Eggshell-Derived Additives in Clay Bodies for Sustainable Decorative Ceramic Tiles.

[1]Dipeolu, H. A and [2]Faleye, O. A

[1]Fine and Applied Arts Education Department
[2]Chemistry Education Department
Federal College of Education (Technical), Akoka, Lagos, Nigeria
dipeoluhakim@gmail.com

Abstract

Nigeria generates about millions of tons of eggshell bio-waste annually, most of which is discarded by informal food vendors, bakeries, and households, creating a significant environmental burden. This study explores the use of eggshell powder composed of roughly 94% calcium carbonate as a sustainable additive in clay bodies for ceramic tile production. The chemical basis lies in the decomposition of calcium carbonate during firing, which releases CO_2 *and forms calcium oxide. This promotes liquid phase sintering, densification, and new mineral phases that enhance mechanical strength and surface quality. Collected eggshells were processed into fine (75 micrometres) and coarse (150 to 300 micrometres) fractions, incorporated into clay at 0–20 weight (wt%), and fired at 900°C, 1000°C, and 1100°C. Tiles were tested for modulus of rupture, porosity, shrinkage, water absorption, and surface finish. Results showed that fine eggshell powder at 10 wt% fired at 1100°C yielded the best performance, with an 18% increase in flexural strength and the lowest porosity (3.2%). Porosity decreased with higher firing temperatures, while shrinkage increased with both temperature and eggshell content. Fine fractions improved surface smoothness at ≥1000°C, whereas coarse fractions at 15–20 wt% caused blistering and high porosity due to localised* CO_2 *release. Overall, the study demonstrates that controlled incorporation of eggshell powder, optimising particle size, proportion, and firing temperature, offers a technically viable, low-cost, and eco-friendly route for ceramic tile production in Nigeria. This approach provides a replicable model for valorizing food industry bio-waste within the domestic ceramics sector.*

Keywords: Eggshells, Ceramic Tiles, Clay Bodies, Sustainability, Waste Management

Introduction

The utilisation of waste materials in industrial processes has gained significant attention in recent years, driven by the need for sustainable practices and environmental conservation. Eggshells are rich in calcium carbonate and have shown potential as an additive in various applications (Murakami et al., 2012; Stadelman, 2010). Eggshells are typically discarded as waste in all environments in Nigeria, such as the Aboki centres known as Ma tea or Ma shai, as popularly called by many in Nigeria in the local language, bread bakeries, small chop baker centres, and some people who use eggshells for other purposes like scoring powder agent and toothpaste gel, among others (Ayorinde et al., 2019; Maduka & Obi, 2021). Environmental pollution from various waste bins in our environment, among which eggshells cannot be eliminated due to the odour after cracking; however, their high calcium carbonate content makes them a valuable local resource material for enhancing the chemical properties of clay in ceramics (Ayorinde et al., 2019; Rahaman, 2010). Other materials like tyres, paper mill, plastics, and wood dust have also been added to clay to reduce the plasticity and weight, but none can withstand the long duration of the heat process of ceramics firing before they evaporate off (Eliche-Quesada et al., 2012; Kumar & Chen, 2021). Eggshells can be more sustainable under the ceramics firing process (Rahaman, 2010; Sutcu & Akkurt, 2021). Granite and other local stones have also been used to strengthen ceramic clay, but these stones increase the weight and delay the maturity of the clay in the firing process (Dondi et al., 2014; Raimondo et al., 2012). Eggshell, in its nature, can also give the same chemical properties as the clay by reducing the weight and firing time. Previous research has indicated that calcium carbonate can improve the strength and durability of ceramics (Smith, 2020). The utilisation of eggshell waste can address waste management issues while also contributing to sustainable practices in the ceramics studio and industry. Composed of roughly 94 to 95 percent calcium carbonate ($CaCO_2$), with the remaining components including proteins, magnesium carbonate, calcium phosphate, and various organic substances arranged in a hierarchically structured layered microarchitecture, eggshells exhibit a distinctive amalgamation of mechanical, chemical, and structural characteristics that render them particularly advantageous as a functional ingredient in ceramic body composition (Stadelman, 2010; Murakami et al., 2012). The preliminary laboratory findings (Ayorinde et al., 2019) suggest that adding eggshells to clay bodies can significantly improve the overall quality of ceramic tiles.

The crystalline arrangement of the palisade layer in the eggshell microstructure, defined by columnar calcite crystals in a radially organised matrix, imparts remarkable compressive strength and regulated porosity to the shell structure while preserving an exceptionally low specific weight. This unique combination of properties has garnered significant interest from materials scientists pursuing sustainable alternatives to traditional synthetic additives in ceramic, construction, pharmaceutical, and cosmetic manufacturing (Döbelin & Kleeberg, 2015; Tsai et al., 2016). Notwithstanding the extensively documented material potential, the vast majority of eggshell waste produced annually by night food vendors, street eateries, small-scale bakers, and urban households in Nigerian cities remains discarded without recovery or productive reuse, exacerbating the accumulation of organic waste in urban settings and signifying a substantial and largely overlooked opportunity for the valorisation of a locally abundant bio-waste resource in domestic ceramic manufacturing. The global ceramic tile industry is a prominent and swiftly growing segment of the construction materials market, with ceramic tiles serving as essential building elements. Their durability, chemical resistance, moisture permeability, and aesthetic versatility render them indispensable in modern architectural practice, applicable to both residential interiors and large-scale public structures (Dondi et al., 2014).

Contemporary ceramic tiles are composite materials meticulously crafted from precisely balanced blends of clay minerals, feldspar, silica, and assorted functional additives, subjected to a series of processes including body preparation, forming, drying, and controlled firing, aimed at attaining defined physical and mechanical characteristics such as modulus of rupture, water absorption, linear firing shrinkage, surface hardness, and dimensional stability (Raimondo et al., 2012).

The increasing incorporation of ceramic tiles into green building initiatives and sustainable urban development programmes has heightened research interest in developing tiles that enhance functional performance while concurrently minimising the environmental impacts of raw material extraction, energy consumption, and industrial waste generation associated with traditional ceramic tile production (Eliche-Quesada et al., 2012).

Ceramic additives, which include various materials added to ceramic body formulations to alter processing behaviour and affect microstructural development during sintering, are crucial in determining the physical, mechanical, and aesthetic properties of the final ceramic product (Rahaman, 2010). Kumar and Chen (2021) demonstrate that additives such as dispersants, binders, plasticisers, and sintering aids impact various stages of the ceramic production process, regulating rheological properties during mixing and forming, influencing drying behaviour and green strength in the unfired body, and engaging in the intricate sequence of physico-chemical reactions including sintering, vitrification, liquid phase formation, and mineral phase transformation during firing, ultimately determining the microstructural characteristics and mechanical properties of the fired ceramic.

The application of eggshell-derived calcium carbonate as a ceramic additive has garnered increasing scholarly interest in recent years, with studies indicating positive effects (Sutcu & Akkurt, 2021) on the densification, mechanical strength, and surface properties of fired ceramic bodies across various clay compositions and firing temperatures. Ayorinde et al. (2019)

document notable enhancements in flexural strength and decreases in water absorption in ceramic tiles containing eggshell powder at optimised addition levels, ascribing these enhancements to the flux activity of calcium oxide from calcite decomposition and its function in facilitating liquid phase sintering and pore closure during firing.

The predominant body of research on bio-waste additives in ceramics has been undertaken within European, North American, or East Asian contexts, utilising base clay bodies, firing apparatus, and quality evaluation standards that may not be directly relevant to the unique clay mineral compositions, firing temperature ranges, and performance criteria inherent to Nigerian ceramic tile manufacturing. Maduka and Obi (2021) contend that the valorisation of locally generated bio-waste materials in Nigerian ceramic production represents an environmental imperative and a significant commercial prospect, emphasising that the progression of practically applicable formulation knowledge requires experimental research specifically designed for the relevant raw materials, processing conditions, and performance criteria within the Nigerian production context. This research gap constitutes the primary academic and practical justification for the present study, which seeks to address it through a controlled experimental investigation of eggshell powder integration in a standard Nigerian clay body, systematically analysing varied particle size fractions, addition proportions, and firing temperatures, thereby producing empirical knowledge directly relevant to improving ceramic tile production in the Nigerian ceramic manufacturing industry.

Materials and Methods

A controlled experimental methodology was adopted in this study, using eggshell waste collected over 8 weeks from 5 major sources within Lagos State, Nigeria. These sources were categorised into five locations: domestic households, bread bakeries, pastry and cake production centres, roadside food vendors and small restaurants, and fast-food outlets. Collected eggshells were cleaned with warm water and detergent to remove any leftover albumen, maggots, and odour, air-dried for four days, and then oven-dried at 105°C for 24 hours to remove moisture.

The dried eggshells were crushed by hand, then pulverised with a locally made cast-iron hand-operated grinder, and finally sieved with a 120-mesh sieve (125 μm aperture) to separate fine and coarse particles. Fine particles were about 75 μm, while coarse ones ranged from 150 to 300 μm and were incorporated into a standard earthenware clay body at weight proportions of 0 wt%, 5 wt%, 10 wt%, 15 wt%, and 20 wt%, and fired at temperatures of 900°C, 1000°C, and 1100°C. Thorough physical, mechanical, and microstructural characterisation was done thereafter.

Eggshell powders were mixed into a standard kaolin-based clay at 0%, 5%, 10%, 15%, and 20% by weight. Water was added to make the clay workable, and it was then shaped into tiles measuring 100 mm by 100 mm by 10 mm. The tiles were dried at room temperature for 14 days, then fired in an electric kiln at 900°C, 1000°C, and 1100°C, with a heating rate of about 100°C per hour and held at the top temperature for one hour.

After firing, the tiles were tested for physical and mechanical properties. Porosity and water absorption were measured in accordance with ASTM C373. The flexibility strength was assessed with a two-point bending test. Linear shrinkage was tested by comparing dimensions before and after firing, and surface quality was evaluated visually and through pictures. After preparing the eggshell powders, several batches of clay mixtures were made and mixed by hand, and the clay was kneaded several times to make it even and to remove any trapped air. Tile samples were shaped with plaster moulds and left to dry for two weeks. Once dry, the samples were bisque-fired, then fired again at 900°C, 1000°C, and 1100°C.

Different clay body compositions used in this study are shown in Table 1 with 5 % water content, Table 2 with 10% water content, and different firing temperatures in Table 3. Each sample was labelled with its composition and firing temperature, then tested for flexibility strength, porosity, shrinkage, water absorption, and surface finish.

Table 1: Composition of Clay Bodies Containing 5% Water

Composition Code	Clay Powder (Kaolin)	Eggshell Powder	Water	Total
A2	60%	35%	5%	100%
B1	70%	25%	5%	100%
B2	80%	15%	5%	100%

Table 2: Composition of Clay Bodies Containing 10% Water

Composition Code	Clay Powder (Kaolin)	Eggshell Powder	Water	Total
C1	50%	40%	10%	100%
C2	60%	30%	10%	100%
D1	70%	20%	10%	100%

Results

Table 3: Physical and Mechanical Properties of Eggshell-Modified Ceramic Tiles Fired at Different Temperatures

Composition Code	**Firing Temp. (°C)**	**Flexibility Strength (Modulus of Rupture)**	**Apparent Porosity (%)**	**Linear Shrinkage (%)**	**Surface Finish Quality**
Control (0 wt%)	1100	Baseline	5.8	2.5	Moderate, slightly porous
A2 (35% eggshell, electric)	900	Reduced vs. control	8.2	1.8	Rough, porous surface
B1 (25% eggshell, electric)	1000	Slight improvement	6.0	2.2	Improved smoothness
B2 (15% eggshell, electric)	1100	+12% vs. control	4.0	3.0	Dense, smooth surface
C1 (40% eggshell, firewood)	900	Reduced strength	9.5	1.5	Blistered surface
C2 (30% eggshell, firewood)	1000	Moderate improvement	6.8	2.4	Slightly smoother
D1 (20% eggshell, firewood)	1100	+10% vs. control	4.5	3.2	Dense, improved finish
Fine fraction (10 wt%)	1100	**+18% vs. control (optimal)**	**3.2 (lowest)**	3.5	**Smooth, homogeneous**
Coarse fraction (15–20 wt%)	900–1100	Reduced strength, blistering	7.5–9.0	2.0–3.0	Poor, blistered surface

Eggshell-Modified Ceramic Tiles fired at different temperatures are shown on plate 1(a-f), and their physical and mechanical properties are qualified in strength, porosity, surface finish e.t.c as revealed in Table 3.

a. Tile Composition (A2) b. Tile Composition (B1) c. Tile Composition (B2)

d. Tile Composition (C1) e. Tile Composition (C2) f. Tile Composition (D1)

Plate1 (a-f): Different modified ceramic tile compositions fired

Clay Bodies used in Visual Decorative Ceramics Tiles Making

Clay bodies as applied in visual decorative ceramics are shown in Plate 2 (a & b) – for Tile Oxide Screen Printing.


Plate 2 (a): Tile Oxide Screen Printing Plate 2 (b): Tile Oxide Screen Printing

The performance outcomes of the clay–eggshell compositions were evaluated in terms of flexural strength (modulus of rupture), apparent porosity, linear firing shrinkage, water absorption, and surface finish quality as summarised in Table 4.

Mechanical Strength

The incorporation of fine eggshell powder at 10 wt%, fired at 1100°C, produced the highest flexural strength, with an 18% increase over the control (0 wt%). Compositions fired below 900°C exhibited reduced strength due to incomplete decomposition of calcium carbonate, leaving residual calcite in the matrix. Coarse-fraction additions at 15–20 wt% consistently reduced strength, with blistering observed across all firing temperatures.

Porosity

Apparent porosity decreased progressively with increasing firing temperature. The lowest porosity value (3.2%) was achieved in the fine fraction composition at 10 wt% fired at 1100°C.

Compositions fired below 900°C showed elevated porosity (>7%), linked to incomplete $CaCO_3$ decomposition.

Shrinkage

Linear firing shrinkage increased as both temperature and eggshell addition rose. At 1100°C, fine fraction compositions showed shrinkage values between 3.0–3.5%, while the control measured 2.5%.

Surface Finish

Fine fraction compositions fired at ≥1000°C produced denser, smoother, and more homogeneous surfaces, while coarse fraction additions at 15–20 wt% caused surface blistering and irregular textures due to localised CO_2 release during calcite decomposition.

Table 4: Summary of performance outcomes for eggshell to clay compositions

Composition	Firing Temp (°C)	Flexural Strength	Porosity (%)	Shrinkage (%)	Surface Finish
Control (0 wt%)	1100	Baseline	5.8	2.5	Moderate, porous
Fine 10 wt%	1100	**+18% (optimal)**	**3.2 (lowest)**	3.5	Smooth, homogeneous
Fine 15 wt%	1000	+12%	4.0	3.0	Dense, smooth
Coarse 15–20 wt%	900–1100	Reduced	7.5–9.0	2.0–3.0	Blistered, poor
Firewood (C1, 40 wt%)	900	Reduced	9.5	1.5	Blistered
Firewood (D1, 20 wt%)	1100	+10%	4.5	3.2	Improved finish

Discussion

The results confirm that eggshell powder, when optimised for particle size and firing conditions, considerably enhances ceramic tile performance. Fine fractions at 10 wt% and 1100°C yielded the best results, with improved strength, reduced porosity, and a superior surface finish. These improvements are attributed to the decomposition of $CaCO_3$ at 840–900°C, which releases CO_2 and forms CaO, consequently promoting liquid-phase sintering and densification.

These results are consistent with prior studies on calcium carbonate additives in ceramics. However, this investigation extends existing knowledge by clearly demonstrating the key role of particle size control. For instance, when added at higher levels, coarse fractions disrupt the ceramic matrix, leading to blistering and elevated porosity.

From a sustainability perspective, using eggshell waste helps reduce the need for mined limestone, cut energy use during firing, and address environmental problems caused by food-industry bio-waste. Eggshell powder is a practical, affordable, and eco-friendly option for Nigeria's ceramic industry. It can lower the environmental impact of eggshell waste and improve the strength, durability, and quality of ceramic tiles. This approach supports the development of sustainable local materials for ceramic wares and can help drive industrial growth in Nigeria.

Suggestions and Recommendations

From the standpoint perspective of findings, these suggestions and recommendations can be made as follows:

1. Optimisation of particle size and addition levels
   Fine eggshell powder at 10 wt% and firing at 1100°C produced the best results. Future ceramic production should adopt this optimised range to balance strength, porosity, and surface finish.
2. Control of Coarse Fractions
   Coarse eggshell particles at higher proportions (15–20 wt%) caused blistering and elevated porosity. Strict control of particle size distribution is recommended to avoid structural defects.
3. Waste Valorisation
   Eggshells represent a low-cost, abundant resource. Their integration into ceramics supports circular economy principles and reduces reliance on mined limestone.
4. Industrial Application
   Pilot studies should be conducted to scale up production in Nigerian ceramic industries, testing consistency across larger batches and diverse clay sources.

5. Future Research
   Investigations should expand to other Agro-wastes (e.g., rice husk ash, glass cullet and aluminium dust) in combination with eggshells, and explore nano-sizing of eggshell powder for enhanced mechanical and thermal properties.

This study shows that adding eggshell powder at controlled sizes and amounts improves the strength, lowers the porosity, and enhances the surface finish of ceramic tiles. Moreover, fine eggshell powder at 10 wt% and a firing temperature of 1100°C produced optimal results, confirming that eggshells are a viable, sustainable additive. Also, using eggshell waste addresses environmental challenges in Nigeria's informal food sector and offers a model for resource use in a circular manner.

Recommendations

Future research should explore scaling production, integrating other agro-wastes, such as sea animal shells, and advancing nano-sized eggshell applications. By bridging waste management with ceramic innovation, this work contributes to both environmental sustainability and industrial growth in Nigeria's ceramics sector.

Definition of Terms

Clay Bodies: Mixtures of clay minerals, often combined with other materials like feldspar and silica, used in ceramic manufacturing to achieve desired properties.

Ceramics Firing: The process of heating ceramic materials to high temperatures to harden them in a kiln.

Valorisation: The process of converting waste materials into valuable products or resources, often through recycling or repurposing.

Morphology: The study of the form and structure of an object or material, often used to describe the shape and arrangement of particles or components.

Calcium Carbonate: A common chemical compound ($CaCO_3$) found in rocks, eggshells, and shells, used in various industries for its properties.

Silk Mesh: A fine, woven fabric made from silk fibres, often used in screen printing or filtration processes.

Follicle: A small, sac-like structure in the body, such as hair follicles or ovarian follicles, where growth or development occurs.

Rice Husk: The protective outer covering of a rice grain, often used as a by-product in agriculture and industry for its fibrous and insulating properties

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