SUSTAINABLE MATERIALS AND INNOVATIONS IN CONSTRUCTION ENGINEERING

EDITOR

Benyahia AMAR

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PREFACE

This book presents a multidisciplinary exploration of natural and engineered materials, each chapter offering practical insights into optimizing resources for industrial and infrastructural advancement. From plant biochemistry to geotechnical innovation, the topics reflect a shared commitment to sustainability and performance enhancement.

The first half focuses on biological and material sciences: optimizing plant secondary metabolites for industrial use, and improving concrete mix designs using river sand to meet modern construction demands. These chapters highlight how thoughtful design and scientific precision can elevate everyday materials into high-value solutions.

The latter chapters shift to ceramic and geotechnical applications, examining the role of clay in sanitary ware production and the use of moorum overlays to strengthen cohesive subgrades. Together, these studies underscore the power of local materials and smart engineering to drive cost-effective, durable outcomes across industries.

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CHAPTER 1
PLANT SECONDARY METABOLITES AND THEIR METABOLIC OPTIMIZATION FOR INDUSTRIAL APPLICATIONS

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INTRODUCTION

The restoration of historic masonry structures requires mortars that are chemically and physically compatible with original materials, while also meeting modern sustainability goals. This challenge is particularly relevant in Algeria, where numerous historical structures from ancient Roman ruins to Islamic and Ottoman architecture, as well as buildings from the French colonial period are facing significant degradation (Figures 1 and 2).

Figure 1. Concrete of the Oued Fodda dam (Orleans-Ville, Algeria)

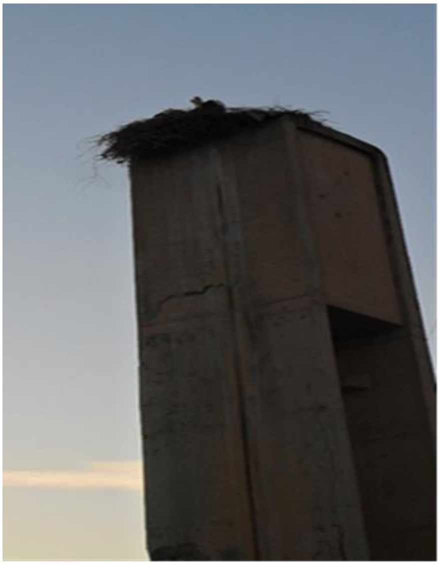

Figure 2. Water tower of the old churchof Oued Fodda (Orleans-Ville, Algeria)

These structures often suffer from material weathering, surface erosion, salt crystallization, biological growth, and structural instability. Many colonial-era buildings, constructed during the 19th and early 20th centuries using lime-based mortars and locally sourced stone or brick, are now deteriorating due to urban pollution, climate-related stresses, and the use of incompatible modern repair materials in past restoration efforts. Given the urgency to preserve this layered architectural heritage, the development of compatible and sustainable restoration materials is essential.

Traditional cement production is highly energy-intensive and a significant source of CO_2 emissions, motivating the search for supplementary cementitious materials (SCMs) derived from industrial or construction waste. In this context, ceramic waste such as crushed bricks, tiles, and pottery has emerged as a promising partial replacement for cement or aggregate in restoration mortars. Reviews of ceramic-added air lime mortars report that finely ground ceramic materials react pozzolanically with calcium hydroxide, forming calcium silicate hydrate (C–S–H) and calcium aluminate hydrate (C–A–H), enhancing hydraulic properties, durability, and compatibility with historic masonry (Yue and Wang 2024). Matias et al. (2018) demonstrated that incorporating milled ceramic residues (red and white ceramics) into air-lime mortars at up to 20% replacement of sand retained or even improved flexural and compressive strengths, water vapor permeability, and workability confirming suitability for heritage applications. A study on lime–cement plasters reported that replacing cement with ceramic dust significantly increased compressive strength by more than threefold, while maintaining acceptable hygrothermal performance, highlighting the environmental and performance benefits of ceramic additions. Broader reviews found that substituting up to 30% of cement with finely ground ceramic waste powder in cementitious composites can improve compressive strength and durability, thanks to pozzolanic and filler effects that densify the matrix (Özkılıç et al. 2025). Finally, experimental concrete studies confirm that modest ceramic dust substitutions (e.g., 5–10%) can enhance early-age compressive strength and refine microstructure particularly with finer particle sizes though higher replacement levels may reduce strength (Ghonaim & Morsy 2023).

The aim of this study is to evaluate the feasibility of using SCWP as a partial replacement for cement in cement–lime mortar formulations, specifically for use in the repair and restoration of old buildings. Mortars were prepared with 0%, 10%, 20%, 25%, and 30% ceramic waste replacement levels by weight of cement. Their fresh and hardened properties including slump flow, dry density, compressive strength, and bond strength were evaluated. The results contribute to the development of eco-efficient, compatible mortars suitable for heritage conservation applications.

1. EXPERIMENTAL

To investigate the performance of cement-lime mortars incorporating SCWP, the following materials were used:

Ordinary Portland Cement (OPC) conforming to EN 197-1 was used as the primary binder in the mortar mixes. It was grey in color, with a specific gravity of approximately 3.15 and a Blaine fineness of 320–350 m^2/kg.

Hydrated Lime

Commercially available hydrated lime (calcium hydroxide, $Ca(OH)_2$), compliant with EN 459-1 CL90-S, was used to improve the workability and compatibility of the mortar with historic masonry substrates.

Sanitary Ceramic Waste Powder (SCWP)

Recycled SCWP was sourced from broken red bricks and ceramic tiles discarded from construction and demolition activities. The waste was manually sorted to remove contaminants, crushed using a jaw crusher, and further milled to a fine powder passing through a 63 μm sieve. The chemical composition was determined via X-ray fluorescence (XRF), indicating a high silica and alumina content, suitable for pozzolanic activity. The chemical composition of the raw materials are listed in Table 1.

Table 1. Chemical composition of the dry cement, Lime and ceramic powder

Oxides	Cement (wt.%)	Lime (wt.%)	SCWP (wt.%)
SiO_2	23.5	0.05	72.6
Al_2O_3	5.8	0.01	23.2
Fe_2O_3	4.1	0.2	1.3
CaO	65	74.1	4.7
MgO	3	0.35	1.6
SO_3	2.8	0.02	--
K_2O	1.2	--	3.6
Na_2O	0.6	--	3.0
L.O.I	2.3	23.3	2.54

a)) Ceramic waste

b) Recycled ceramic powder

Figure 3. SCWP used

Fine Aggregate

Natural river sand was used as the fine aggregate. The sand was well-graded, clean, and free from organic impurities, with a maximum particle size of 1 mm. Sieve analysis confirmed compliance with ASTM C144 grading limits for masonry mortars.

Water

Tap water conforming to ASTM C1602 standards was used for all mixing and curing processes.

Mix Proportions

Five mortar mixes were prepared, with SCWP replacing cement at proportions of 0% (control), 10%, 20%, 25%, and 30% by weight. All mixes maintained a constant binder\sand ratio of 1:3 by weight and a fixed lime content of 20% of the total binder. The water-to-binder ratio was adjusted to achieve comparable flowability among mixes.

Table 2. Mix proportions of

Mix ID	Cement	Lime	Ceramic	Sand	Water
M0	175	250	0	980	212.5
M10	157.5	250	17.5	980	212.5
M20	140	250	35	980	212.5
M25	131.25	250	43.75	980	212.5
M30	122.5	250	52.50	980	212.5

Mixing and Sample Preparation

All mortar mixes were prepared in a laboratory pan mixer. Dry materials (cement, lime, ceramic waste, and sand) were first blended for 2 minutes to ensure uniform distribution. Water was then gradually added, and mixing continued for an additional 3–5 minutes until a homogeneous mix was obtained.

2. TESTS AND METHODS

The workability of fresh SCWP is determined using the flow table method as described in EN 1015-3. To evaluate the dry bulk density of hardened mortar, EN 1015-10 is used, which involves drying specimens and measuring their volume to calculate density. The mechanical strength (compressive strength) of SCWP, is tested under EN 1015-11, involving bending and compression procedures on prepared prisms. Drying shrinkage of SCWP is a critical parameter that influences dimensional stability and long-term performance, especially in restoration applications. To assess this property, the most commonly referenced standard is EN 12617-4, which measures the linear shrinkage of hardened mortars under controlled environmental conditions. This test captures the development of shrinkage from the early ages typically starting after demolding and continuing through 1, 7, 15, and 28 days allowing for the evaluation of both initial and progressive deformation over time.

For assessing how well the SCWP adheres to substrates such as concrete or masonry, a three-point bending (3PBD) test was used on prism composites consisting of the repair material bonded to the substrate. In this method, the composite prism typically composed of half original substrate and half repair mortar is subjected to a flexural load until failure. The test evaluates the interfacial bonding performance between the repair mortar and the existing material, providing insight into the mechanical integrity and effectiveness of the bond. This indirect approach allows observation of crack propagation paths, indicating whether failure occurs at the interface (adhesion failure) or within one of the materials (cohesive failure), which is critical for assessing long-term durability and compatibility of repair systems.

3. RESULTS

3.1 Slump Flow

Figure 4 illustrates the variation of slump for mixes containing increasing amounts of ceramic waste as a partial replacement for cement. As the SCWP content increases from 0% (Mix M0) to 30% (Mix M30), a clear decreasing trend in slump flow is observed from approximately 155 mm to 128 mm. This reduction in workability is primarily attributed to the high porosity and irregular particle shape of SCWP, which increases water demand and internal friction within the mix. Similar findings were reported by Al Fakih et al.2023, where cementitious mortars with up to 30% ceramic tile powder showed reduced slump values while maintaining structural integrity. Additionally, a review by Karat et al. (2025) noted that although SCWP contribute to pozzolanic activity, their physical characteristics negatively impact fresh-state properties such as flowability.

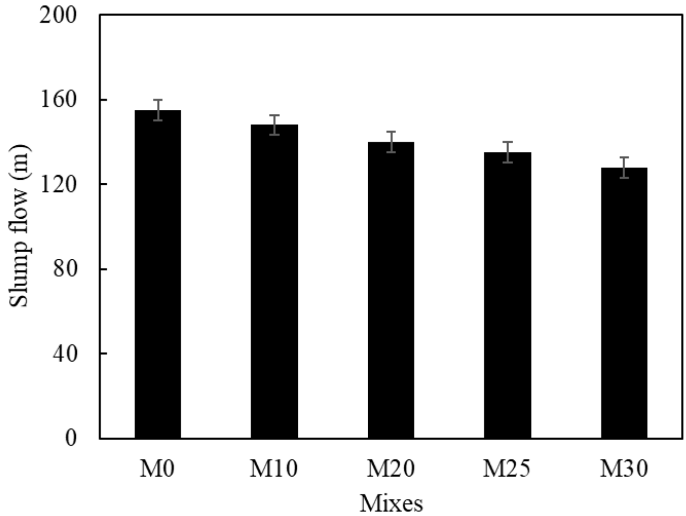

Figure.4 Influence of CW on slump flow of mixes

4. DRY DENSITY

Figure 5 shows the variation in dry density for mortar mixes incorporating different levels of ceramic waste as a partial replacement for cement. As ceramic content increases from 0% in Mix M0 to 30% in Mix M30, a gradual decrease in dry density is observed from approximately 1850 kg/m³ to 1750 kg/m³. This trend is primarily attributed to the lower specific gravity and higher porosity of ceramic waste compared to ordinary Portland cement. The porous nature of crushed ceramic materials reduces the overall mass per unit volume of the hardened mortar, leading to lighter mixes. A similar reduction in density was observed in similar systems where ceramic tile powder or waste brick powder were used, making the mortars well-suited for lightweight and heritage applications. For instance, in studies replacing cement with ceramic waste powders, dry density declined due to the lower material density of ceramic powders (around 2.45–2.66 g/cm³ vs. typical cement at 3.14 g/cm³) Tawfik et al.2023). Another investigation reported up to an 8 % reduction in hardened mortar density with high ceramic substitution levels, which is consistent with light weighting trends for prefabricated elements (De Hita et al.2019).

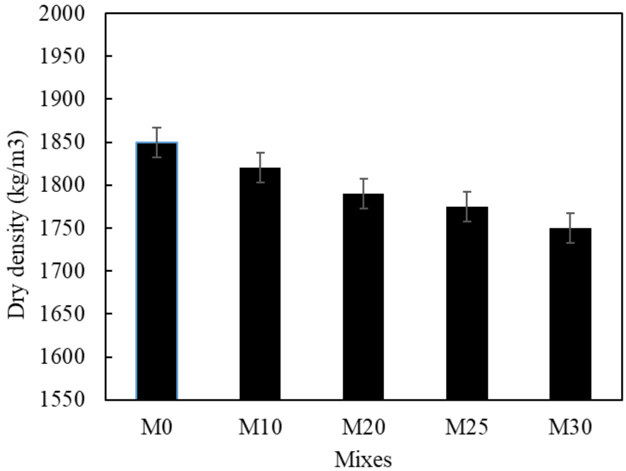

Figure 5. Influence of CW on dry density of mixes

5. COMPRESSIVE STRENGTH

Figure 6 shows the evolution of compressive strength over 2, 7, and 28 days in mortar mixes with incremental ceramic waste used as partial cement replacements. At early ages, strength is lower in ceramic-containing mixes with M0 (0%) at 3.1 MPa, M10 at 2.9 MPa, and M20 at 2.7 MPa likely due to delayed pozzolanic reactions. By 7 days, differences narrow: M0 at 5.6 MPa, M10 at 5.4 MPa, and M20 at 5.1 MPa. At 28 days, strengths reach 7.5 MPa (M0) 7.2 MPa (M10), and 6.8 MPa (M20), showing that up to 20% ceramic substitution maintains acceptable performance. Higher levels (25–30%) see steeper declines: M25 6.2 MPa, M30 5.6 MPa. These observations align with prior studies mixed results show moderate increases or comparable strength at late ages (e.g., 10% replacement), but most report diminishing compressive strength with higher ceramic content, especially at earlier curing stages, due to reduced cementitious binder and slower early hydration (Reig et al.2022).

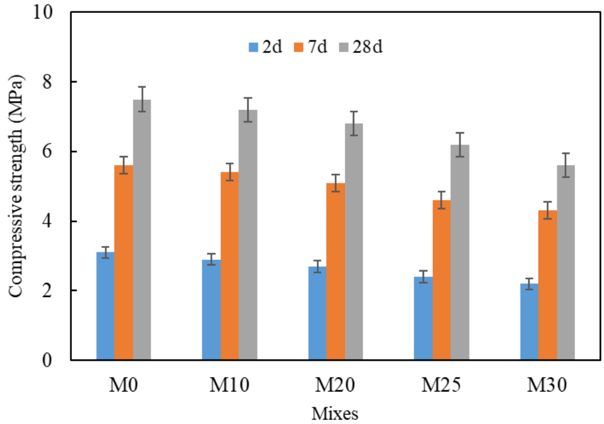

Figure 6. Influence of CW on compressive strength of mixes

6. DRYING SHRINKAGE

Figure 7 shows the evolution of drying shrinkage of mortars with and without ceramic powder over a 28-day curing period. The control mortar (M0), which contained no ceramic powder, exhibited the highest shrinkage at all ages, starting from 0.22 mm/m at 1 day, rising to .60 mm/m at 7 days, and reaching 0.72 mm/m at 28 days. In contrast, mortars incorporating ceramic powder showed a consistent reduction in shrinkage across all time points.

For instance, mortar M30 (30% ceramic) exhibited shrinkage values of only 0.15 mm/m at 1 day, 0.41 mm/m at 7 days, and 0.48 mm/m at 28 days, representing a 33% reduction compared to the control at 28 days. Intermediate mixes followed the same trend: M10, M20, and M25 reached final shrinkage values of 0.66 mm/m, 0.59 mm/m, and 0.54 mm/m, corresponding to reductions of 8%, 18%, and 25%, respectively, relative to M0. Notably, most shrinkage occurred within the first 7 days in all mixes, accounting for approximately 80–85% of the total 28-day deformation, which is consistent with drying shrinkage kinetics in blended cement–lime mortars. These reductions are attributed to the filler effect and partial pozzolanic reactivity of finely ground ceramic powder. The ceramic particles reduce pore connectivity and refine the microstructure, limiting moisture loss and internal capillary stresses. Additionally, the lower content of Portland cement reduces autogenous shrinkage and thermal cracking risks, further stabilizing the matrix.

This behavior aligns with findings by Al-Khafaji & Behaya (2015), Samadi et al. (2025), and Silva et al. (2023) who demonstrated that ceramic additions enhance dimensional stability and long-term durability in restoration mortars. Overall, the incorporation of ceramic waste not only improves environmental sustainability but also significantly mitigates drying shrinkage, making it a valuable material for conserving historical masonry structures.

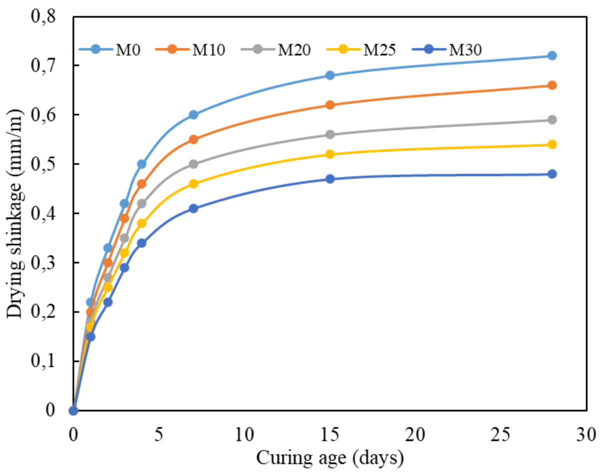

Figure 7. Influence of CW on drying shrinkage of SCWP

7. BONDING

Figure 8 illustrates the adhesion behavior of mortar mixes incorporating ceramic waste as a partial cement replacement, evaluated using the three-point bending (3PB). The three-point bending (3PB) test indicates that replacing cement with ceramic waste up to 20% results in a compatible repair mortar. In these mixes (M10 and M20), fractures occurred primarily within the substrate, while the repair mortar remained well-adhered, demonstrating good interfacial bonding. However, at replacement levels above 20% (Mixes M25 and M30), the mortars became incompatible with the substrate, as evidenced by fractures occurring at the interface. This interfacial failure suggests a significant reduction in bond strength, with the repair material detaching cleanly from the substrate during testing.

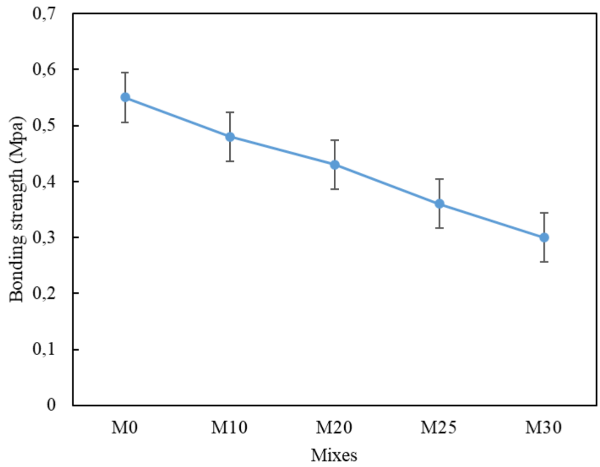

Figure 8. Influence of CW on bond strength of mixes

CONCLUSION

Based on the experimental results, the following conclusions can be drawn regarding the effect of ceramic waste as a partial cement replacement in lime–cement mortars:

- Workability, as measured by slump flow, decreased progressively with increasing ceramic content due to the higher water demand and rough surface texture of ceramic particles.
- Dry density also declined with higher replacement levels, attributed to the lower specific gravity and porous nature of ceramic waste, which can be beneficial in producing lightweight mortars for heritage applications.
- In terms of mechanical performance, compressive strength remained within acceptable limits up to 20% replacement, benefiting from pozzolanic activity that contributes to matrix densification. However, strength decreased noticeably beyond this threshold.
- Drying shrinkage decreased significantly with the addition of CW, particularly at higher replacement levels. At 28 days, shrinkage was reduced from 0.72 mm/m in the control mix to 0.48 mm/m at 30% replacement representing a 33% reduction.

This behavior is attributed to the filler effect and microstructural refinement provided by the ceramic particles, which lower capillary stresses and improve dimensional stability at early and later ages. This reduction in shrinkage is especially beneficial for heritage mortars, where crack resistance and volume stability are essential.

- Regarding bonding behavior, mortars with up to 20% ceramic waste exhibited good adhesion, with fractures occurring in the substrate during the 3-point bending test, indicating compatibility. At higher replacement levels (25% and 30%), failure occurred at the interface, signaling reduced bond strength and incompatibility with the substrate.
- In summary, replacing cement with ceramic waste up to 20% by weight offers a sustainable and technically viable solution for producing compatible repair mortars, while maintaining acceptable fresh and hardened properties. Exceeding this limit may compromise both mechanical and adhesive performance.

Recommandations

Ceramic waste should replace no more than 20% of the cement by weight to ensure that both mechanical strength and bonding behavior remain within acceptable limits for structural and heritage applications.

Since increased ceramic content reduces workability, consider adjusting the water-to-binder ratio or incorporating compatible plasticizers to improve slump flow without compromising strength.

For non-structural or insulation applications, where strength is less critical, higher ceramic waste content (above 20%) can be explored to take advantage of reduced density and thermal benefits.

When using ceramic waste-based mortars for repair, especially on heritage structures, perform adhesion tests on the specific substrate to ensure compatibility, particularly if using mixes near the 20% replacement threshold.

To optimize particle packing and mitigate the rough texture and porosity of ceramic waste, ensure adequate mixing and consider pre-processing or grading the ceramic waste to improve performance.

Promote the use of ceramic waste mortars as part of sustainable building strategies, emphasizing their eco-friendly profile, waste valorization, and suitability for heritage conservation.

Given the observed decline in compressive and bond strength at higher replacement levels, do not use mortars with more than 20% ceramic waste in applications where mechanical performance is critical.

Encourage future research into the long-term durability (e.g., freeze-thaw resistance, sulfate attack) of ceramic waste mortars to validate their use in various environmental conditions.

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CHAPTER 2
PERFORMANCE ENHANCEMENT OF RIVER SAND CONCRETE MIX DESIGN

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INTRODUCTION

Building collapse has been an age long problem in the building industry. Dating far back into the reign of Hammurabi (1792 – 1750 BC). This is the reason why the penal code 229 was included in the laws promulgated during his reign. The code stipulates death penalty for any contractor that builds a house that collapse afterwards (Harper, 1904). Several studies have been carried out to eliminate this menace, but the desired result has not been attained. In our present day Nigeria, the increasing cost of concrete production in Nigeria has led to lots of compromise in Concrete Mix Design resulting in low quality concrete. This according to Awoyera (2021) Ekponyo et. al. (2025) and Ajayi et. al. 2024 is one of the factors responsible for cases of building collapse.

Concrete is a construction material that can be used for a wide range of residential and agricultural applications, according to Shelton and Harper (1982). It is resistant to numerous acids, silage, milk, manure, fertilizers, water, fire, and abrasion when made with the right materials and methods. Portland cement, water, aggregates, and occasionally admixtures make up concrete. The aggregates are bonded together by the cement and water forming a paste that hydrates and hardens. The quantity and characteristics of the materials used, as well as how the concrete is laid, finished, and cured, all have a direct impact on its quality.

The use of either nominal or prescribed mix proportioning of the constituent materials of concrete is the common practice in many construction sites in Nigeria. This method does not take into consideration the variations of the properties of these constituent materials especially aggregate. In view of the observed short comings of this practice, various methods are being evolved to optimize concrete production (that is production of concrete at minimal cost and with the required performance in terms of workability, strength and durability). This can also be a contributory factor to cases of building collapse. Therefore, due consideration should be given to the evolvement of mix proportions that will produce concrete that meets the desired property to satisfy the optimal requirements.

Mix proportioning has been defined as the process whereby the proportions of the different constituents in a concrete are selected, and the yield of the mix is determined (Alexander and Mindess, 2010) while Neville (2011) defined it as the process of choosing suitable ingredients of concrete and determining their relative quantities with the objective of producing as economically as possible, concrete of certain minimum properties, notably strength, durability, and a required consistency. Alexander and Mindess (2010) added that aggregates play their most important role in governing these proportions to satisfy the requirements for the plastic mix. Proportioning a concrete mixture for optimum workability is therefore both a science and an art. In terms of economy, proportioning should reduce the quantity of cement needed without compromising the quality of the concrete.

Proportioning of a concrete mixture for optimum workability is therefore both a science and an art. In terms of economy, proportioning should reduce the quantity of cement needed without compromising the quality of the concrete. Wang et al (a and b, 2015) posited that the optimisation of concrete mix proportion should take care of the construction processes, sustainability and economy. With respect to economy, Richardson et al. (1994), Brough et al (2002) and Ravikumar et al (2010) stated that the cement content op the prescribed method of mix proportioning is greater than what is needed for the anticipated performance. According to Puertas et al (2011), performance is a measure of the potential of the concrete to fulfill its desired function assigned by engineers based on the required application.

1. Procurement of Materials

All the constituent materials used in the study were purchased from local dealers in Ilaro. This was done because it was readily available. The use of locally available materials or the study was aimed at reducing cost of transportation which further ensures that the cost of production is considerably reduced. Comprehensive tests were carried out on the properties of all the constituent materials before their usage to confirm that it meets the required standard for making concrete as specified in the relevant British standards. Table 1 shows the tests carried out to ascertain the suitability of the cement used in the study.

Table 1. List of Tests on the Physical Properties of Cement

Material property	Relevant British Standard
Specific Gravity test	BS EN 196 – 5:1995
Fineness test	BS EN 196 – 3:2016
Soundness test	BS EN 196 – 3:2016
Consistency test	BS EN 196 – 3:2016
Initial setting time test	BS EN 196 – 3:2016
Final setting time test	BS EN 196 – 3:2016

The fine aggregate used for the study is river sand. This is because of its good characteristics as a preferred choice of fine aggregate. It is clean free from impurities, well graded, sharp and rounded in shape. These properties provide a concrete with improved workability, increased strength, and better bonding. To ascertain its suitability for use in making concrete, relevant tests were carried out on the properties of the sample of the material. The tests carried out are shown in Table 2.

Table 2. List of Tests on the Physical Properties of River Sand

Material property	Relevant British Standard
Sieve analysis test	BS EN 933 – 2: 2020
Specific Gravity test	BS EN 12390 – 7:2022
Water Absorption Test	BS EN 12390 – 7:2022
Moisture content test	BS 812 – 109:1990
Bulking test	**BS 812-2:1995**
Percentage Silt Content test	**BS EN 1097-6:2022**.

Granite was the coarse aggregate used in the study. Its preferred choice was based on its strength durability, texture and resistance to impact and abrasion. The material used was angular in shape, this make it a very good choice of material in that it will enhance the interlocking of the particles. Consequently, it will improve the mechanical properties off the concrete. The maximum nominal size used was 20 mm. The choice was made with due consideration to ensuring that concrete with optimal strength and was obtained. The list of tests carried out on the physical properties of granite is contained in table 3.

Table 3. List of Tests on the Physical Properties of Granite

Material property	Relevant British Standard
Sieve analysis test	BS EN 933 – 2: 2020
Specific Gravity test	BS EN 12390 – 7:2022
Water Absorption Test	BS EN 12390 – 7:2022
Moisture content test	BS 812 – 109:1990
Aggregate Impact Value Test	BS 812 – 109:1990
Aggregate Abrasion Value Test	BS 812 - 112:1990
Aggregate Crushing Value test	BS 812 - 110:1990

The water used in the wet mixing stage of the production of the cubes or the study was clean, portable, and free from any chemical impurity capable of met the specified standard of BS EN 1008:2002. It was sourced from the laboratory and hence it guarantees that undesirable chemical reaction that can compromise hydration process thus resulting in the formation of weak compounds within the hardened concrete is avoided. Similarly, the water used for curing of the hardened concrete was obtained from the same source.

2. Determination of the Variation by Weight of the Effect of Component Materials

The determination of the variation by weight of the effect of component materials in this study was a critical step in optimizing the concrete mix design. This process involved carefully adjusting the proportions of the constituent materials to assess their impact on the overall properties of the concrete. By doing so, the research aimed to identify the most effective combinations of materials that enhance the performance and durability of concrete.

3. Experimental Design of Mix Proportion

The experimental design of mix proportion was carried out by methodical variation of the proportions of key parameters used in concrete production. The following parameters were considered: water-cement (w/c) ratio, coarse aggregate-to-total aggregate (CA/TA) ratio and cement content (cc). Trial batches were methodically prepared. The varied proportions of these components were used to establish the relationship between these parameters and the properties of concrete. The approach assists in reducing the number of trial batches required, consequently, both time and resources are minimsed.

This structured method further ensures that the generated data was all-inclusive and dependable, providing insights into the effects of different material combinations on the concrete's mechanical properties and durability. As a result of all these the study effectively identified the optimal mix proportions which enhances the overall performance of the concrete while cost efficiency and sustainability of the mix is maintained.

4. Determination of Key Performance Indicators of Concrete Mix

In establishing the key performance indicators (KPIs) for the concrete mix, reference was made to the guidelines provided in BS 5328-1. These KPIs considered the various factors that influence the overall quality, strength, and durability of the concrete. The four primary categories of the performance indicators considered for this study are workability, strength, exposure condition, and durability requirement.

- **Workability Requirement**

This deals with the ease of handling, placement, and compaction of the concrete without segregation or bleeding. The predetermined workability requirement for this study was taken to be 75mm. This value corresponds to medium workability as outlined in Table 11 of BS 5328-1.

- **Strength Requirement**

The significance of concrete strength in the determination of its load-bearing capacity and its ability to withstand various stresses during its service life cannot be over emphasised. Hence the water-cement (W/C) ratio and cement content (CC) considered in setting the strength requirement for this study was set based on the structural requirements and exposure conditions. The strength levels were specified are 20 N/mm^2, 30 N/mm^2, and 40 N/mm^2.

These strength levels were chosen to ensure that the concrete meets the necessary structural and safety standards for the intended application, based on varying exposure conditions.

- **Exposure Requirements**

This refers to the environmental factors to which the concrete will be exposed during its service life, which can considerably influence its durability. The exposure conditions outlined in Table 6 of BS 5328-1 were categorized into mild, moderate, and severe conditions. For the purpose of this study the cement grade used for this study was specified as C42.5 for moderate condition of exposure, These provides the concrete with sufficient resistance to environmental factors such as moisture and chemical attack.

- **Durability Requirements**

Durability requirement gives due consideration to the concrete's ability to resist degradation over time due to environmental factors such as freezing and thawing, chemical exposure, and abrasion. The durability requirements for moderate exposure conditions was set according to the specifications in BS 5328-1for a maximum nominal size of coarse aggregate of 20mm and the minimum Cement Content (CC) of 325 Kg/m^3. This ensures that the concrete achieves the required resistance to environmental factors, particularly for moderate exposure conditions.

All these performance indicators guarantee that the concrete mix meets the structural, functional, and durability needs specified in the study. They also provide a balanced approach to both strength and long-term performance under various exposure conditions.

5. Level of Key Performance Indicators

The three parameters that are germane to the design of a concrete mix for the achievement the desired characteristic performance in terms of workability, strength and durability are the water/cement ratio, cement content and coarse aggregate/total aggregate ratio. These three parameters were taken into consideration in the study. Based on the above considerations, the minimum cement content used was 325 kg/m^3. The minimum water/cement ratio is 0.35 while the coarse aggregate and total aggregate ratio was varied between 0.6 and 0.7.

All these are in line with the value specified in Table 6 of BS 5328-1 thereby satisfying the durability requirement for moderate exposure conditions, ensuring adequate resistance to environmental factors and contributing to the concrete's overall strength and longevity.

The specific proportions of the various components used in this study, based on the above parameters, are presented in Table 4, which serves as a reference for the trial mixes designed to meet the performance objectives. These proportions are systematically optimized to provide a concrete mix that fulfills both strength and durability requirements under the given exposure conditions.

Table 4. Proportion of Components Used in the Study

Component	1	2	3	Level
WCR	0.35	0.4	0.45	3
CC (kg/m^3)	325	350	375	3
CA/TA ratio	0.6	0.65	0.7	3

5.1 Concrete Production and Testing

Twenty-seven trial mixes were set up in producing all the cubes that were cast, pit sand and river sand were used separately as fine aggregate while granite was used as coarse aggregate

- **Batching of Constituent Materials:** The specific gravity of the different component materials was used to determine the absolute volume of the trial mix.

Figure 1. Photograph of weighing process of materials used in the study

Which is 27 in number. 27 trial mixtures were prepared and three samples of each trial mix were produced thus making a total of 81 specimens for each of the two types of fine aggregates (pit sand and river sand). Batching was carried out by weight due to the small to avoid bulking effect of sand used in the study (Figure 1).

- **Mixing of Constituent Materials:** Manual mixing was done because of the small quantity of the materials used in each trial mix. The mixing was done in two stages (dry mixing and wet mixing stages).

Figure 2. Photo graph of the Mixing process of Concrete

- Slump Test: The test was conducted in line with stated procedures in BS EN 12350-2: (2019).

Figure 3. Photograph of Procedure of Slump Test and Casting of cubes

Figure 4. Photograph of Slump Test Specimen and Cone

- **Casting of Cubes:**This test was conducted in line with the stated procedure in BS EN 12390 – 2:2019.
- **Compressive Strength Test:** The test was conducted in line with the procedure specified in BS EN 12390 -3:2009. Test equipment is shown in Figure 5.

Figure 5. Compressive Strength Testing Machine

Results of the Physical Properties of Aggregates Used in the Study

The results of the tests conducted on the cement used in this study indicate that the specific gravity is 3.02 which is slightly below 3.15 stated in literature (Siddique n. d.). The fineness, soundness initial and final setting times of the sample are 6%, 5mm, 75 minutes and 4½hours respectively. All these values are below the specified value in BS EN 197 -1:2000.

Table 5. Results of Tests on the Physical Properties of Cement used in the Study.

Property Compressive	Specific Gravity	Fineness %	Soundness (mm)	Normal Consistency %	Initial Setting Time(mins)	Final Setting Time(Hrs)	Strength
Values	3.02	6	5	26	75	4.5	33.5

6. Fineness Modulus (FM)

According to CRD-C 104-80, 1980, fine aggregate's fineness modulus must fall between 2 and 4. According to Backus (n d) when creating a concrete mix, the FM is a useful metric to specify the ratios of fine and coarse material. The aggregate's fineness or coarseness can be inferred from its value. Higher values imply coarse material while lower values indicate fine material. The FM is not a definition parameter of the grading curve. It gives an indication of paste requirement of the mix. This implies that fine aggregate with lower value require more paste, this results in a more workable but more costly mix. Table displays the findings of the FM of the fine aggregates. It shows that river sand with FM of 3.4 is a coarse material, The FM of coarse aggregate is 5.17. This is slightly below the recommended value of 5.5 – 8.0 stated in Fineness Modulus (n d).

Coefficient of Curvature and Coefficient of Uniformity of Sand

The USCS gave prescription for grading classification of aggregates as to whether it is well graded or poorly graded.

For fine aggregate to be well graded, the Coefficient of uniformity (Cu) must be greater than or equal to 6 while the Coefficient of curvature (Cc) must be between 1 and 3 otherwise it is poorly graded. If both values are equals to 1, then it is said to be uniformly graded (Nduka et al., 2018). Considering the results presented in Table 6 both materials are well graded.

Specific Gravity (SG)

The strength of the material is believed to be proportional to the aggregate's SG. A strong material is indicated by a high SG value (Amuda et al. 2014). According to Shetty (2010), the aggregate's specific gravity must fall between 2.6 and 2.8. All of the aggregates listed in Table 6 have specific gravities that are within the range, making them appropriate for use as aggregates in the construction of concrete.

Water Absorption (WA)

ACI E1-07 (2007) states that, particularly for fine aggregates, it is rarely possible to achieve the ideal condition of saturated surface dry aggregate in practice. As a result, the concrete mix design needs to take into account the aggregates' water absorption property. Neville (2011) asserts that aggregate water absorption has an impact on concrete's workability and W/C. According to BS 8007:1987, the water absorption limitation value is 3%. Every aggregate employed in this investigation is below the limitation value. The values of granite and river sand are 0.85%, and 1.9%, respectively. Hence they are very suitable for the study.

Moisture Content of Sand

The conditions stipulated for water absorption equally applies to moisture content of aggregates. Based on the findings of the sand's moisture content, which are shown in Table 6 it can be noted that the moisture content off both materials are less than the stated 3% in BS 8007:1987.

Percentage Silt Content of Sand

The value of 8% is the acceptable amount as stated in BS 882:2004.

The percentage silt content values for the aggregate samples taken into consideration in this investigation are shown in The presence of high percentage of silt in aggregates especially FA is that it can reduce the bond between cement and other constituent materials of concrete. Additionally, it increases the water demand which in turn affects the strength and durability of concrete. The value of the percentage silt content off the river sand used I the study as presented in Table 6 is 5.4%. This is less than the 8% specified in the code. Hence, it is well suited for the study.

Bulking of Sand

None of the consulted literatures specifies any particular value or range of values for bulking of FA. But according to Koirala and Joshi (2017), Fine aggregate bulking can reach up to 30% of the initial dry volume. Regarding bulking, they also provided two types of Fine aggregate. The two types are fine sands with bulking value higher than 15% and coarse sand with bulking value lower than 15%. From the presentation of the value of bulking of river sand as shown in Table 6 reveals that the material can be classified as fine sand.

Soundness Value of Coarse Aggregates

Table 6 displays the granite samples' soundness value of 2.5. This suggests that soundness value is significantly lower than the 16 percent required by applicable standards and literature. Therefore, it can be concluded that the sample is reliable and suitable for use in concreting projects.

Aggregate Crushing Value of Granite

One of the parameters utilized in the construction of roads and pavements is the ACV. According to Neville and Brooks (2010), BS 882:1992, and Shetty (2010), the strength of aggregate is inversely related to the ACV value. In other words, strength decreases with increasing value and vice versa. According to Shetty (2010), aggregates with values between 30% and 45% are suitable for various concreting tasks, while those with values below 30% can be utilized to build roads and pavement with wearing surfaces. The ACV of 11.1% obtained for the granite sample used for the study as shown in Table 6 is very adequate.

Aggregate Impact Value of Granite

BS EN 882:2004 specifies limiting values for the AIV, which are 45% for others, 30% for pavement-wearing surfaces, and 25% for heavy-duty concrete floor finishes. The result of AIV for the granite sample as presented in Table 6 is 36. 1%. Considering the specifications in BS EN 882:2004, this value is lower than the 45% specified in the code as satisfactory for general concreting work. Hence it is suitable for use in the study.

Aggregate Abrasion Value of Granite

The result AAV of the granite sample as presented in Table 6 is 34.7%. From the result, it can be observed that the granite sample is below 45% abrasion values specified for concreting works for wearing surfaces in Shetty (2010). Therefore, it is suitable for use in any kind of concreting operation and as such it is suitable for the study.

Table 6. The Physical Properties of Aggregates used in the Study

Properties	River Sand	Granite	BS Standard Requirement
Fineness Modulus	3.4	5.17	5.5 – 8
Cu	4.88	2.66	>3
Cc	1.44	1.11	1-3
Specific Gravity	2.64	2.65	2.67
Water Absorption(%)	1.9	2.31	0.85
Moisture Content (%)	1.26	1.22	3
Percentage Silt Content (%)	5.4	-	8
Bulking (%)	14.28	-	-
Aggregate Abrasion Value (AAV %)	-	36.1	45
Aggregate Crushing Value (ACV %)	-	11.1	45
Aggregate Impact Value (AIV %)	-	34.7	45
Soundness		2.5	

7. Results of the Observed and Predicted Compressive Strength of Trial Mixes for River Sand

The results of observed and predicted compressive strength of each of the trial mixes were obtained and presented in Figures 1 and 2.

The generated compressive strength was the results obtained by crushing the cubes cast with the compressive strength testing machine after the cubes have attained its 28 days strength. On the other hand, the computed values were obtained using the equation of the regression model. Figure 1 presents the chart of observed compressive strength for river sand at W/C ratio of 0.35, 0.4 and 0.45.

From the figure, the maximum compressive strength of 40.71N/mm2 was achieved at CA/TA ratio of 0.35, CC of 375kg/m3 and CA/TA ratio of 0.65 for the experimental mix. In Figure 4.32 are the predicted values for river sand at W/C ratio of 0.35, 0.4 and 0.45. From the figure, the maximum value of the compressive strength of 36.98N/mm2 was attained at W/C ratio of 0.35 CC of 375kg/m3 and CA/TA ratio of 0.6.

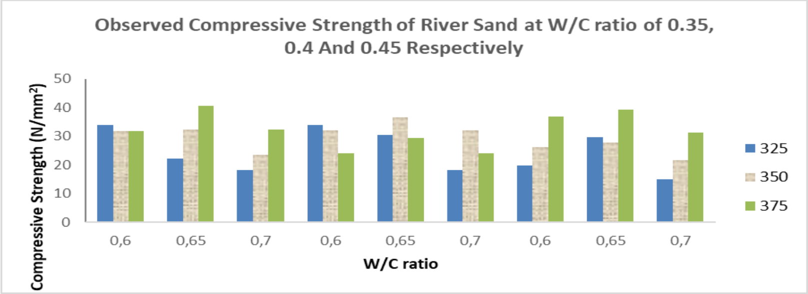

Figure 6. Observed Compressive Strength of River Sand at W/C ratio of 0.35, 0.4 and 0.45 respectively

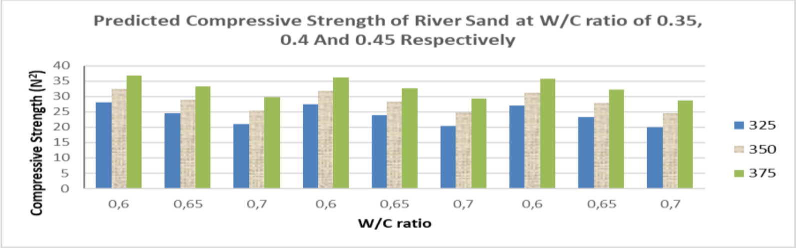

Figure 7. Predicted Compressive Strength of River Sand at W/C ratio of 0.35, 0.4 and 0.45 respectively

Effect of Variation by Weight of the Different Component Materials on the Compressive Strength of Concrete

As stated earlier, the weight proportion of the various component materials were varied to produce the twenty seven (27) trial mixes. The effects of these variations are examined in this section.

Effect of Variation of Water Cement Ratio and Cement Content on the Compressive Strength of Concrete made with Pit Sand

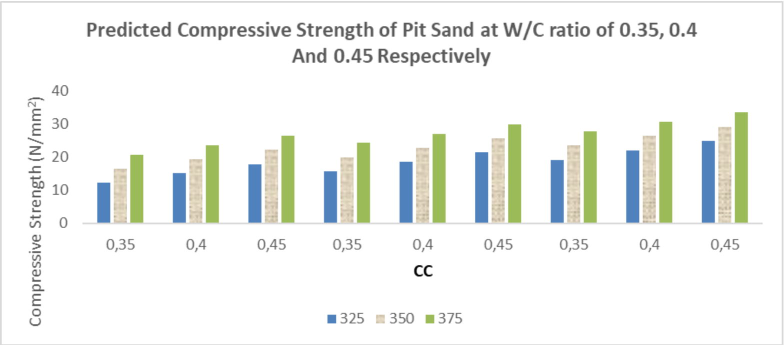

Figure 8. Chart of the Effect of Variation of W/C ratio and CC on the Compressive Strength of Concrete made with Pit Sand

Figure 8 examines the relationship between compressive strength, W/C ratio and CC. In the figure, the chart shows that the compressive strength of mix increases as the weight of the CC increases for all the values W/C ratio. Similarly, the compressive strength increases with increase in W/C ratio. The minimum value of the compressive strength is 12.21N/mm2 which occurs at W/C ratio of 0.35 and of 325KN/m3, while the maximum value of the compressive strength is 33.49N/mm2 which occurs at W/C ratio of 0.45 and CC of 375KN/m3. This follows that the compressive strength of concrete produced with pit sand is directly proportional to both the W/C ratio and the CC.

Effect of Variation of Water Cement Ratio and Cement Content on the Compressive Strength of Concrete made with River Sand

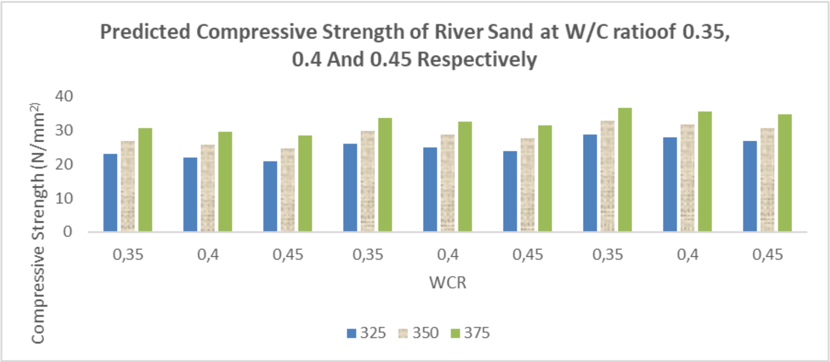

Figure 9. Chart of the Effect of Variation of W/C ratio and CC on the Compressive Strength of Concrete made with River Sand

Figure 9 examines the relationship between compressive strength, W/C ratio and CC. In the figure, the chart shows that the compressive strength of mix increases as the weight of the CC increases for all the values W/C ratio. Similarly, the compressive strength decreases with increase in W/C ratio. The minimum value of the compressive strength is 20.82N/mm2 which occurs at CC ratio of 0.45 and CC of 325KN/m3, while the maximum value of the compressive strength is 36.59N/mm2 which occurs at W/C ratio of 0.35 and CC of 375KN/m3. This follows that the compressive strength of concrete produced with pit sand is directly proportional to the CC and inversely proportional to the W/C ratio.

Effect of Variation of Coarse Aggregate/Total Aggregate Ratio and Cement Content on the Compressive Strength of Concrete made with River Sand

Figure 10: presents the result of the relationship between compressive strength, CA/TA ratio and CC. In the figure, the chart shows that the compressive strength of mix increases as the weight of the CC increases for all the values of CA/TA ratio. However, the compressive strength decreases with increase in CA/TA ratio.

The minimum value of the compressive strength is 20.82N/mm2, which was attained at the CA/TA ratio of 0.7 and CC of 325KN/m3, while the maximum value of the compressive strength is 36.59N/mm2 which occurs at CA/TA ratio of 0.6 and CC of 375KN/m3. This follows that the compressive strength of concrete produced with pit sand is directly proportional to the CC and inversely proportional to CA/TA ratio.

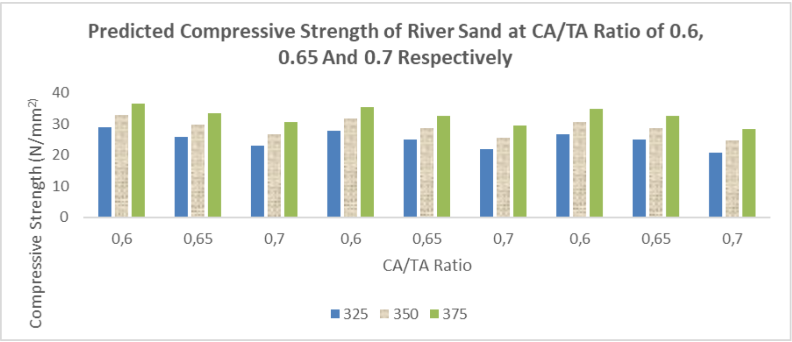

Figure 10. Chart of the effect of Variation of CA/TA Ratio and CC on the Compressive Strength of Concrete made with River Sand

Effect of Variation of Water Cement Ratio and Coarse Aggregate/Total Aggregate Ratio on the Compressive Strength of Concrete made with Pit Sand

Considering the relationship between W/C ratio and CA/TA ratio as presented in Figure 11, it was observed that increase in the CA/TA ratio results in decrease in the compressive strength of the mix while increase in W/C ratio results in decrease in compressive strength. The minimum compressive strength of 20.82N/mm2 was observed at CA/TA ratio of 0.7 and W/C ratio of 0.45 while the maximum compressive strength of 36.59N/mm2 was observed at CA/TA ratio of 0.6 and W/C ratio of 0.35. lt thus follows that the compressive strength of the mix is inversely proportional to both the WCR and the CA/TA ratio.

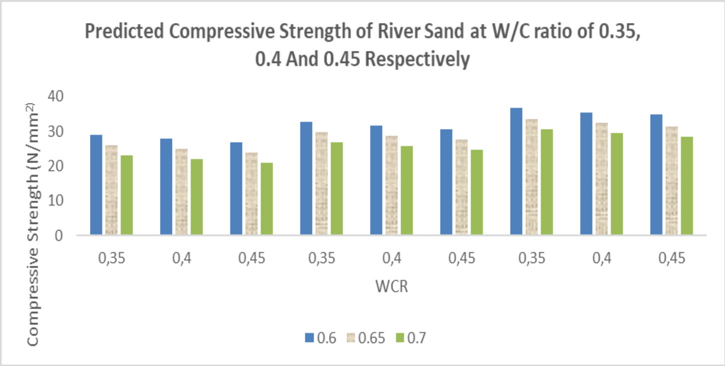

Figure 11. Chart of the effect of Variation of W/C ratio and CA/TA Ratio on the Compressive Strength of Concrete made with Pit Sand

To obtain the maximum compressive strength of concrete produced with river sand, the value of 36.59 N/mm2 was attained at W/C ratio of 0.35 CA/TA ratio of 0.6 and CC of 375N/m3.

CONCLUSIONS

Based on the result of the experimental trial mixes, it was discovered that there are significant effects of the variation of constituent material content on both the compressive strength and cost of concrete. The followings are the observed effects of the each of the various constituent materials on the compressive strength of concrete.

1. Increase in CC results in increase in the compressive strength of concrete made with granite as coarse aggregate and pit sand and river sand as fine aggregates respectively.
2. Increase in WCR results in increase in the compressive strength for the same amount of CC made with granite as coarse aggregate and pit sand and river sand as fine aggregates respectively.
3. Decrease in the CA/TA ratio results in increase in the compressive strength for the same amount of CC made with granite as coarse aggregate and pit sand and river sand as fine aggregates respectively. The same trend is observed in both the river sand and pit sand.

The followings are the observed effects of the each of the various constituent materials on the unit cost per cubic meter of concrete.

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CHAPTER 3
THE USE OF CLAY IN THE PRODUCTION OF CERAMIC SANITARY WARE

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INTRODUCTION

One of the most important raw materials in the ceramics industry is clay, especially when it comes to making sanitary gear like sinks, toilets, bidets, and bathtubs [1]. Because of its special physical and chemical characteristics, this naturally occurring substance which is created when feldspar-rich silicate rocks weather chemically is essential to the production of technical and sanitary ceramics [2]. Its exceptional plasticity makes it simple to shape intricate shapes and guarantees robust cohesiveness throughout the molding process [3]. Clay greatly enhances the finished products' mechanical strength, impermeability, and long-term durability after firing [4].

The final products' appearance and functionality are directly impacted by the quality of the clay used in the sanitary ceramics industry [5].

The best balance of plasticity, drying shrinkage, and fire behavior is achieved by carefully choosing and frequently blending several kinds of clay, including kaolinite, bentonite [6], and ball clay [7].

This chapter covers in detail the most popular varieties of clay used in the sanitary ceramics industry, their preparation and processing methods, and the crucial function clay plays in the production process. Particular focus will be placed on how clay's characteristics affect the end products' quality as well as technical advancements meant to enhance clay-based formulations to satisfy the increasing expectations for sustainability, performance, and design aesthetics.

1. Classification of Clay-Based Ceramics

Ceramics are utilized in numerous applications in contemporary science. Clay-based ceramics are particularly prevalent in the production of technical ceramics, refractory products, non-structural items, and structural construction materials. Common examples include sanitary ware, earthenware, porcelain, stoneware, cement clinker, firebricks, acid-resistant bricks, quarry tiles, and electrical insulators.

Coarse and fine particles are the two main categories into which clay-based ceramics fall. Depending on their weight %, coarse particles are further divided into two categories: porous and dense.

The material is categorized as dense if the weight percentage is less than 6% and as porous if it is larger than 6%. Similarly, tiny particles are classified as dense (less than 2%) or porous (weight percentage larger than 2%).

Coarse-particle porous ceramics are commonly utilized in refractories and structural construction materials. Technical and non-structural ceramics can be categorized as dense or porous. Stoneware, porcelain, and technical ceramics are the three primary categories of dense fine-particle ceramics, whereas earthenware is an example of porous ceramics made from fine particles.

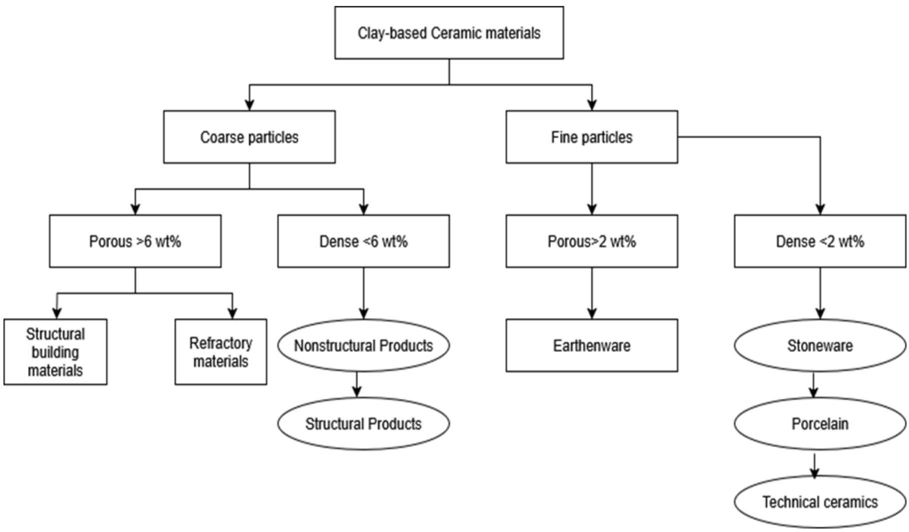

Figure 1. Flowchart for classification of clay-based ceramics [8]

2. Types of Clay Used

The main types of clay used in sanitary ware production include:

2.1 Kaolin

Kaolin, sometimes referred to as China clay, is an essential raw material used to make ceramic sanitary ware. Because of its purity, whiteness, and refractory qualities, it is essential for creating high-quality, durable, and aesthetically pleasing sanitary products [9].

Kaolin is a naturally occurring clay composed primarily of the mineral kaolinite ($Al2Si2O5(OH)_4$). It is formed through the weathering or hydrothermal alteration of alumino-silicate minerals like feldspar [10].

Kaolin is a silicate clay mineral with layers that is a member of the kaolinite group. One tetrahedral silica (SiO4) sheet connected to one octahedral alumina (AlO6) sheet forms each structural unit in its repeating 1:1 layer structure (see Figure 2).

Its primary characteristics are low percentages of iron and titanium oxides, which guarantee higher whiteness, and a high alumina (Al2O3) content [11], which offers strength and durability. Furthermore, the material is distinguished by its high refractoriness, which indicates exceptional heat resistance, and its fine particle size, which improves its reactivity and workability [12].

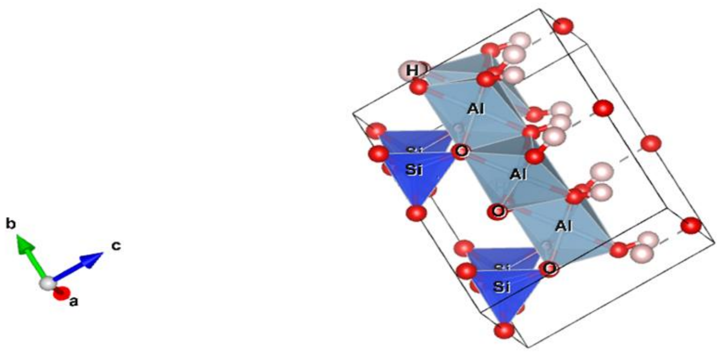

Figure 2. 3D crystal structure of kaolinite generated using VESTA software. The structure consists of alternating tetrahedral (SiO4) and octahedral (AlO6) sheets arranged in a 1:1 layer type. Color coding of atoms: silicon (Si) = yellow, aluminum (Al) = pink, oxygen (O) = red, and hydrogen (H) = white.

2.2 Plastic clays (Ball clays)

Ceramic sanitary ware manufacture relies heavily on plastic clays, sometimes referred to as ball clays. They are highly valued for their tiny particle size, high flexibility, and workability-enhancing capabilities, which make them indispensable for forming intricate sanitary goods such as urinals, washbasins, and toilets [13].

Higher grades of ball clay, which is mostly kaolinitic and sedimentary, burn to a white or nearly white color in an oxidizing atmosphere. Ball clay is a fine-grained, very pliable clay.

They have white or almost white burning properties and are valued economically because they improve the workability and strength of different ceramic bodies.

They are composed of different ratios of kaolinite, mica, and quartz, with trace quantities of organic matter and other minerals [14].

2.3 Bentonites

Montmorillonite, a member of the smectite group, is the main component of bentonite. Its structure is categorized as a 2:1 layered silicate, commonly known as phyllosilicate; each structural layer is made up of one octahedral alumina/magnesium (AlO6 or MgO6) sheet sandwiched by two tetrahedral silica (SiO4) sheets (see Figure 3).

Bentonite is utilized to increase workability and plasticity during the forming process in sanitaryware body compositions. Slip casting, the predominant shaping technique for sinks, toilets, and other sanitaryware goods, benefits greatly from this.

Usually employed in small quantities (1–3% by weight) of the entire ceramic body, bentonite is frequently combined with feldspar, ball clay, kaolin, and quartz (silica) [15, 16].

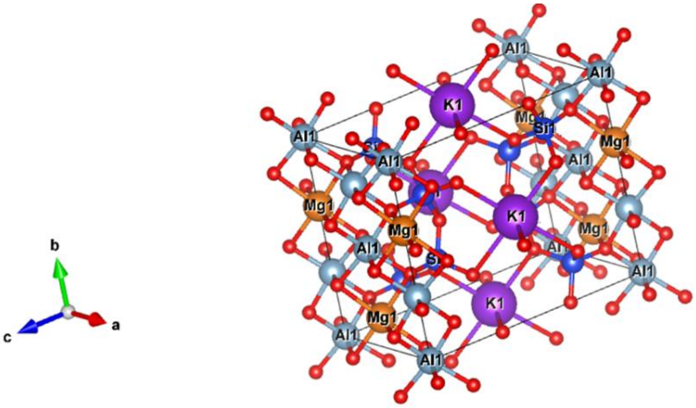

Figure 3. 3D crystal structure of bentonite (montmorillonite) generated using VESTA software. The structure is a 2:1 layered phyllosilicate, where an octahedral sheet is sandwiched between two tetrahedral sheets. Color coding of atoms: silicon (Si) = yellow, aluminum (Al) = pink, magnesium (Mg) = green, oxygen (O) = red, and hydrogen (H) = white.

3. Role of Clay in Sanitary Ceramic Formulation

Clay serves as the structural and functional foundation of the body recipe for sanitary ceramic formulations, such as bidets, washbasins, and toilets. It influences the final product's strength, whiteness, and vitrification in addition to determining how the slip acts during formation [17].

Provides Plasticity for Shaping

When creating sanitary ware, plasticity is a crucial characteristic since forming techniques like pressure casting and slip casting call for a slip that is cohesive enough to hold its shape after being taken out of the mold. In order to provide this plasticity, clays are essential. Ball clay and bentonite provide great plasticity and binding power, whereas kaolin guarantees the end product's whiteness while having only moderate plasticity. This equilibrium makes it possible for the slip to flow easily during casting while yet creating a robust "green" body (unfired condition), which is essential for handling and firing later on.

Acts as a Binder for Non-Plastics

Clay not only gives the ceramic body its plasticity but also serves as a binder for non-plastic components like feldspar, which serves as a flux, and quartz, which aids in shrinkage control. Both in the wet and dry conditions, the fine clay particles successfully link these coarser grains, giving the unfired pieces enough green strength. Before being fired, the former goods may be handled, transported, and processed further without breaking because this binding capability [19].

Controls Water Retention and Slip Rheology

Heavy minerals are kept from settling in the casting tank by bentonite and fine clays, which also aid in maintaining suspension stability and ensuring uniform wall thickness by slowing down the discharge of water from the slip into the plaster mold [20].

Influences Firing Behavior

As kaolin is being fired, the endothermic reaction, which occurs at temperatures between 450 and 600 °C, is the initial stage of this transformation series; it is due, in fact to, the release of all the structural water included in the kaolinite contained in the kaolin with the formation of a dehydroxylated kaolinite defined as metakaolinite (2SiO2Al2O3).

The overall reaction is as follows:

$$2SiO_2.Al_2O_3.2H_2O \text{ (Kaolinite)} \rightarrow 2SiO_2.Al_2O_3\text{(metakaolinite)} + 2H_2O \quad (1)$$

The beginning of the structural reorganization of metakaolinite is at a temperature of about 980°C, with an exothermic reaction. The beginning of the recrystallization of metakaolinite forms either a γ-alumina phase or a spinel structure (overstoichiometric mullite in Al2O3) following the following reactions [21]:

$$2SiO_2.Al_2O_3\text{(metakaolinite)} \rightarrow 2SiO_2 \text{ (amorphe)} + Al_2O_3\text{(Alumine } \gamma) \quad (2)$$

$$2SiO_2.Al_2O_3\text{(metakaolinite)} \rightarrow SiO_2 \text{ (amorphe)} + SiAl_2O_4\text{(Spinelle)} \quad (3)$$

At higher temperatures around 1100°C, mullite is formed by the following reactions:

$$2SiO_2 \text{ (amorphe)} + Al_2O_3\text{(Alumine } \gamma) \rightarrow 1/3\ (2SiO_2.3Al_2O_3)\text{(Mullite)} + 4/3SiO_2\text{(amorphe)} \quad (4)$$

$$SiO_2 \text{ (amorphe)} + SiAl_2O_4\text{(Spinelle)} \rightarrow 1/3\ (2SiO_2.3Al_2O_3)\text{(Mullite)} + 4/3SiO_2\text{(amorphe)} \quad (5)$$

The amount of mullite increases with increasing temperature.

The transformation above 1100°C is due to the formation of cristobalite according to the following reaction:

$$(2SiO_2.3Al_2O_3)\text{(Mullite)} + 4SiO_2\text{(amorphe)} \rightarrow (2SiO_2.3Al_2O_3)\text{(Mullite)} + 4SiO_2\text{(amorphe)} \quad (6)$$

Above 1500°C, cristobalite is changed to amorphous glass according to the following reaction [22]:

$$(2SiO_2.3Al_2O_3)(\text{Mullite}) + 4SiO_2(\text{Cristobalite}) \rightarrow (2SiO_2.3Al_2O_3) + 4SiO_2(\text{amorphe}) \quad (7)$$

The flowchart in Figure 4 shows the steps of transformation of kaolinite into mullite at high temperature.

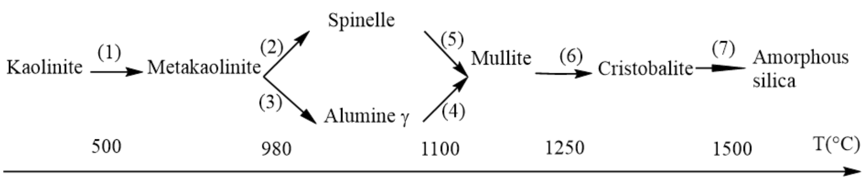

Figure 4. Flowchart of the kaolinite-mullite reaction

In sanitary ware, mullite and the glassy phase create a dense, vitreous body that is water absorbent at less than 0.5% (required for sanitary standards) [23].

Controls Color and Surface Quality

Kaolin's high purity gives a white fired color, essential for the bright glossy glaze typical of sanitary ware. In contrast, impurities (Fe2O3, TiO2) must be low to prevent discoloration [24].

4. Preparation of the Ceramic Sanitary Ware Body

The preparation of a ceramic sanitary ware body (like washbasins, toilets, urinals, etc.) involves creating a homogenous mixture of raw materials that will yield the required strength, shape, and surface quality after firing and glazing. This process is carefully designed to balance workability during forming with mechanical strength and durability after firing.

Here's the detailed step-by-step outline (see Figure 5):

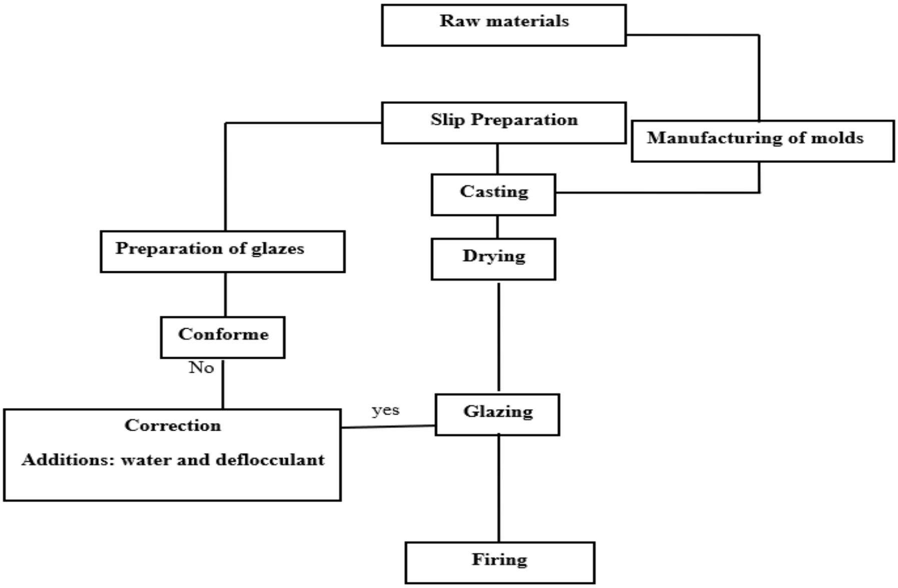

Figure 5. Flow diagram to prepare ceramic sanitary ware body

Selection of Raw Materials

Typical composition and functional roles of raw materials in sanitary ware bodies are presented in table 1.

Table 1. Composition and functional roles of raw materials in sanitary ware body

Raw material	Typical proportion (%)	Role in the body	Effect on final product
Ball clay	25–35%	Offers high plasticity and binding power	guarantees the strength of the green body and the workability of the slip.
Kaolin	20–30%	Leads whiteness and moderate plasticity	Enhances color and refractoriness of the fired ware
Quartz	20–25%	Reducesshrinkage and increases rigidity	Prevents excessive deformation and maintains steady dimensions
Feldspar	20–25%	Lowers the melting temperature by acting as a flux.	Improves vitrification and formation of a dense, glassy phase

Raw Material Processing

In order to guarantee higher quality in the finished product, raw material processing seeks to minimize particle size and remove contaminants. The first step in the process is crushing, which reduces big pieces into smaller, easier-to-handle pieces. Screening comes next, which aids in removing large particles and achieving a consistent distribution of particle sizes. Lastly, iron impurities that would otherwise result in undesired patches and flaws in the material are removed via magnetic separation.

Slip Preparation (Wet Milling)

The majority of sanitary ware goods are made using slip casting, which necessitates making a liquid slurry called "slip." This is accomplished by first ball milling the raw ingredients, which involves mixing them with water and grinding them into extremely fine particles.

The residue on a 45 µm screen usually doesn't exceed 0.5%. In order to retain a high solids content (about 68–72%) while yet being fluid enough to increase the casting rate, deflocculants like sodium silicate or sodium carbonate are used at this step to minimize viscosity. To remove any leftover coarse particles, the resultant mixture is sieved through fine meshes. To avoid discoloration or flaws, iron is subsequently removed using magnetic filters or high-intensity magnets. The created slip next goes through an aging procedure, where it is kept to guarantee that its rheological characteristics are stabilized and homogenized, preparing it for casting.

Slip Properties Control

To make sure the slip is suitable for casting, it is assessed by a number of important property tests prior to usage. While the viscosity is monitored because it directly affects both the casting speed and the effectiveness of mold filling, the specific gravity is examined to regulate the solids content. Since pH is essential to the overall stability of the slip and the efficacy of deflocculants, it is also checked. Since too many coarse particles might degrade the final product's surface quality and smoothness, the residue is finally measured.

Forming

Depending on manufacturing needs, the produced slip can be used in a variety of forming procedures. The most popular technique, slip casting in porous plaster molds, involves absorbing water into the mold and creating a solidified layer that progressively takes on the required shape. Pressure casting is used for large-scale enterprises that need to produce more quickly because it speeds up the consolidation process and cuts down on casting times, which increases productivity.

Drying

In order to avoid flaws like cracks, distortion, or warping, drying is an essential step in the manufacture of sanitary ware and must be done under carefully monitored circumstances. In order to guarantee enough strength and dimensional stability prior to the firing step, the moisture content of the produced pieces is progressively decreased during this process until it drops below 0.5%.

Biscuit Firing

The initial fire step in the manufacturing of sanitary ware is biscuit firing, which is often done at temperatures between 1200 and 1250 °C. At this point, the ceramic body becomes sufficiently strong without losing its porosity to create what is referred to as the "biscuit" body. Because it enables the subsequent glazing process to achieve high adhesion and uniform coverage, this regulated porosity is crucial.

Glazing and Glost Firing

The last steps in the manufacturing of sanitary ware are glazing and glost burning. In order to give the previously burned biscuit body a smooth, attractive, and protective coating, a glaze is carefully applied in this phase. After that, the ware is fired again at a temperature of around 1200–1250 °C, which vitrifies the glaze and the body. Durability, water resistance, and aesthetic appeal are guaranteed by the thick, hard, and non-porous end product produced by this technique [25, 26].

Sanitary Ware Shaping

Slip casting in plaster molds, which involves pouring the clay-rich slurry into molds, is the most popular forming technique. Clay's exceptional flexibility and particle binding abilities guarantee superior flow characteristics, forming, and simple demolding.

Vitrification and Firing

The usual temperature range for firing is 1200°C to 1250°C. Clay helps create the glassy phase at this stage, which gives the ceramic product its smoothness, watertightness, and resistance to heat shock and chemicals.

5. Technical Advantages Of Utilizing Clay

The preparation of ceramic sanitary ware bodies heavily relies on clay, whose technical benefits are linked to both production efficiency and product quality. The primary technical benefits are as follows:

Plasticity and Workability

In the manufacturing of sanitary ware, plasticity and workability are crucial qualities that are mostly supplied by the clay component. The ceramic body's high plasticity makes it simple to mold it during forming procedures like pressure or slip casting. Good mold conformance is ensured by this plastic behavior, which enables the slip to easily enter small features without leaving any flaws. In order to minimize deformation or damage during handling and drying, the body must also have enough green strength, which enables the.

Binding and Cohesion

Clay particles serve as a natural binder and are primarily responsible for the binding and cohesiveness of sanitary ware bodies. They maintain the structural integrity of the unfired body in the green stage by holding together the non-plastic elements like feldspar and quartz. In addition to improving the ceramic mixture's homogeneity, this binding action dramatically lowers the possibility of separation or cracking during shaping, drying, and handling before firing.

Suspension Stability in Slip

One of clay's most important functions in sanitary ware compositions is suspension stability in slip. Clay helps to maintain the non-plastic elements evenly suspended during slip casting, which reduces sedimentation and guarantees a constant composition throughout the casting process. The slip's thixotropic behavior, which improves its ability to flow into molds while maintaining enough structure for a smooth mold release, is further enhanced by the plate-like structure of the clay particles.

Controlled Drying Behavior

Another crucial role of clays, especially kaolin and ball clay, in the manufacturing of sanitary ware is controlled drying behavior. These clays lessen internal tensions by assisting in the more equal distribution of shrinkage throughout the body during the drying phase.

This reduces the possibility of warping, cracking, and deformation, guaranteeing that the formed parts retain their structural integrity and dimensional precision prior to biscuit burning.

Firing Performance

The clay minerals found in sanitary ware bodies have a major influence on their firing performance. Clays, especially kaolinite, undergo phase changes during firing that result in the creation of mullite, a stable ceramic phase that greatly increases the body's fired strength and resilience to thermal shock. Furthermore, clays work with fluxes like feldspar to encourage vitrification, which leads to the formation of a thick, impermeable microstructure. This combined effect guarantees that the finished product will fulfill the strict performance standards of sanitary ware by having minimal water absorption and mechanical durability.

Color and Surface Quality

The purity and properties of the clay materials employed have a significant impact on the color and surface quality of sanitary ware bodies as well as their firing performance. A white firing color is guaranteed by the extremely low iron and titanium content of premium kaolin and well-refined ball clays, which is essential for the sanitary ware's visual attractiveness. Additionally, their even distribution of particle sizes results in a finer surface finish on the fired body, making it simpler to apply glaze and guaranteeing a more consistent and flawless glazed surface.

Cost and Availability

Clays are abundant, relatively low-cost, and easily processed, making them an economical backbone material for sanitary ware production [27].

6. Limitations And Environmental Considerations

A thorough analysis of the drawbacks and environmental issues associated with the use of clay in the manufacture of ceramic sanitary ware is provided below:

Shrinkage and Warping During Firing

When clay is used to make sanitary equipment, shrinkage and warping during firing are frequent problems. Clay shrinks and may distort during the drying and high-temperature firing processes, which might affect the works' dimensional correctness. These impacts, if not properly managed, can lead to faulty goods like warped or twisted ware, which will eventually increase waste rates and lower manufacturing efficiency overall.

Porosity Before Glazing

Raw clay bodies are naturally porous before glazing, and they continue to be porous and extremely absorbent following the initial fire. The material is inappropriate for hygienic applications due to its inherent porosity, which allows it to easily absorb pollutants and water. In order to get over this restriction, glazing and glost firing are crucial manufacturing procedures that turn the porous biscuit body into a thick, sanitary, and water-resistant product fit for use in sanitary equipment.

Brittle Final Product

Even though clay-based ceramics are hard, they are also brittle and prone to cracking or chipping under impact.

Raw Material Variability

Variability in raw materials has a significant impact on sanitary ware quality. Depending on its geological origin, clay's qualities can differ greatly, which impacts the final product's uniformity and dependability. Changes in the distribution of particle sizes or mineral content might affect fire performance, drying behavior, and plasticity. Furthermore, the appearance and functionality of the ware may be compromised by the presence of impurities like iron or titanium oxides, which can cause flaws, discoloration, or surface irregularities.

Long Processing Time

Clay-based ceramics involve several stages (shaping, drying, firing, and glazing), making the manufacturing process time-consuming and resource-intensive [28].

7. Environmental Considerations of Clay Use

Non-Renewable Resource Extraction

Despite its seeming abundance, the exploitation of clay from non-renewable resources poses serious environmental issues. Clay is usually mined by open-pit extraction, which drastically changes ecosystems and natural landscapes. Such actions have the potential to degrade nearby habitats and produce long-term ecological disruptions by causing habitat loss, soil erosion, and dust pollution.

Energy-Intensive Firing

One of the main environmental issues in the manufacture of ceramics is energy-intensive firing. The procedure necessitates heating clay bodies to extremely high temperatures typically up to 1300 °C which needs a significant amount of energy. Since fossil fuels are often used to generate this energy, the process contributes significantly to greenhouse gas emissions and climate change.

Water Usage

Because huge amounts are needed for mixing, shaping, and cleaning operations, especially in the mass production of ceramics and sanitary ware, water use in clay-based industries is significant. This increased demand may put strain on nearby water supplies and lead to resource depletion if it is not properly managed. Furthermore, if wastewater produced while manufacturing is not well cleaned, it may contain chemicals, suspended particulates, or glaze leftovers, which can harm ecosystems and the environment.

Waste and Breakage

Since a sizable percentage of pieces may be rejected due to cracking, warping, or firing faults, waste and breakage are major problems in clay-based manufacturing. Because of their changed chemical and physical structure after fire, these faulty products are challenging to recycle. The majority of this garbage eventually ends up in landfills, adding to the wasteful use of resources and the environmental burden.

Difficult End-Of-Life Recycling

One of the main sustainability issues with clay-based ceramics is their difficult end-of-life recycling. Through their complex mineral makeup and irreversible alterations during firing, ceramics become non-biodegradable and very challenging to recycle once fired. Because of this, damaged or discarded ceramic pottery ends up in landfills for generations, adding to the accumulation of solid waste over time and having an adverse effect on the ecosystem [29, 30].

CONCLUSION

Clay remains an indispensable raw material in the sanitary ceramics industry due to its unique combination of plasticity, binding capacity, and firing performance. Its role extends beyond shaping to influencing the strength, whiteness, vitrification, and overall quality of the final products. By blending different types of clay, such as kaolin, ball clay, and bentonite, manufacturers can optimize workability, stability, and aesthetics. However, challenges such as shrinkage, porosity before glazing, and environmental impacts from extraction and energy-intensive firing must be addressed. Understanding and controlling clay properties is therefore essential not only for maintaining high production standards but also for advancing innovation and sustainability in sanitary ware manufacturing.

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CHAPTER 4
ENHANCEMENT OF COHESIVE SUBGRADE WITH MOORUM OVERLAY

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INTRODUCTION

Since the subgrade soil serves as the foundational layer that transmits loads to the ground, its strength and stability have a fundamental impact on the longevity and performance of pavement systems. The planned lifespan of road infrastructure might be jeopardized by a weak or troublesome subgrade, which can cause rutting, premature pavement degradation, and excessive maintenance costs (Yoder & Witczak, 1975). In India, where rural roads make up the majority of the road network, subgrade soil performance is very important for maintaining connectivity and fostering socioeconomic development.

Throughout the Indian subcontinent, soft cohesive soils are frequently found, especially in alluvial areas. Unwanted properties of these soils include creep under prolonged load, low resilience modulus, loss of strength upon saturation, high shrink-swell potential, and low shear strength (Das, 2016). They need stabilization or enhancement techniques to improve their engineering behavior because of these restrictions, which prevent them from being used directly as subgrade material in pavement structures.

1. India’s Road Network and the Importance of Rural Roads

At almost 63 lakh kilometers as of 2025, India has one of the world's largest road networks, with 72.97% of its length consisting of rural roads (MoRTH, 2024). The foundation of last-mile connection is made up of rural roads, which provide access to markets, healthcare, and education, promoting equitable growth and reducing poverty (World Bank, 2018).

Through programs like the Pradhan Mantri Gram Sadak Yojana (PMGSY), the Indian government has continuously made investments to develop the rural road network. With the PMGSY-IV program aiming for 62,500 km by 2029, PMGSY had built over 98,588 km of rural roads by July 2025 (National Rural Infrastructure Development Agency [NRIDA], 2025). The strategic significance of rural infrastructure is shown in the concurrent significant increase in investments in subsequent five-year plans, which went from ₹1165 crore in the sixth plan to ₹3100 crore in the seventh (Planning Commission, 1990).

Significant obstacles are presented by the expense of creating and maintaining such a vast rural network using traditional construction techniques.

To guarantee the lifespan and effectiveness of rural pavements, this calls for the adoption of cost-effective, long-lasting, and sustainable solutions.

2. India's Challenges of Weak Subgrades

Approximately 40% of India's geographical area is made up of alluvial soils, which presents significant engineering issues (Raychaudhuri, 1971). The Ganga, Damodar, and Kasai rivers have left behind alluvial soils, which predominate in states like West Bengal, Bihar, and Uttar Pradesh. Despite being fertile for agriculture, these soils are frequently inappropriate for road subgrades because of their cohesiveness and moisture sensitivity.

The following are the main issues with weak subgrades:

- Low shear strength, which causes depressions and rutting (Das, 2016).
- Seasonal cracking is a result of the high shrink-swell propensity.
- Wetting causes a loss of strength, particularly during monsoon seasons (IS:2720 Part 5, 1985).
- Under prolonged load, the pavement becomes less serviceable.
- Performance is compromised with frequent traffic loading due to a low robust modulus (IRC:37-2018).

Such soils undermine investments in road infrastructure by accelerating pavement deterioration if left untreated.

3. Soil Stabilization as a Remedial Measure

The practice of enhancing soil qualities including strength and durability through mechanical compaction, proportioning, or the use of stabilizing chemicals is known as soil stabilization (Sherwood, 1993). Indian road design standards (IRC:SP:72-2015) strongly advise it.

In general, the stabilization approach entails:

1. Soil property evaluation.
2. Deficits in soil behavior are identified.
3. Choosing appropriate stabilizing techniques (chemical, mechanical, or admixture-based).
4. Stabilized mixtures are designed to satisfy durability and strength specifications.
5. Cost-effective promotion of locally sourced materials.

Due to a lack of funding, the prevalence of troublesome soils, and the pressing need for sustainable development, soil stabilization is especially important in India (IRC:37-2018).

4. Alluvial Soils in West Bengal: A Case for Improvement

The landscape of West Bengal serves as an example of how important soil improvement efforts are. Much of the state is covered with alluvial soils, especially in the delta and northern plains. There are substantial alluvial deposits in districts like Murshidabad, Bankura, Burdwan, Hooghly, Birbhum, and Medinipur. While the earlier Vindhya alluvium on the Chotanagpur plateau produces soils with weaker mechanical qualities, North Bengal is dominated by the lush and fertile Ganga alluvium (Raychaudhuri, 1971).

These soils are not ideal as subgrades without alteration because of their cohesive character, which makes them prone to deformation under traffic stresses. Their extensive dispersion highlights the necessity of cost-effective stabilization methods according to regional circumstances.,

5. Moorum Overlay: An Economic and Practical Solution

It has been determined that morum, a lateritic soil that has broken down and is high in iron oxides, is a useful substance for improving subgrade. It has advantageous qualities including granular texture, good drainage, and adequate strength, and it is widely accessible in several Indian states (IS:1498, 1970).

Moorum has the following benefits when applied as an overlay over poor cohesive soils:

- Better load distribution, which lessens subgrade stress.
- Because of its drainage properties, it is less susceptible to moisture.
- Cost-effectiveness because it needs less processing and is readily available locally.
- Compatibility with chemical stabilizers, enabling integrated techniques for increased strength.
- Simplicity of construction, making it appropriate for rural construction projects (Rao & Reddy, 2012).

In rural India, where budgets are limited, moorum overlays are a good substitute for traditional aggregate bases because they provide a compromise between performance and affordability.

6. Relevance in the Indian Context

Adoption of economic stabilization strategies such as moorum overlay is not only desirable but essential in the Indian environment. Among the causes are:

1. Financial Sustainability: India's extensive rural road network cannot be sustained at the high expense of traditional pavement development.
2. Local Availability: Since morum deposits are widespread among states, transportation expenses are decreased.
3. Compliance with Sustainability Objectives: Utilizing locally sourced materials lowers carbon footprints related to quarrying and material transportation (IRC:SP:72-2015).
4. Vast Extent of Rural Roads: Since almost three-fourths of the country's road network is rural, moorum overlays can save a lot of money if they are used widely.
5. Socioeconomic Benefits: According to the World Bank (2018), long-lasting rural roads boost rural economies, facilitate agricultural trade, increase connectivity, and make schools and hospitals more accessible.

In India, improving soft cohesive subgrades with moorum overlays is a creative, cost-effective, and environmentally friendly method of building roads. This method uses locally accessible materials to save costs while addressing the engineering constraints of weak soils. The extensive rural road network, budgetary limitations, and the requirement for long-lasting solutions that can tolerate traffic demands and climate variations highlight its significance in the Indian setting.

India can guarantee long-term socioeconomic benefits by implementing stabilization techniques like moorum overlays, which will greatly improve the performance of its rural road infrastructure. As a result, the study is both pertinent and crucial since it supports national objectives for resource efficiency, equitable growth, and sustainable development.

Enhancing village road networks is essential for promoting rural economic development by making it easier to access markets, healthcare, and education. Many rural roads in India are built on clayey subgrades, which have poor drainage, high plasticity, and low shear strength.

These circumstances frequently result in increased maintenance expenses, decreased service life, and severe deformation. Therefore, subgrade enhancement—which is often measured using the California Bearing Ratio (CBR)—is necessary for sustainable rural road building.

Due of cost and environmental concerns, using locally accessible materials has drawn a lot of attention among the several subgrade rehabilitation strategies. Moorum, a gravelly lateritic soil that occurs naturally, has demonstrated promise in enhancing the strength properties of weak subgrades. It is a feasible material for low-cost road construction due to its abundance and advantageous geotechnical characteristics, particularly in areas with clayey or soft alluvial deposits.

Subgrade and sub-base stabilization with admixtures and substitute materials has been the subject of numerous investigations. Murty and Krishna (2023) looked into how to improve Telangana's moorum soils for rural road construction by adding cement and lime admixtures. In order to achieve the 20% soaking CBR criterion for gravel sub-base construction, they stabilized three distinct types of moorum soils with varying compositions and plasticities using 2%–3% cement. After seven days of curing, cement-stabilized sub-base courses with a cement content of 10–12% reached the necessary UCS of 17 kg/cm^2. The soaking CBR requirements for base layers were also met by a number of combinations, indicating the usefulness of these stabilized mixtures for rural roads. The mechanical characteristics of cementitious stabilized moorum materials (CSMM) for pavement design were investigated by Saurav and Sinha (2023). On Bihar moorum, they tested its flexural strength, indirect tensile strength, durability, shrinkage, UCS, and soaking CBR. In order to examine pavement performance, their study established correlations between these features. They came to the conclusion that strength and shrinkage characteristics were crucial in deciding if CSMM was acceptable for use as road base and sub-base. Using cement and lime for subgrade infill, Liu et al. (2023) improved overly damp red clay soil.

A 6% additional fraction raised UCS values above 0.6 MPa, according to laboratory tests using SEM, CBR, water absorption, and UCS. The amended soil also showed less water sensitivity and was simpler to compact. Stable subgrade moisture conditions were ensured by increased additive proportions, which also enhanced CBR values and decreased water absorption.

Field tests also showed that the enhanced clay was suitable for use as a subgrade. Barve and Sugandhi (2022) studied the stabilization of moorum with cement and bitumen emulsion, aiming to improve strength and water resistance. Tests showed significant increases in soaked CBR and UCS values with these stabilizers. For sub-base layers in rural roads, the optimal mix was 3% cement and 2% emulsion, ensuring durability and stability of the stabilized mixture. Amakye et al. (2022) investigated the sustainable stabilization of clay by substituting cement and lime in partial amounts (11.75% and 23.5%, respectively) with waste materials such as brick dust waste, GGBS, recycled plastic, and recycled glass. Atterberg limits, compaction, CBR, and swell characteristics were tested, and then pavement design using DMRB criteria was carried out. The results demonstrated notable decreases in swell (from ~5% to <1%) and increases in CBR values (from 8–9% to 57–97%), which allowed for a reduction in pavement thickness and structural loads while reducing fatigue and rutting susceptibility. The economic and environmental advantages of eco-friendly treated clay were further illustrated by life cycle cost and embodied carbon assessments.Triaxial tests were performed on red clay reinforced with basalt chopped fiber (BCF) and compared to polypropylene fiber (PPF) reinforcement by Zhao et al. (2021). In order to measure strength gains, their study used a reinforcing coefficient. They found that BCF greatly improved cohesion but had no influence on the internal friction angle. Under the same conditions, BCF demonstrated faster strength improvements than PPF, indicating its efficiency in stabilizing clay. The ideal fiber length for reinforcement was 10–13 mm. The application of moorum mixed with different proportions of fly ash (0–30%) for building road embankments was assessed by Turkane and Chouskey (2021). For moorum-fly ash blends, the study evaluated Atterberg limits, specific gravity, grain size, compaction, direct shear, and CBR testing.

Their research shed light on the improvements in slope stability and geotechnical properties brought about by fly ash blending in embankment building. Taking into account better subgrade techniques, Prasad and Reddy (2021) used the CBR method to build flexible pavements on brown and black clay subgrades. Designs included CNS cushion layers and sand blankets for black clay.

They examined the financial effects of various upgrading techniques and discovered that while improved subgrades improved pavement performance, they also raised construction costs by 18% for brown clay and 5% for black clay. Rameez and Malik (2020) investigated how bitumen emulsion for water resistance and cement for strength could improve moorum. Although it pointed out that this strategy greatly raised building and maintenance expenses, the study concentrated on raising CBR and UCS values. It was determined that using locally accessible moorum in flexible pavements was a more affordable option than developing costly asphalt pavements. The impact of gravel and red clay mixtures on road performance was examined by Zeng et al. (2018). Red clay displayed twin peaks in compaction curves, with the second peak being the actual maximum dry density, according to compaction experiments. Dry density and CBR values were increased by adding gravel and controlling the vibration settings (the ideal gravel content was 30%, the vibration frequency was 45 Hz, and the vibration time was 5 minutes). They suggested appropriate subgrade construction techniques utilizing red clay-gravel combinations in light of their findings.The impact of a compacted fly ash layer on top of a soft clay subgrade was investigated by Sengupta et al. (2017), who concentrated on factors like the ratio of fly ash to soil thickness, compaction energy, and molding water content. Significant CBR augmentation was observed in the data, especially at higher fly ash layer thicknesses (2:1 ratio). In the best circumstances, the CBR values for fly ash-soil composites rose from 3.24% for untreated clay to as high as 32.73%.

The use of moorum overlays directly over soft clay subgrades without chemical stabilization has received little attention, according to the literature that is currently available. For rural roads, this approach provides a straightforward, reasonably priced, and field-implementable solution.

In places where conventional stabilization materials are either unavailable or not economically viable, it can be very advantageous. Therefore, the purpose of this study is to assess how applying moorum overlays with different thickness ratios can improve the California Bearing Ratio (CBR) of soft clay subgrades and to examine how this improvement affects the performance of flexible pavements built over these clayey subgrades.

7. Materials And Methods

Clay

Clay, a soft, compressible soil, was acquired for this investigation from Barrackpore, 24 Parganas (North). Laboratory testing in compliance with applicable IS regulations have established the clay's geotechnical characteristics. The findings are shown in Table 1 below.

Moorum

Clay and moorum taken from Kantabani, Bankura, West Bengal, have been subjected to laboratory tests in the current study. Through laboratory testing carried out in compliance with pertinent IS regulations, the geotechnical characteristics of moorum have been established. The findings are shown in Table 1 below:

Table 1. Properties of Clay and Moorum

Characteristics	**Value**	
	Clay	**Moorum**
Specific Gravity	2.42	2.66
Particle Size Distribution		
a) Sand (%)	24	63
b) Silt (%)	59	09
c) Clay (%)	17	28
Liquid Limit (%)	40	41
Plastic Limit (%)	19	18
Plasticity Index (%)	21	23
Classification of Soil	CH	CH
Standard Proctor Test		
a) Maximum Dry density **(kN/m^3)**	16.6	21
b) Optimum Moisture Content	16	12

Test Program

The performance of clay, moorum, and the clay–moorum matrix under varied moisture conditions will be assessed by the testing program that follows. In the clay–moorum matrix, a 1:1 thickness ratio has been maintained by overlaying moorum on top of compacted clay. In Table 2, the comprehensive exam schedule is displayed.

Table 2. Summary of Proposed Test Program

<table>
<tr><th>Material</th><th>Sl. No.</th><th>Thickness Ratio</th><th>Test</th><th>Moulding Water Content</th></tr>
<tr><td>Clay</td><td>1</td><td>-</td><td>CBR (Soaked)</td><td>At OMC</td></tr>
<tr><td>Moorum</td><td>2</td><td>-</td><td>CBR (Soaked)</td><td>At OMC</td></tr>
<tr><td rowspan="4">Clay-Moorum Matrix</td><td>3</td><td rowspan="4">1:1</td><td rowspan="4">CBR (Unsoaked and Soaked)</td><td>Clay and Moorum at OMC,</td></tr>
<tr><td>4</td><td>Clay at OMC+2%, Moorum at OMC</td></tr>
<tr><td>5</td><td>Clay at OMC+4%, Moorum at OMC</td></tr>
<tr><td>6</td><td>Clay at OMC+6%, Moorum at OMC</td></tr>
</table>

In compliance with IS: 2720 (Part 16) – 1987, which outlines the standard process for calculating the CBR value of soil, the California Bearing Ratio (CBR) tests have been carried out. In accordance with IS: 2720 (Part 7) – 1980, sample compaction was performed using light compaction (Standard Proctor) to replicate the subgrade conditions of normal low-volume rural roads. In terms of CBR, which is crucial for enhancing subgrade performance in flexible pavement design, this experimental program has been developed to better understand the impact of molding moisture change in the clay layer on the strength behavior of the clay–moorum matrix.

Test Results

Soaked samples of clay and moorum under light compaction have been subjected to the California Bearing Ratio (CBR) tests. Figure 1 displays the relevant load-penetration curves.

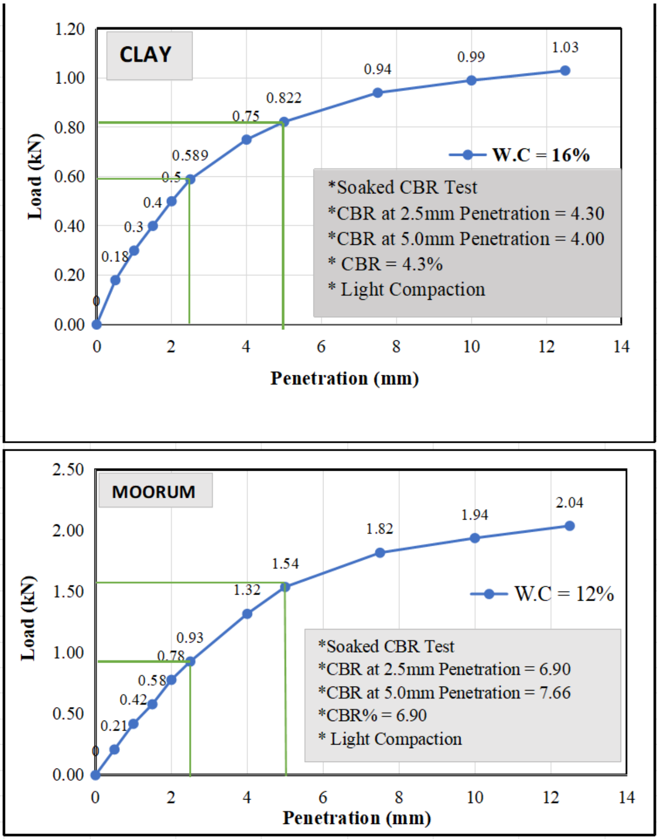

Figure 1. Soaked CBR Results for Clay and Moorum

At a water content of 16% (OMC), the soaking CBR values for clay at 2.5 mm and 5.0 mm penetrations were found to be 4.30% and 4.00%, respectively, suggesting low load-bearing capacity. With soaking CBR values of 6.79% and 7.52% at 2.5 mm and 5.0 mm, respectively, moorum has demonstrated superior performance. According to IS: 2720 (Part 16) – 1987, the final CBR has been calculated to be 7.52% at a water content of 12% (OMC).

Figures 2 and 3 show typical load-penetration curves for wet and unsoaked CBR testing on the clay–moorum matrix, with the molding water content for both clay and moorum kept at OMC.

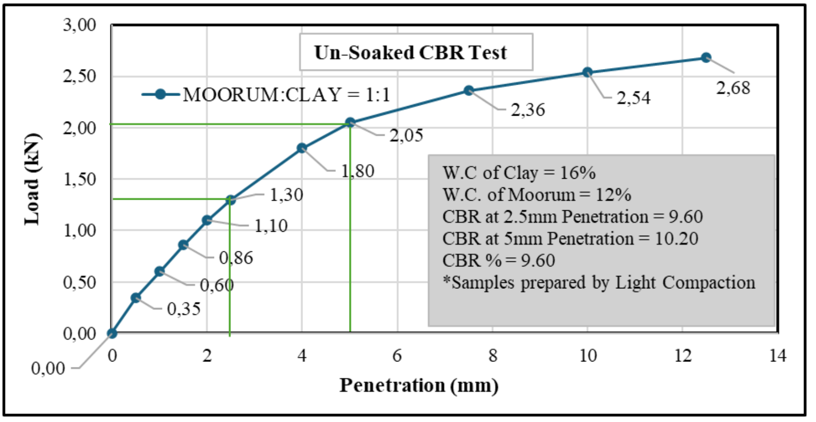

Figure 2. Load-Penetration Curve for Clay- Moorum Matrix (Unsoaked)

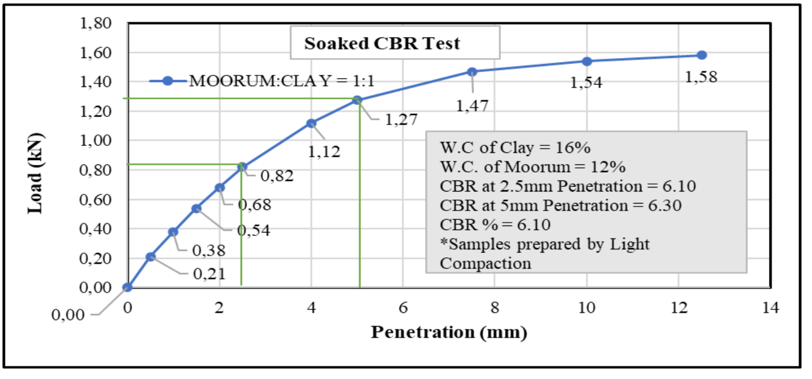

Figure 3. Load-Penetration Curve for Clay- Moorum Matrix (Soaked)

Table 3 provides a summary of the relevant CBR test findings for various moisture conditions in the clay–moorum matrix (1:1 thickness ratio).

Table 3. CBR Results for Clay-Moorum Matrix

Material	Moulding water Content	CBR Results	
		Unsoaked	Soaked
Clay-Moorum Matrix (Thickness 1:1)	Clay and Moorum at OMC,	9.6	6.1
	Clay at OMC+2%, Moorum at OMC	8.8	5.8
	Clay at OMC+4%, Moorum at OMC	8.0	5.3
	Clay at OMC+6%, Moorum at OMC	6.9	4.7

8. Numerıcal Anaylsıs By Iıt-Pave

In this study, IITPAVE, a software program created by IIT Kharagpur under MoRTH Research Scheme R-56, has been used to assess the pavement thickness for two subgrade types: clay and clay–moorum matrix. IITPAVE, an improved FPAVE, is frequently used to analyze the structure of flexible pavements utilizing a multi-layer linear elastic model. In order to study pavement reaction under various loading conditions, the application uses the Finite Element Method (FEM), taking into account variables including traffic load, material qualities, and environmental impacts. It computes important reactions that are important markers of wear and rutting potential, such as vertical compressive strain at the top of the subgrade and horizontal tensile strain at the bottom of the bituminous layer. The software is used to simulate pavement behavior by entering design data such layer thickness, CBR values, tire pressure, wheel load, and material qualities. A thorough evaluation of pavement performance is made possible by the output, which contains stresses, strains, and deflections at critical locations. CBR values and traffic data serve as the foundation for establishing suitable layer thicknesses in the analysis, which adheres to the design guidelines specified in IRC:37-2018. IITPAVE has been a useful tool in the pavement design process for this study because of its analytical capabilities and practical interface.

8.1 Input parameters

The main input variables utilized in IITPAVE to analyze pavement performance requirements are compiled in Table 4:

Table 4. Input parameters for the Clay and Clay-Moorum Matrix pavement performance criterion analysis

Sl. No.	Description of input parameters	Particulars
1	Air voids (V_a)	3.50%
2	Binder content (V_{be})	11.50%
3	Resilient Modulus of Bitumen (Mr)	3000 MPa
4	Sub Base - 1 (Separation layer)	GSB - Gr. - V
5	Sub Base - 2 (Drainage layer)	GSB - Gr. -III
6	Base – 1	WMM
7	Binder Course	DBM
8	Wearing Course	BC
9	Ambient Temperature	35° C
10	Design Traffic (Rutting life for granular layer) *	13.74 MSA
11	Design Traffic (Fatigue life for bituminous layer) *	13.74 MSA

[* Note 1: "Improvement of Performance of a Cohesive Subgrade Modified with Tyre Scrap for Flexible Pavement" (2024), presented by Sujoy Sarkar to Jadavpur University, is where the design traffic values were obtained.
Note 2: Every other value is derived from IRC:37-2018.]

The critical stresses for pavement performance evaluation have been computed based on these parameters and in compliance with IRC:37-2018. At the top of the subgrade, the maximum vertical compressive strain (εv) is 0.0006276, and at the bottom of the bituminous layer, the maximum horizontal tensile strain (εt) is 0.0003325. When evaluating rutting and fatigue performance in flexible pavement design, these strain values are crucial markers. The structural performance of pavements built over clay and clay-moorum subgrades has been evaluated using these values in IITPAVE. The clay-moorum matrix subgrade's soaked CBR values, which are shown in Table 3, have been taken into consideration for this study's thickness design utilizing IITPAVE.

8.2 Output from IITPAVE

The structural performance of pavements built over clay and clay–moorum matrix subgrades has been assessed using trial pavement thickness analysis using IITPAVE software.

Table 5. Results obtained from IITPAVE

Layers		Analysis Cases				
		Clay at OMC (16%)	**Clay-Moorum Matrix (1:1) at OMC (16%)**	**Clay-Moorum Matrix (1:1) at OMC+2 % (18%)**	**Clay-Moorum Matrix (1:1) at OMC+4 % (20%)**	**Clay-Moorum Matrix (1:1) at OMC+6 % (22%)**
Bituminous Layer	BC	30mm	30mm	30mm	30mm	30mm
	DBM	70mm	55mm	60mm	60mm	65mm
Granular layer	WMM	250mm	250mm	250mm	250mm	250mm
	GSB	180mm	150mm	150mm	160mm	160mm
Total Pavement thickness		530mm	485mm	490 mm	500 mm	505 mm
Calculated tensile train at bottom of bituminous layer		0.0003259	0.0003262	0.0003191	0.0003242	0.0003197
Calculated Vertical Strain at Subgrade		0.0006098	0.0005830	0.0005841	0.0005847	0.0005894

9. Results and Discussion

The results of laboratory and numerical analyses conducted to assess the performance of clay and clay–moorum matrix subgrades for flexible pavements are presented in this section. Strength at varying moisture conditions has been evaluated in laboratory testing, such as wet and unsoaked CBR.

Pavement reaction has been examined using IITPAVE software in accordance with IRC:37-2018, with 80% reliability, based on the soaking CBR values. The analysis focuses on horizontal tensile strain at the bottom of the bituminous layer and vertical compressive strain at the top of the subgrade.

9.1 Variation of CBR with Moulding Water Content

Based on the information in Table 3, Figure 4 illustrates how the CBR of moorum overlay over clay (1:1) varies under mild compaction energy and varying clay molding moisture content. The moorum's OMC, or 12%, has been maintained for the moulding water.

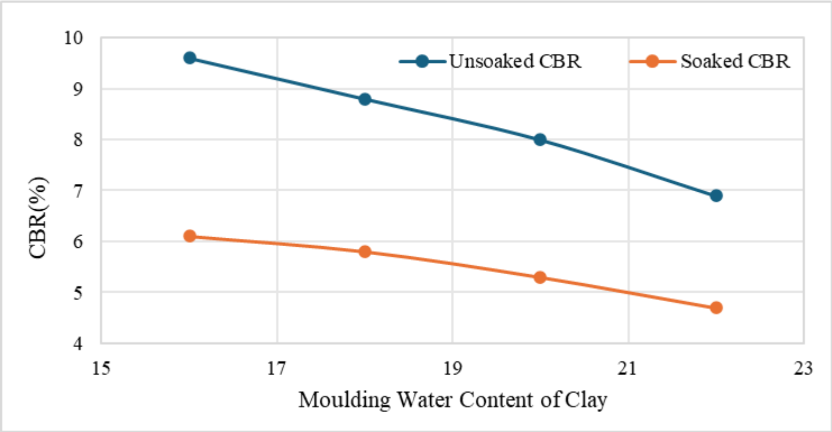

Figure 4. Variation of CBR of Moorum Overlay on Clay (1:1) under Light Compaction Energy and Different Moulding Moisture Content

The figure shows how variations in moisture affect the clay-moorum matrix's strength properties as determined by the California Bearing Ratio (CBR) test. The CBR values of the composite soil progressively decrease as the molding water content of the clay component rises when the moorum is kept at its Optimum Moisture Content (OMC). This pattern highlights how important moisture equilibrium is to the soil matrix. Compaction of clay and moorum at their respective OMCs yields the highest CBR values. At this point, the soil mixture reaches its maximum density and the particles form stronger links with one another, increasing its ability to support loads.

The soil system's most effective packing and bonding configuration is represented by this advantageous state.

However, a consistent drop in both soaked and unsoaked CBR values is noted after the clay fraction is exposed to moisture levels that are 2%, 4%, and 6% higher than its OMC. The way cohesive soils behave when exposed to too much water explains the strength loss. More moisture causes the pore water pressure to increase while the effective stress decreases at the same time. This reduces the soil's capacity to withstand applied loads by weakening the soil skeleton and upsetting the structural arrangement of clay particles..

The effect is significant in terms of numbers. A reduction of 22.9% is achieved when the soaking CBR value drops from 6.1% to 4.7%. The decline in the unsoaked CBR is significantly more noticeable, going from 9.6% to 6.9%, with a maximum reduction of 28.12%. These numbers unequivocally demonstrate how sensitive the clay-moorum mixture is to changes in water concentration.

The results highlight how important moisture control is to obtaining dependable subgrade performance. Strength can be significantly weakened by even minor departures from the OMC, especially in soil systems that contain clay fractions. This suggests that rigorous control of compaction moisture during construction is necessary for field applications in order to guarantee the pavements' long-term serviceability and durability. Therefore, it is not only desirable but also essential to keep the clay-moorum matrix near its OMC in order to preserve the best possible subgrade strength and reduce failures under traffic loads.

9.2 Variation of Pavement Thickness with Moulding Water Content

Table 6 illustrates how the molding water content of the clay–moorum matrix has a substantial impact on the necessary pavement thickness, according to the IITPAVE analysis results.

Table 6. Effect of Moulding Water Content on Pavement Thickness (from IITPAVE Analysis)

Subgrade Condition	Total Pavement Thickness (mm)	% Decrease in Thickness
Clay at OMC (16%)	530	–
Clay–Moorum Matrix (1:1) at OMC (16%)	485	8.49%
Clay–Moorum Matrix (1:1) at OMC + 2%(18%)	490	7.55%
Clay–Moorum Matrix (1:1) at OMC + 4%(20%)	500	5.66%
Clay–Moorum Matrix (1:1) at OMC + 6%(22%)	505	4.72%

Studying composite soil systems, such the clay–moorum matrix, offers important insights into how the behavior of the subgrade affects the specifications for pavement construction. When clay and moorum are mixed in a 1:1 ratio and molded at varying water concentrations, Table 6 shows how the necessary pavement thickness varies. The findings unequivocally show how moisture control affects California Bearing Ratio (CBR) values, which in turn affect pavement thickness as advised by IITPAVE analysis.

The baseline pavement thickness is determined to be 530 mm for clay utilized alone at its Optimum Moisture Content (OMC) of 16%. When clay serves as the only subgrade material, this is the design thickness required to guarantee proper performance. Although clay is reasonably effectively compacted at its OMC, a slightly thicker pavement section is necessary to withstand repeated traffic loads because of its intrinsic cohesive nature, low shear strength, and propensity to lose stability when wet.

The planned pavement thickness is greatly reduced to 485 mm when clay and moorum are mixed in a 1:1 ratio and molded at the same OMC. When compared to the pure clay subgrade, this represents an 8.49% decrease in thickness.

The reduction can be ascribed to the advantageous function of moorum, which has superior drainage qualities, stiffness, and granular strength in comparison to clay. Its incorporation into the matrix raises the soil system's overall CBR value, which raises the subgrade's load-bearing capability. The subgrade's CBR strength is directly related to the IITPAVE design thickness, so a higher strength means a thinner pavement is needed. This demonstrates unequivocally how soil modification can result in significant material quantity reductions without sacrificing structural performance.

The pavement thickness starts to increase once more, rising between 490 mm and 505 mm, as the molding water content of clay is raised beyond its OMC by increments of 2%, 4%, and 6%. The thickness increases by 4.12%, from 485 mm to 505 mm, between OMC and OMC + 6%. This pattern emphasizes how too much water damages the soil matrix's clay component. The extra moisture fills the gaps, raises the pore water pressure, and breaks the inter-particle bonding in the clay when the water concentration surpasses OMC. The soil structure becomes more compressible and the cohesive strength decreases. As a result, the CBR values drop, necessitating a thicker pavement section to make up for the decreased strength.

The strength increases in this case are somewhat counterbalanced by the loss of cohesion and frictional resistance inside the clay, even if the moorum still offers structural advantages due to its stiffness and granular characteristics. Thus, as the equilibrium shifts unfavorable due to excessive moisture, the total thickness of the pavement starts to increase. The results highlight how important it is to regulate moisture during compaction, particularly in mixed soil systems where one component is extremely sensitive to water content.

The IITPAVE analysis's findings highlight the usefulness of clay-moorum matrices in road construction. This blend can successfully improve subgrade performance while lowering construction material needs, as seen by the notable reduction in pavement thickness at or around OMC. In the Indian setting, where resource limitations and the demand for affordable rural road solutions are urgent issues, such reductions are especially pertinent. For low-to-medium traffic roads, the clay-moorum system provides a cost-effective and environmentally friendly alternative by permitting thinner pavement designs without sacrificing strength.

Furthermore, because moorum is readily available locally in many parts of India, particularly in areas with lateritic and red soil, its usage as a stabilizing agent is very practical. Its use in rural road projects funded by programs like the Pradhan Mantri Gram Sadak Yojana (PMGSY) may result in significant construction cost savings as well as enhanced long-term performance. Adopting such soil alteration techniques could increase pavement life, lower maintenance requirements, and promote more sustainable infrastructure development in areas with primarily cohesive subgrades.

In summary, the IITPAVE study's findings emphasize three important ideas. First, the CBR is greatly increased by mixing clay and moorum in equal amounts and compacting at OMC, which lowers the need for pavement thickness by over 9%. Second, this improvement is less effective when the water content is higher than OMC, leading to slight improvements in pavement thickness. Third, the results validate the clay-moorum matrix's promise as a workable and cost-effective subgrade rehabilitation method, particularly for low-traffic and rural roads where durability, affordability, and sustainability are equally important.

9.3 Variation of Strain of Subgrade with Moulding Water Content

The IITPAVE analysis revealed that the vertical compressive strain at the top of the subgrade is greatly influenced by variations in the molding water content. Table 7 shows the % reduction in strain when compared to the base case of clay subgrade compacted at its Optimum Moisture Content (OMC) as well as the vertical strain values for various clay and clay–moorum matrix combinations.

Table 7. Vertical Strain on Subgrade and Percentage variation for clay–moorum matrix (IITPAVE results)

Case Description	Vertical Strain on Subgrade	% Variation (w.r.t. Clay at OMC)
Clay at OMC (16%)	0.0006098	0.00%
Clay-Moorum Matrix (1:1) at OMC (16%)	0.0005830	4.39%
Clay-Moorum Matrix (1:1) at Clay OMC+2% (18%)	0.0005841	4.22%
Clay-Moorum Matrix (1:1) at Clay OMC+4% (20%)	0.0005847	4.11%
Clay-Moorum Matrix (1:1) at Clay OMC+6% (22%)	0.0005894	3.34%

The findings unequivocally show that the moorum overlay over clay has continuously decreased the subgrade's vertical compressive strain. When both clay and moorum are compacted at their respective OMCs, the greatest reduction (4.39%) is seen. This improvement is ascribed to the clay–moorum matrix's improved compaction properties and higher rigidity. However, the vertical strain rises from 0.0005830 to 0.0005894, or 1.10%, from OMC to OMC + 6%. Though the values are still lower than those of the original clay subgrade, the vertical strain somewhat increases as the molding water content of clay rises above its OMC because the extra water weakens the soil matrix

CONCLUSIONS

The current investigation may lead to the following conclusions:

1. The CBR performance at Optimum Moisture Content (OMC) is greatly enhanced by adding moorum overlay in a 1:1 ratio with clay. However, the CBR values decrease as the clay's molding water content rises over OMC; unsoaked, they go from 9.6% to 6.9%, and soaked, they go from 6.1% to 4.7%, with the highest reductions being 28.12% and 22.9%, respectively.
2. The necessary pavement thickness is reduced by 8.49% from the typical clay subgrade, from 530 mm (clay at OMC) to 485 mm (clay–moorum at OMC).

As the water content of OMC increases, the thickness of OMC+6% grows from 485 to 505 mm, a 4.12% increase. The first decrease demonstrates the enhanced subgrade's capacity to support loads, while the minor recovery at higher moisture levels demonstrates how excessive water degrades strength and stiffness.

3. Due to better compaction and greater matrix stiffness, IITPAVE analysis reveals that the greatest decrease in vertical strain (4.39%) happened when both clay and moorum were compacted at their respective OMCs. However, the vertical strain rises by 1.10% from OMC to OMC + 6%, suggesting a minor deterioration in subgrade performance with additional moisture.

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