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Assessment of physical and mechanical properties of ceramic tiles incorporating Coconut Coir Ash (CCA)

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Abstract

Ceramic tiles are popular in construction due to their durability, aesthetics, and versatility. Given that coconut coir, an abundant agricultural waste contains valuable components like SiO_2, Al_2O_3, and CaO, it presents a viable alternative raw material for tiles-production. Utilizing coconut coir in this way could reduce dependence on traditional resources like silica and feldspar. This study is the first to explore Coconut Coir Ash (CCA) (0%, 5%, 15%, 20%) as an eco-friendly material for tile production, evaluating its mechanical and physical properties. The water absorption rate (6.15%-lowest) and porosity (11.53%-lowest) significantly decreased with increasing CCA-content, particularly in the 15% batch. Conversely, firing shrinkage yielded mixed results, while loss of ignition increased proportionally with the CCA-content. Also, physical properties like impact strength, tensile strength, modulus of rupture, etc., showed mixed results but generally improved with higher CCA-content. Further tests on fuel-efficiency and cost-effectiveness will assess the feasibility of mass-producing CCA-based tiles.

Keywords: Tiles production, Waste Management, Sustainable production, Mechanical property.

1. Introduction

With industrialization and the rise in global population, waste generation has become a major environmental concern. In 2016, global municipal solid waste reached 2.01 billion tonnes, and if current trends continue, it is projected to rise to 3.40 billion tonnes by 2050 [1]. Over 33% of waste is mishandled, and only 13.5% is recycled globally [2]. With diminishing natural resources and increasing environmental impacts, researchers have turned to waste utilization, yielding promising results. Ceramic tiles, a heterogeneous product, can incorporate various waste materials. Technological advancements, particularly in porcelain tiles, have improved both performance and aesthetics. Modern ceramics can recycle waste without quality loss and store heavy metals through sintering [3]. In 2017, ceramic tile production reached 13.552 million square meters, with a 5.2% annual growth, demonstrating the industry's potential to recycle large amounts of waste and reduce raw material use [4].

In recent years, the ceramics industry has increasingly embraced waste materials, such as coconut coir, as valuable raw materials for ceramic tile production. The global cultivation of coconuts spans over 94 countries, with coconut husk making up about 35% of a coconut's weight, and coir accounting for 30% of the husk [5]. In 2019, global coconut production reached 62 million tons [5], yielding 20 million tons of husks and an estimated 6 million tons of coir [2]. Global coir production has grown at a rate of 3.6% annually, reaching 995,000 tons in 2017, with projections of 1,170,000 tons by 2027 [6]. So, with abundant global coconut production and a steady increase in coir output, there is significant potential for utilizing coconut coir as a sustainable raw material. In that manner, In Thailand, coconut coir ash is used in the production of ceramic tiles, enhancing their crack resistance and improving their strength-to-weight ratio compared to conventional tiles [7]. In India, it is applied in the manufacturing of ceramic cookware, which offers greater durability and heat resistance than traditional options [8]. In the Philippines, coconut coir ash is utilized in ceramic art pottery, producing unique and environmentally sustainable pieces [9].

Basically, Coconut coir ash (CCA), a byproduct of coir combustion, has shown potential for various applications, particularly in ceramic tiles, where its use of up to 20% has been found not to compromise material properties [10]. The chemical composition of CCA varies depending on the origin of the coconut coir and the combustion conditions, but it typically includes the minerals listed in Table 1.

This article examines the incorporation of CCA into ceramic tile compositions at 0%, 5%, 15%, and 20% to assess its impact on the tile's mechanical and physical properties. We will evaluate firing shrinkage, ignition loss, impact strength, compressive strength, tensile strength, and modulus of rupture to determine whether CCA-based tiles can be mass-produced on an industrial scale. Beyond physical and mechanical properties, additional tests will

assess whether CCA-based tiles are environmentally friendly (requiring less energy during firing), cost-effective, and suitable for household use. Based on these comprehensive results, we can then determine the feasibility of manufacturing CCA-based tiles at a factory level.

Table 1. Chemical composition of CCA [11]

Mineral	Percentage (%)
SiO_2	30-50
Al_2O_3	10-25
Fe_2O_3	2-5
CaO	10-20
MgO	5-10
K_2O	2-5

2. Materials, batch calculation, and methodology

Materials

Ball clay, China clay, quartz (SiO_2), Feldspar, and PVA (polyvinyl alcohol) all materials are provided by the "Glass and Ceramic Department" of Rajshahi University of Engineering & Technology (RUET), Rajshahi, Bangladesh. Coconut coir (to form CCA) was bought from Shaheb Bazar, Rajshahi, Bangladesh.

Batch calculation

The raw materials were taken as per batch calculation. Here, the entire batch is computed and subtracted in accordance with the addition of coconut coir ash. This is because the main ingredients of coconut coir ash are silica and alumina [11], which are also found in feldspar, ball clay, and China clay. Also, quartz is 99% silica, so it can also be replaced by coconut coir ash [12, 13].

Table 2. Batch composition of the ceramic tiles sample

Batch	Weight Percentage of Raw Materials (%)				
	Ball Clay	China Clay	Quartz	Feldspar	CCA
B_0	15	15	40	30	0
B_5	14.25	14.25	38	28.5	5
B_{15}	12.75	12.75	34	25.5	15
B_{20}	12	12	32	24	20

Methodology

First, the coconut coir was thoroughly washed to remove impurities and foreign particles, then dried until all moisture evaporated. The dried coir was combusted, and the resulting ash was calcined at 800°C to produce the coconut coir ash (CCA).

To prepare the ceramic tile samples, the raw materials were weighed. Mineral materials like quartz and feldspar were washed, crushed using a jaw crusher (EAS90L), and ground with a mortar and pestle for 2 hours to obtain an ultrafine powder. A sieve shaker was used to remove larger particles. The materials were then ball-milled with water in a milling pot at 600 rpm for one day. Afterwards, the slurry was dried at 100°C for one day to form a powder, which was hand-ground to eliminate lumps.

A steel mold (42 mm diameter, 5 mm thickness) was used to shape the tile body. The mold was filled with powder and a PVA binder, then pressed at 5 tons of force for 45 seconds. The pressed body was sintered using a heating cycle of 3°C/min to 500°C, held for 30 minutes, and further heated to 1100°C at the same rate, held for 1 hour. The tiles were cooled at 3°C/min to room temperature, completing the ceramic sample preparation.

3. Instrumentation

Apparent porosity

To estimate apparent porosity, the bulk and pore volumes of 10g round samples were measured. The sample diameter was measured with a slide caliper, and the bulk volume was calculated using the following equation.

$$V_b = 4\pi r^3 \quad (1)$$

Where, V_b = Bulk volume of the sample and r= Radius of the sample.

To estimate pore volume, the dried sample was first weighed, then saturated in water for 24 hours. The saturated sample was weighed again, and the mass of water in the pore volume was calculated using the following formula:

$$V_p = \frac{\text{Mass of water in pore}}{\text{Density of water}} \quad (2)$$

Where, Vp = The volume of water present within the pore. Finally, the sample's porosity was measured using the following formula:

$$P = \frac{V_p}{V_b} \quad (3)$$

Water absorption and loss of ignition (LOI)

The water absorption test, alternatively referred to as the water absorption porosity test, is a widely employed method utilized for the purpose of ascertaining the porosity of a ceramic specimen. The Loss on Ignition (LOI) is the percentage of weight that a ceramic material loses when it is fired. To conduct a water absorption test, a dry sample was weighed (W_1) and then submerged in distilled water for 24 hours. Afterwards, the excess surface water was wiped off, and the sample was reweighed (W_2). Same for the LOI test, the only difference is for LOI; W_1= initial or green sample weight and W_2= weight after firing. Both values can be calculated using the following equation:

$$\text{Water absorption/LOI of a sample} = \frac{W_2 - W_1}{W_1} * 100\% \quad (4)$$

Firing shrinkage

As a green sample body dries, water is removed, leading to shrinkage as the particles tighten and pack. Firing causes further shrinkage, providing insight into the material's properties after firing compared to its green state. Firing shrinkage is measured as the percentage change in length or width of the sample after firing.

Impact strength

Impact strength measures a material's ability to withstand damage under an impact load, indicating its capacity to deform or fracture without failure. Flat-type samples were used for measurement. The sample thickness was first measured with slide calipers, then placed in a pendulum-type impact tester. The impact load, starting at 0.01 on a 40Z scale, was gradually increased until fracture occurred, at which point the load was recorded. The following formula was used to calculate the strength factor for flat samples tested for impact.

$$S = 12I/t^2 \quad (5)$$

Where, S= Strength factor, I= Average impact to produce initial fracture, and T= Average thickness of specimen at point of impact.

Tensile and compressive strength

Both the tensile and compressive strength of the tiles sample are measured using a Universal Testing Machine (UTM). For this experiment, the UTM used was the H10K model manufactured by Hounsfield in the United Kingdom. The compressive force exerted on the side of the disc virtually results in the generation of tensile stress that is oriented perpendicular to the vertical plane intersecting the disk's center. The value of compressive strength is practically measured in terms of the average change in stress and strain with the applied force.

$$\text{Tensile strength} = \frac{2*\text{Applied force}}{\pi*\text{Diameter}*\text{Thickness}} \quad (6)$$

Mathematically,

$$\text{Compressive strength} = \frac{\text{Applied force before failure}}{\text{Area of the sample}} \quad (7)$$

Modulus of rupture (3-point bending test)

Modulus of rupture, or flexural strength, measures the stress at which a ceramic beam or slab fails under bending pressure. It is tested using the ASTM C78 (Figure 1) standard with the third-point loading technique and is expressed in megapascals (MPa). Flexural strength is a key indicator of ceramic material quality. Mathematically,

$$\sigma = \frac{3FL}{2bd^2} \tag{8}$$

Where, F = Load at the fracture point, L = Length of the support span, b = Width, and d = Thickness.

4. Result Analysis

Firing shrinkage

Samples containing 5 wt-% CCA (Figure 1a) have lower firing shrinkage. At 5 wt-%, percolation likely occurs. That is, at these low CCA addition levels, the fluxing particles of CCA (and, to a lesser degree, feldspathic sand) are isolated and, when softened or melted, remain isolated. Owing to their large size relative to the fine clay particles, they effectively restrain shrinkage as a result of their inertia. However, at higher levels of CCA addition, the slag particles are in contact, thereby forming a monolithic shrinkage network [14].

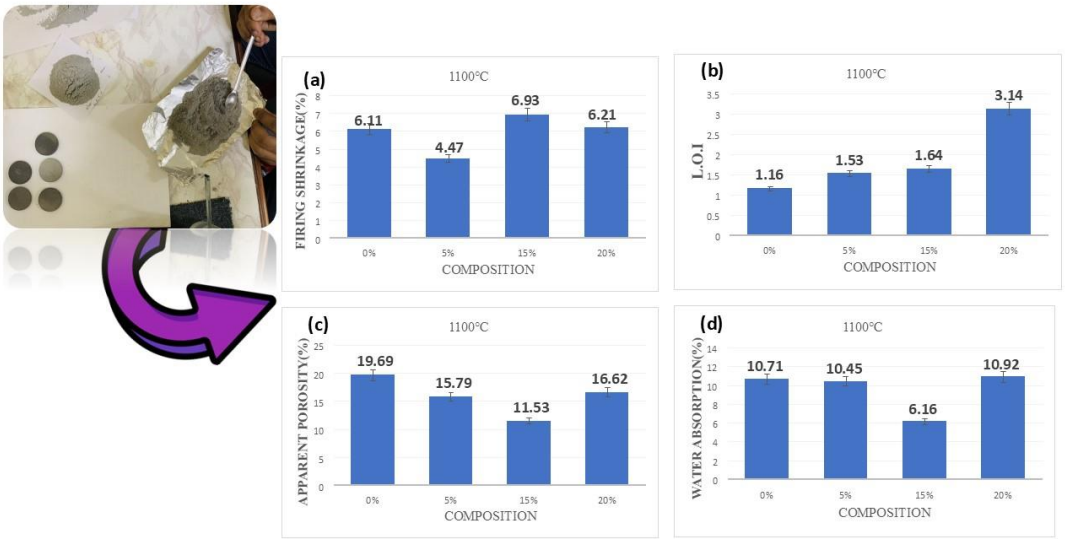


Figure 1. Different properties of CCA-based tiles sample: a) firing shrinkage, b) LOI, c) apparent porosity, and d) water absorption.

Loss of ignition (LOI)

A higher loss of ignition (LOI) indicates more volatile or combustible components in a material. Figure 1b shows a gradual increase in LOI with increasing CCA content, with a sharp rise at 20% CCA. This is due to the organic nature of CCA, which contains volatile inclusions. At lower CCA levels, these inclusions are negligible, but they increase significantly at higher content, leading to a sharp LOI rise between 15% and 20%.

Porosity

Figure 1c illustrates the variation in porosity with different CCA compositions. With 15% CCA showing the best properties, while at 20% CCA, the properties decline. During sintering, K-feldspar and silica react with CCA oxides to form a viscous liquid that reduces porosity by closing and isolating pores through surface tension and capillarity, enhancing densification [15].

Thus, this would further minimize the water absorption and porosity of tiles containing CCA from 5% to 15%. The iron oxide content in CCA tends to reduce the densification range of ceramic tiles, and in high amount leads to the incomplete sintering process [16] and eventually yields tiles with high closed porosity [17]. Due to these reasons, water absorption and porosity of tiles containing 20% CCA deteriorated, while samples with 15-20 wt-% CCA have higher firing shrinkage than the base body.

Water absorption

From the graph in Figure 1d, we can see that the water absorption decreases with the addition of CCA content in the composition. Water absorption from 5wt%-15wt% inclusion is decreased [18]. However, for the sample containing 20% CCA content, Water absorption is increased. The addition of CCA into the composition provides alkali oxides [11] which reduces surface pores [15] that would otherwise enhance water absorption. The 15 wt% composition shows the lowest absorption. However, excess CCA content beyond the optimum limit increases surface imperfection. Hence, we see the increased water absorption of the 20 wt% composition.

Impact strength

Impact strength is directly linked to the physical properties of the samples, as shown in Figure 2a, with variations in porosity and relative density depending on the CCA content in the tiles. The behavior of the mechanical properties and relative density are similar. The high impact strength of the sample with 15 wt-% CCA can be related to the high relative density and the greater amount of dissolved quartz. On the other hand, at lower amounts of CCA (lower than 15 wt-%), recrystallization and β transformation of a large amount of quartz phase would lower the strength [19]At elevated amounts of CCA (higher than 15 wt-%), strength decreases due to a decrease in the solid cross-sectional area due to increased porosity.

Compressive strength

In Figure 2b, we observe improved compressive strength in the compositions containing CCA. The compressive strength is increased in the 5 wt% CCA sample and superior in the 15 wt% sample as expected from the data from previous tests. Without any deviation, 20 wt% composition shows degraded compressive strength compared to 15 wt% composition [19].

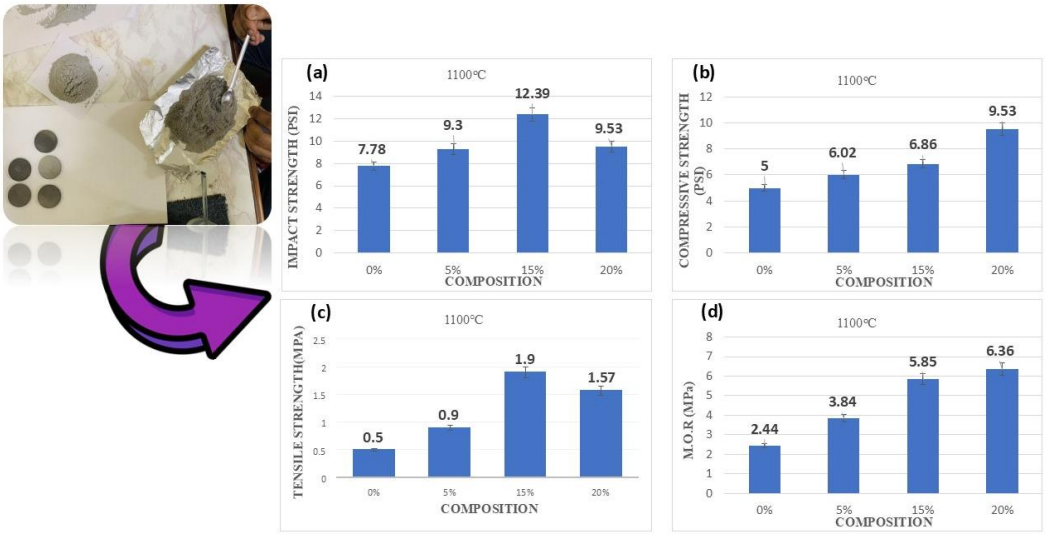


Figure 2. Different properties of CCA-based tiles sample: a) impact strength, b) compressive strength, c) tensile strength, and d) modulus of rupture.

Tensile strength

Figure 2c depicts the graphical data for compositions with the variation of tensile strength or, more accurately, diametrical tensile strength. The incorporation of CCA into the batch composition gives a significant rise in tensile strength. Only a 5 wt% addition of CCA gives an 80% increase from the base composition. 15 wt% CCA composition shows surprisingly high tensile strength. However, the trend remains the same as the improved tensile strength falls at 20 wt% CCA composition [19].

Modulus of rupture

The results of the 3-point bending test are shown in Figure 2d. Base composition aside, flexural strength is maximum in 15 wt% CCA composition and minimum in 20 wt%. Flexural strength first increases with CCA and then decreases significantly. The Flexural strength of the composition containing 20% wt CCA content is surprisingly low compared to its performance in other tests. Its strength is barely above the base composition [20]. The reason behind these results is the anorthite-forming minerals in the CCA. The presence of this anorthite phase in ceramic composition drastically improves mechanical strength. The decrease in 20 wt% composition is due to the iron oxide in the CCA, which in excess amounts prevents densification of the ceramic composition [16]. This results in decreased solid cross-sectional area due to the increased porosity. From the results, it is evident that as soon as the amount of iron oxide exceeds the permitted limit, the property drops drastically.

5. Conclusion

This research successfully incorporated CCA waste into ceramic tiles and determined the optimal composition for achieving superior physical and mechanical properties. The results showed that increasing CCA content improved these properties until a peak at 15% CCA, where impact strength and tensile strength were highest, while water

absorption was lowest. Beyond 15%, at 20% CCA, the tiles exhibited increased water absorption, and reduced impact strength, and compressive strength. The optimal ceramic tile composition—15 wt.% CCA, 12.75 wt.% ball clay, 12.75 wt.% china clay, 34 wt.% K-feldspar, and 25.5 wt.% quartz—fired at 1100°C, demonstrated the best balance of low porosity and high strength. This study highlights the economic benefits of recycling agro-industrial waste, such as CCA, in ceramic production, reducing solid waste disposal costs for the agro-industry and lowering raw material expenses for the ceramic industry, enabling the production of low-cost ceramic tiles.

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