molecular weight of 40. The SS solution was prepared by mixing silicate powder with water at a fixed ratio of 70:30. Both solutions were allowed to equilibrate for 24 hours before use. During soil preparation, the maximum dry density (MDD) served as a reference for compaction. Geopolymer-treated deltaic clay samples were then produced, incorporating a fixed 4-hour rest period before curing in a temperature-controlled oven. The curing temperature was varied according to the experimental design parameters outlined in the Q-FFD.

2.2.3 Indirect Tensile Strength (ITS) Testing of Geopolymer Treated Soil Samples

The indirect tensile strength (ITS) of the geopolymer-treated deltaic clay was determined using the split-cylinder method, following the guidelines of ASTM C496/C496M-11 (2011). The test was conducted on cylindrical specimens measuring 50 mm in diameter and 100 mm in height. During the test, a diametral compressive load was applied until failure, inducing tensile stress along the vertical diameter of the sample. The ITS was then calculated using the standard equation provided in ASTM C496 (Equation 1), which relates the applied load to specimen dimensions.

$$\sigma_t = \frac{2P}{\pi D t} \qquad (1)$$

Where; P is the tensile failure load, D is the diameter or width of the stabilized deltaic soil specimen and t represents the thickness.

2.2.4 Mix Design Parameter or Factor Effect and Significance Analysis

a. Effect Computations

In the computation of effects for screening analysis, emphasis is placed solely on main (individual) effects and two-way interaction effects, as these are considered the most critical in preliminary experimental investigations. Higher-order interactions (e.g., three-way or more) are generally aliased with lower-order effects in fractional factorial designs and are therefore not interpreted independently (Montgomery, 2017). Table 2 presents the quarter fractional factorial design (Q-FFD) using high (+1) and low (–1) coded levels, illustrating only the main and two-way interaction effects of the seven selected factors, as denoted by the corresponding alphabets. The magnitude of these effects was then computed using Equation (2), which estimates the average influence of each factor and interaction on the ITS.

$$Main\ effect\ of\ factor = \frac{\sum_{i=1}^{i=n} Y_{Hi} - \sum_{i=1}^{i=n} Y_{Li}}{n} \quad (2a)$$

$$Interaction\ effect\ of\ factors = \frac{\sum_{i=1}^{i=n} Y_{Hij} - \sum_{i=1}^{i=n} Y_{Lij}}{n} \quad (2b)$$

Where; Y_{Hi} = ITS value associated with the high level of factor i,
Y_{Li} = ITS value associated with the low level of factor i,
Y_{Hij} = ITS value associated with the high level for the two-way interactions between factors i and j,
Y_{Lij} = ITS value associated with the low level for the two-way interactions between factors i and j,
n = number of experimental runs associated with the high and low levels = 16

Table 2: Q-FFD in terms of Highs and Lows of Factors and their Two-way Interactions

A	B	C	D	E	F	G	AB	AC	AD	AE	AF	AG	BC	BD	BE	BF	BG	CD	CE	CF	CG	DE	DF	DG	EF	EG	FG
-1	-1	-1	1	1	-1	1	1	1	-1	-1	1	-1	1	-1	-1	1	-1	-1	-1	1	-1	1	-1	1	-1	1	-1
1	-1	-1	-1	1	-1	1	-1	-1	-1	1	-1	1	1	1	-1	1	-1	1	-1	1	-1	-1	1	-1	-1	1	-1
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
-1	1	1	-1	1	1	1	-1	-1	1	-1	-1	-1	1	-1	1	1	1	-1	1	1	1	-1	-1	-1	1	1	1
-1	1	1	1	-1	-1	1	-1	-1	-1	1	1	-1	1	1	-1	-1	1	1	-1	-1	1	-1	-1	1	1	-1	-1
1	-1	-1	1	1	1	-1	-1	-1	1	1	1	-1	1	-1	-1	-1	1	-1	-1	-1	1	1	1	-1	1	-1	-1
1	-1	1	1	-1	-1	1	-1	1	1	-1	-1	1	-1	-1	1	1	-1	1	-1	-1	1	-1	-1	1	1	-1	-1
-1	1	-1	1	1	1	-1	-1	1	-1	-1	-1	1	-1	1	1	1	-1	-1	-1	-1	1	1	1	-1	1	-1	-1
-1	-1	-1	-1	-1	1	1	1	1	1	1	-1	-1	1	1	1	-1	-1	1	1	-1	-1	1	-1	-1	-1	-1	1
1	-1	1	1	1	-1	-1	-1	1	1	1	-1	-1	-1	-1	-1	1	1	1	1	-1	-1	1	-1	-1	-1	-1	1
1	1	-1	1	-1	-1	-1	1	-1	1	-1	-1	-1	-1	1	-1	-1	-1	-1	1	1	1	-1	-1	-1	1	1	1
1	1	1	1	-1	1	-1	1	1	1	-1	1	-1	1	1	-1	1	-1	1	-1	1	-1	-1	1	-1	-1	1	-1
-1	-1	-1	1	-1	-1	-1	1	1	-1	1	1	1	1	-1	1	1	1	-1	1	1	1	-1	-1	-1	1	1	1
1	-1	1	-1	1	1	1	-1	1	-1	1	1	1	-1	1	-1	-1	-1	-1	1	1	1	-1	-1	-1	1	1	1
-1	1	-1	-1	-1	-1	-1	-1	1	1	1	1	1	-1	-1	-1	-1	-1	1	1	1	1	1	1	1	1	1	1
-1	-1	1	-1	1	-1	-1	1	-1	1	-1	1	1	-1	1	-1	1	1	-1	1	-1	-1	-1	1	1	-1	-1	1
-1	-1	-1	-1	1	1	-1	1	1	1	-1	-1	1	1	1	-1	-1	1	1	-1	-1	1	-1	-1	1	1	-1	-1
1	-1	1	-1	-1	1	-1	-1	1	-1	-1	1	-1	-1	1	1	-1	1	-1	-1	1	-1	1	-1	1	-1	1	-1
-1	1	1	1	1	-1	-1	-1	-1	-1	-1	1	1	1	1	1	-1	-1	1	1	-1	-1	1	-1	-1	-1	-1	1
1	1	-1	1	1	-1	1	1	-1	1	1	-1	1	-1	1	1	-1	1	-1	-1	1	-1	1	-1	1	-1	1	-1
1	1	1	-1	-1	-1	1	1	1	-1	-1	-1	1	1	-1	-1	-1	1	-1	-1	-1	1	1	1	-1	1	-1	-1
-1	1	-1	-1	1	-1	1	-1	1	1	-1	1	-1	-1	-1	1	-1	1	1	-1	1	-1	-1	1	-1	-1	1	-1
1	1	-1	-1	1	1	-1	1	-1	-1	1	1	-1	-1	-1	1	1	-1	1	-1	-1	1	-1	-1	1	1	-1	-1
-1	-1	1	1	-1	1	-1	1	-1	1	1	-1	1	-1	1	1	-1	1	-1	-1	1	-1	1	-1	1	-1	1	-1
-1	-1	1	1	1	1	1	1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	1	1	1	1	1	1	1	1	1	1
-1	1	-1	1	-1	1	1	-1	1	-1	1	-1	-1	-1	1	-1	1	1	-1	1	-1	-1	-1	1	1	-1	-1	1
1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

A	B	C	D	E	F	G	AB	AC	AD	AE	AF	AG	BC	BD	BE	BF	BG	CD	CE	CF	CG	DE	DF	DG	EF	EG	FG
1	1	-1	-1	-1	1	1	1	-1	-1	-1	1	1	-1	-1	-1	1	1	1	1	-1	-1	1	-1	-1	-1	-1	1
-1	-1	1	-1	-1	-1	1	1	-1	1	1	1	-1	-1	1	1	1	-1	-1	-1	-1	1	1	1	-1	1	-1	-1
1	1	1	1	1	-1	-1	1	1	1	1	-1	-1	1	1	1	-1	-1	1	1	-1	-1	1	-1	-1	-1	-1	1
-1	1	1	-1	-1	1	-1	-1	-1	1	1	-1	1	1	-1	-1	1	-1	-1	-1	1	-1	1	-1	1	-1	1	-1
1	-1	-1	-1	-1	1	1	-1	-1	-1	-1	1	1	1	1	1	-1	-1	1	1	-1	-1	1	-1	-1	-1	-1	1

b. Factors Significance Analysis

The significance of all main effects and two-way interactions was evaluated by comparing the calculated t-values against the critical t-value at a 95% confidence level. The calculated t-values were derived using Equation (3), which quantifies the statistical significance of each effect relative to experimental variability.

$$t_i = \frac{Effect_i}{SE} \quad (3)$$

Where, t_i = calculated t-statistics for factor i.
$Effect_i$ = effect of factor i
S.E = standard error for considered factors, which is computed as presented in Equation (4)

$$S.E = \frac{standard\ deviation\ of\ response\ variable}{\sqrt{n}} \quad (4)$$

A factor or interaction is considered statistically significant if its calculated t-value exceeds the critical value of 2.13, corresponding to a 95% confidence level with 4 degrees of freedom. The degrees of freedom were determined by subtracting the number of estimated parameters (28) from the total experimental runs (32), following standard statistical procedures.

3. RESULTS AND DISCUSSION

3.1 Indirect Tensile Strength (ITS) of RHA-Based Geopolymer Stabilized Clay Soil

Figure 3 presents the indirect tensile strength (ITS) outcomes for RHA-based geopolymer-stabilized deltaic clay soil, as part of a screening effort to identify the most influential factors and interactions among the seven selected mix parameters. The ITS values observed ranged from 0.49 MPa to 0.66 MPa, indicating a measurable improvement in tensile resistance compared to untreated deltaic soils.

These ITS values are consistent with other studies employing rice husk ash as a pozzolanic additive or geopolymer precursor, where RHA incorporation improved the mechanical performance of soils and concrete composites (Kumar & Kumar, 2011; Chindaprasirt & Rattanasak, 2017). The moderate strength enhancement reflects the effectiveness of the alkaline activation process and highlights the importance of optimizing factors such as activator ratios, curing conditions, and moisture content.

The observed ITS range underscores the variability introduced by the different levels of the mix parameters within the quarter fractional factorial design. Similar research on stabilized clay soils has reported ITS improvements in the range of 0.4 to 0.7 MPa when stabilized with pozzolanic or geopolymer materials (Amah, 2015; Akinrinade *et al.*, 2021). These values suggest that RHA-based geopolymer treatment can significantly enhance the tensile strength and durability of problematic deltaic soils, making them more suitable for construction applications.

However, the relatively narrow ITS range also suggests that the interaction effects between factors may play a crucial role, emphasizing the need for detailed factorial analysis and optimization to achieve maximum performance benefits. Understanding the individual and combined influences of curing time, temperature, activator concentration, and water content is critical for tailoring geopolymer stabilization to specific site conditions (Montgomery, 2017)

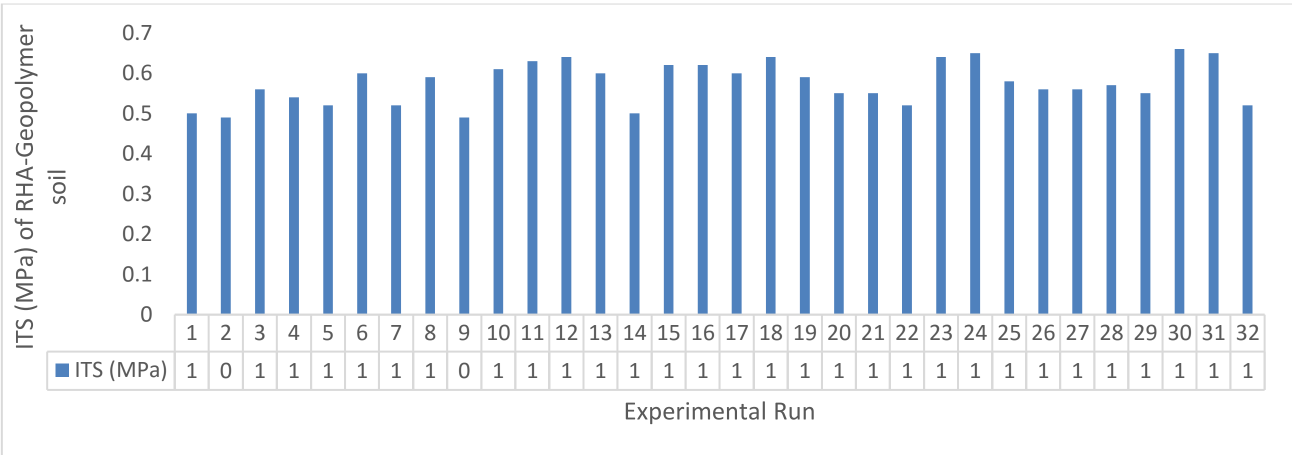

Figure 3: ITS Results of Geopolymer Stabilized Clay Soil

3.2 Effect of Factors or Mix Design Parameters and Interactions on the ITS of RHA Based Geopolymer Stabilized Clay Soil (Screening Effect Analysis)

3.2.1 Individual or Main Effect Analysis

Figures 4 and 5 present the results of the manual screening and statistical significance analyses, respectively, evaluating the influence of seven individual mix design parameters on the Indirect Tensile Strength (ITS) of RHA-based geopolymer-stabilized deltaic clay. The effect values were first ranked to assess directional impact, followed by t-statistical evaluation to determine the significance of each factor using a 95% confidence level and a critical t-value of 2.13 (based on 4 degrees of freedom).

Among the evaluated parameters, compaction delay (Dc) had the most pronounced main effect, with a large negative effect value (–0.0869) and a corresponding t-value of –9.379. These results underscore the detrimental impact of delayed compaction on tensile strength, likely due to premature setting, water loss, or early gelation that reduces particle bonding and densification. Prior studies support this conclusion, emphasizing that immediate or timely compaction is essential to achieving optimal geopolymer microstructure and mechanical performance (Obianyo & Ezeokonkwo, 2021; Akinrinade *et al*., 2021).

Following Dc, the sodium silicate to sodium hydroxide ratio (SS/SH) exhibited a positive effect value of 0.0220 and a t-value of 2.381, confirming its statistical significance. Increasing the SS/SH ratio enhances ITS by providing additional soluble silica that promotes the formation of aluminosilicate gels, which are critical for matrix integrity and tensile capacity (Chindaprasirt & Rattanasak, 2017; Malkawi *et al*., 2022). However, excessively high or low ratios can disrupt workability or hinder proper gelation, so maintaining a balanced ratio is key to optimizing strength.

The sodium hydroxide concentration (SHc) also showed a positive effect value (0.0210) and a significant t-value of 2.237, suggesting that higher NaOH molarity improves ITS by accelerating the dissolution of reactive silica and alumina in the RHA. This promotes efficient geopolymerization and strengthens the soil matrix. Nonetheless, the literature cautions that overly high molarity levels may introduce brittleness or reduce workability (Kumar & Kumar, 2011; Temuujin *et al*., 2010), underscoring the need for balance within the optimal range.

In contrast, the remaining factors, alkaline activator to RHA ratio (AA/RHA), curing period (Cp), curing temperature (Ct), and water-to-solid ratio (w/s), exhibited relatively minor effect values and t-statistics below the 2.13 threshold. This renders them statistically insignificant in terms of direct influence on ITS within the tested design space. While these factors are known to influence properties such as setting time, compressive strength, and long-term durability (Chindaprasirt *et al*., 2017), their impact on tensile performance appears less dominant in this phase of analysis.

In summary, the combined effect ranking and t-statistical evaluation confirm that Dc, SS/SH, and SHc are the most influential and statistically significant parameters affecting the ITS of RHA-geopolymer stabilized deltaic soil. These factors are therefore to be prioritized for further investigation and optimization of RHA based geopolymer stabilized deltaic clay soil.

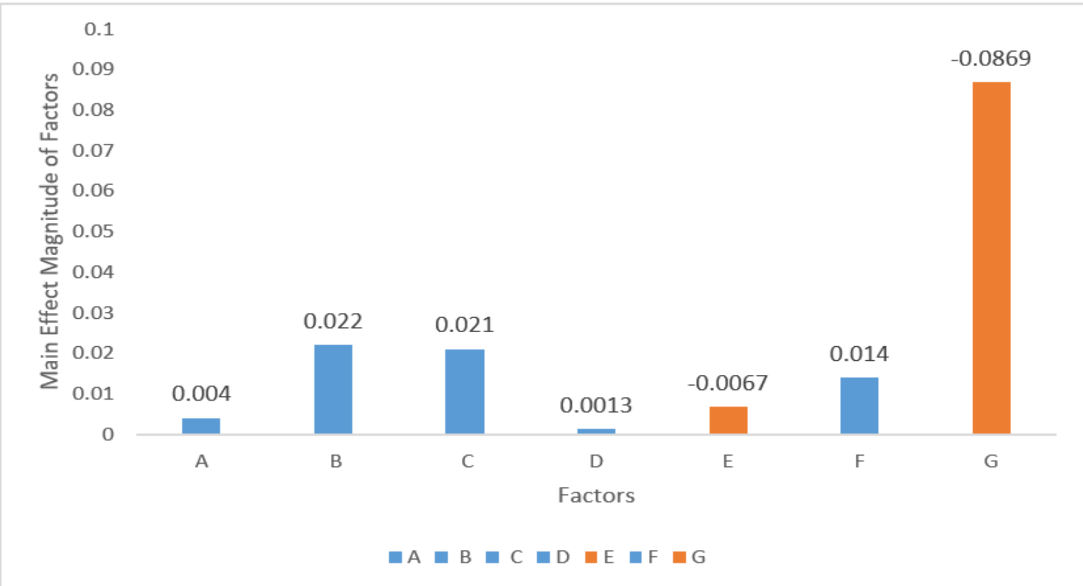

Figure 4: Main or Individual Effect of Factors on Mean ITS

A = AA/RHA; B= SS/SH; C = SHc; D = Cp; E = Ct; F = w/s; G = Dc

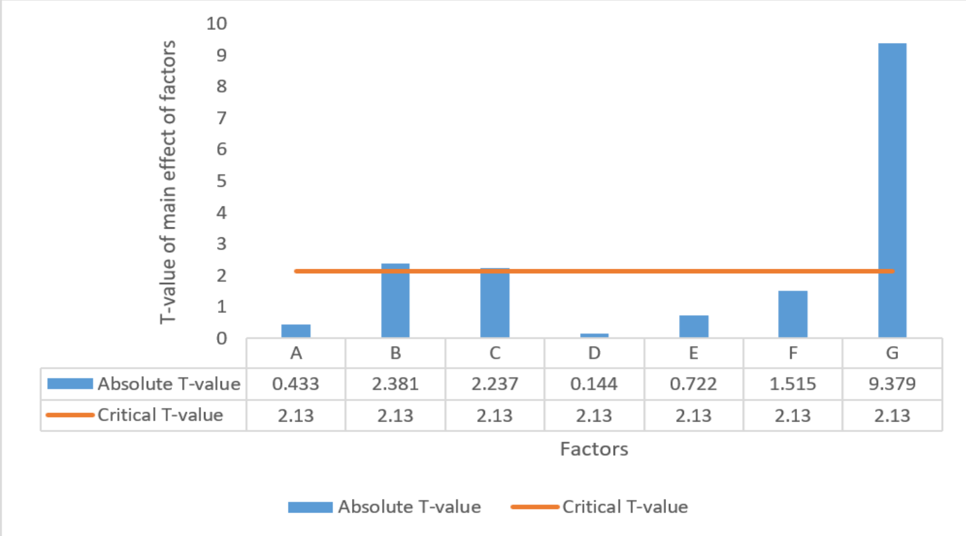

Figure 5: Significance of Main Factor Effect on Mean ITS

A = AA/RHA; B= SS/SH; C = SHc; D = Cp; E = Ct; F = w/s; G = Dc

3.2.2 Interaction Effect Analysis

Figures 6 and 7 present a comprehensive manual screening analysis of two-way interaction effects among key mix design parameters affecting the Indirect Tensile Strength (ITS) of Rice Husk Ash (RHA)-geopolymer stabilized deltaic clay soil. Derived using Equation 2, the analysis explores both the magnitude and statistical significance of interaction effects to establish a robust basis for mix optimization. While Figure 6 ranks the interaction effects based on their absolute values, Figure 7 complements this by evaluating the statistical significance of these effects using the t-statistic, with a critical threshold of 2.13 set at the 95% confidence level.

The most dominant interaction, based on both magnitude and statistical significance, is that between the alkaline activator-to-RHA ratio (AA/RHA) and the sodium silicate-to-sodium hydroxide ratio (SS/SH), which recorded an effect value of 0.0230 and a t-value of 2.453. This makes it the only statistically significant interaction among those evaluated. The strength of this synergy suggests that a well-balanced combination of precursor content and activator chemistry significantly improves geopolymer matrix development, particularly in terms of gel structure and strength acquisition. According to Malkawi *et al*. (2023), the Na_2SiO_3/NaOH ratio influences both the silicate availability and viscosity of the activator, while the AA/RHA ratio governs the extent of reactive aluminosilicate input. The interplay between these two parameters facilitates optimal gel formation, thereby enhancing ITS. Temuujin *et al*. (2011) similarly noted that maximizing the chemical reactivity between activators and precursors leads to denser microstructures and improved mechanical properties in geopolymer systems.

The statistical significance of the AA/RHA × SS/SH interaction also reveals that factors involved in significant interactions must be retained, even if their individual effects are not independently significant. This viewpoint is strongly supported by Wu and Hamada (2011), who emphasized the importance of including such interaction-involved variables in further analysis and optimization to avoid model under-specification.

Other interactions evaluated showed varying degrees of influence based on effect values, although they did not meet the statistical significance threshold. For instance, the interaction between sodium hydroxide concentration (SHc) and curing period (Cp) exhibited the second-highest magnitude, with an effect value of 0.0171, suggesting that longer curing times can amplify the polymerization benefits of alkaline activation. Olajide *et al*. (2023) observed similar outcomes, showing that extended curing supports continued gel formation and densification of the matrix, particularly under favorable alkaline conditions.

The next strongest interaction was between SHc and curing temperature (Ct), with an effect value of 0.0124. Although statistically insignificant ($t < 2.13$), this pairing aligns with the well-documented principle that elevated temperatures accelerate dissolution and polycondensation in geopolymer systems. Zawrah *et al*. (2020) confirmed that thermal curing improves early-age strength development due to the activation of faster geopolymerization kinetics in highly alkaline environments.

An interesting negative interaction was observed between compaction delay (Dc) and curing temperature (Ct), with an effect value of –0.0116. The inverse relationship implies that delayed compaction under elevated temperatures may compromise the microstructure due to premature setting or moisture loss. Similar degradation in performance due to delayed compaction was reported by Abdullah *et al*. (2022), who noted that such delays hinder workability and reduce strength gains in geopolymer concrete.

The curing period (Cp) and curing temperature (Ct) interaction ranked fifth in terms of magnitude (0.0095), underscoring the cumulative effect of heat and time in advancing geopolymeric reactions. El Didamony *et al*., (2020) validated this behavior by showing that longer thermal curing enhances the rate and completeness of gel network formation, thereby improving mechanical performance.

The interaction between AA/RHA and SHc (effect = 0.0077) also indicated a modest positive influence. This reinforces the importance of pairing appropriate precursor dosage with alkaline concentration, as excessive SHc without enough reactive material can lead to gel instability. Malkawi *et al*., (2023) emphasized that such imbalances can result in weak binding phases and reduced strength.

A further negative effect was observed in the interaction between AA/RHA and compaction delay (Dc), which recorded an effect value of –0.0068. High AA/RHA ratios combined with compaction delays can lead to premature stiffening, making densification ineffective. Davidovits (2015) warned against premature setting, stating it compromises internal bonding and can introduce microstructural flaws that degrade long-term performance.

Lastly, the interaction between SS/SH and SHc recorded the lowest effect value (0.0061) and was also statistically insignificant. Although both parameters are crucial individually for determining the chemistry of the activator system, their joint influence appeared minimal within the evaluated design space. This observation aligns with Malkawi *et al*., (2023), who found that variations in SS/SH and SHc tend to independently influence different properties, such as setting time and workability, rather than ITS.

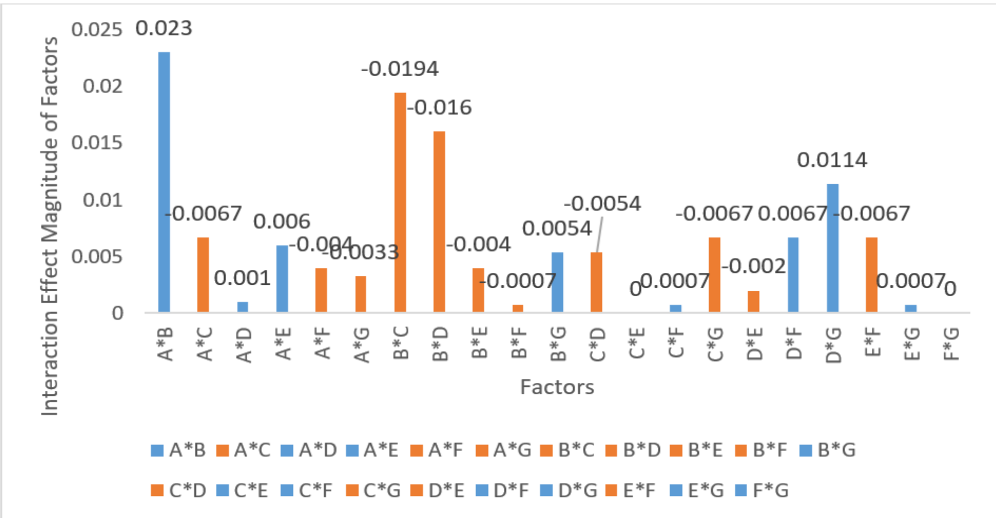

Figure 6: Magnitude of Interaction Effect of Factors on Mean ITS

A = AA/RHA; B= SS/SH; C = SHc; D = Cp; E = Ct; F = w/s; G = Dc

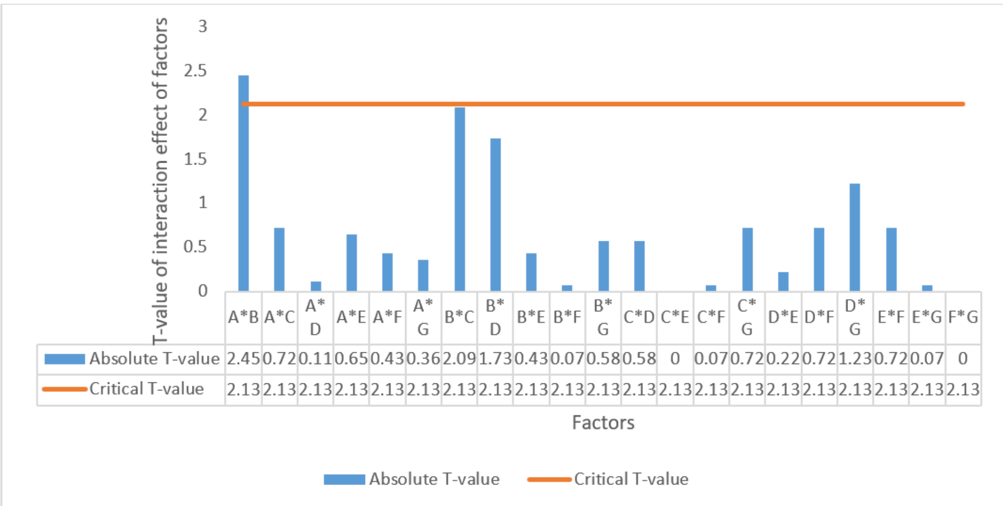

Figure 7: Significance of Interaction Effect of Factors on Mean ITS

A = AA/RHA; B= SS/SH; C = SHc; D = Cp; E = Ct; F = w/s; G = Dc

4. CONCLUSION

This study investigated the indirect tensile strength (ITS) behavior of rice husk ash (RHA)-based geopolymer stabilized deltaic clay soil using a quarter fractional factorial screening approach to identify critical mix parameters and interaction effects. Through experimental testing and manual effect analysis, supported by t-statistical evaluation, the following conclusions were drawn;

I. The indirect tensile strength (ITS) of RHA-geopolymer stabilized deltaic clay soil ranged from 0.49 MPa to 0.66 MPa, indicating a notable improvement over untreated soil. This enhancement confirms the effectiveness of geopolymerization using rice husk ash and alkaline activators in boosting tensile resistance. The results support the suitability of this method for stabilizing problematic soils.

II. Compaction delay (Dc) was identified as the most critical factor, exerting a strong negative impact on ITS due to premature setting and moisture loss. This undermines the densification process, leading to reduced tensile strength. In contrast, both the sodium silicate-to-sodium hydroxide ratio (SS/SH) and sodium hydroxide concentration (SHc) showed positive effects on ITS. Their influence is linked to improved silica availability and enhanced dissolution of reactive materials, which support gel formation and matrix strength.

III. Among the two-way interactions analyzed, only the combination of alkaline activator-to-RHA ratio (AA/RHA) and sodium silicate-to-sodium hydroxide ratio (SS/SH) was statistically significant, highlighting its key role in optimizing the geopolymer matrix. This significant synergy underscores the need to balance precursor content with activator composition to maximize tensile strength.

IV. Optimization efforts should focus on both the main effects and significant interaction effects identified in the analysis. The four key factors to prioritize are compaction delay (Dc), sodium silicate to sodium hydroxide ratio (SS/SH), sodium hydroxide concentration (SHc), and alkaline activator to RHA ratio (AA/RHA). Although AA/RHA was not significant as a main effect, its important interaction with SS/SH warrants its inclusion in optimization. Addressing these factors together will enable more effective enhancement of the ITS performance of RHA-based geopolymer stabilized soils.

V. This study highlights that RHA-based geopolymer stabilization offers a sustainable and effective solution for improving the mechanical properties of challenging clay soils. To maximize tensile strength, it is crucial to optimize not only individual factors but also their interactions, especially those affecting early setting and gel formation. Careful control of curing and compaction conditions is essential to achieving a durable and cohesive soil matrix.

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