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Physical and mechanical properties of a tile produced with Burkina Faso clay

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Abstract: This study proposes an approach for manufacturing wall tiles from raw clayey material from Burkina Faso for use in the local ceramic industry. To this end, a clay sampled of Kodeni (KOD), primarily composed of kaolinite (62 wt.%), quartz (31 wt.%), and goethite (3 wt.%), with contents of 60.79 wt.% SiO_2 and 24.36 wt.% Al_2O_3 was used for wall tile manufacture. All the results of the physico-mechanical tests on the tiles developed at temperatures of 1150°C, 1200°C, and 1250°C show that these tiles meet the standards for mechanical strength of water absorption and thermal conductivity for ceramic applications. The formulation of the samples enriched with feldspar (25 wt.%) and fired achieved maximum flexural strengths of 22.58 MPa at 1250°C for the formulation containing no feldspar (F0) and 25.69 MPa at 1200°C for the formulation containing 25 wt.% feldspar (F1), confirming the densifying effect of feldspar at moderate temperatures. In addition, the water absorption and porosity of the tiles decreased progressively with increasing temperature, ensuring properties in line with ISO 13006 for wall use. The tiles also exhibited low thermal conductivity (≤ 1 W/(m.K)), limited and controllable linear shrinkage, and reduced deformation. These results suggest that KOD clay, amended with 25 wt.% feldspar at 1200°C temperature, is suitable for manufacturing wall tiles. Scanning electron microscopy analysis is planned to explore the evolution of the microstructure and viscous phase as a function of firing temperature to understand better the sintering processes and the interactions between the different stages.

Keywords: wall tile; raw clayey material; feldspar; physico-mechanical properties.

1. Introduction

The use of local raw materials in the manufacture of construction materials represents a promising avenue for industrial and economic development in many developing countries. In Burkina Faso, the ceramics industry remains underdeveloped, limiting the supply of local products, particularly ceramic tiles, which are widely used in modern buildings. The absence of a tile production industry has led to an almost exclusive reliance on imports to meet growing demand. This situation results in high costs for local consumers and hampers the economic development and autonomy of the construction sector. Therefore, this study aims to manufacture wall tiles from local clay, make the most of Burkina Faso's abundant mineral resources, reduce dependence on imports, and increase the country's economy.

Previous research has explored using various Burkinabe clays to improve the properties of ceramic materials as a function of different fluxing agents and firing temperatures. For example, the work of M. Seynou et al. 2013 [1] demonstrated the effect of a feldspar-talc mixture (20 wt.% feldspar + 3 wt.% talc) on LOU and Korona clays, located in the Centre-North and Cascades regions respectively. This mixture reduced the water absorption of the samples to below 4 wt.% and increased their flexural strength to around 40 MPa. Similarly, Sawadogo et al. 2014 [2] observed, with the addition of 4 wt.% talc to SIT clay (Cascades region), a significant improvement in modulus of rupture (≈ 50 MPa) as well as water absorption of less than 2 wt.%. Scientific research carried out by Y. Sawadogo et al. 2020 [3] revealed interesting properties (water absorption < 0.5 wt.%, porosity < 1%, flexural strength > 35 MPa) from 1250°C with a mixture of pegmatite and NONG clay from the northern region. K. Traore et al. 2007 [4] achieved a breaking strength of 30.04 MPa by incorporating 5 wt.% calcite in a lump of clay from the Poa village, illustrating the influence of the flux on the mechanical properties of ceramics. Abdelhak

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et al. 2007 [5] studied the structural and mechanical properties of clay-based ceramics, particularly the influence of the feldspar source.They evaluated two Moroccan feldspar sources regarding their grind ability, chemical and mineralogical compositions, and thermal behavior. The results show that the feldspars' mineralogical composition determines the sintered products' technological and mechanical properties. The work of Farid Lachib et al. 2023 [6] explores the recycling of glass waste in the production of ceramic tiles by analyzing its effects on the physical and mechanical properties of the materials. Tiles were manufactured from Algerian bentonite (35%) and waste glass (60-70%) with two different particle sizes and then sintered at 900°C. The results show that incorporating 65% waste glass produces ceramic tiles with good physical-mechanical and thermal properties and chemical durability, highlighting the potential of this process for sustainable ceramic applications. Work by O.R. Njindam et al. 2018 [7] investigates the incorporation of waste glass powder into clay mixes to produce porcelain stoneware floor and wall tiles. Tests revealed that an optimum glass content of 30 wt%, fired at 1150°C, significantly improves the physico-mechanical properties of the tiles, with low water absorption (0.4%) and high flexural strength (39.06 MPa), meeting ISO 13006. However, a glass content of more than 30% degrades the physical properties of the products. Microstructural analyses confirmed a compact texture and a dense microstructure containing mullite fibers, giving the tiles exceptional mechanical performance.

These studies show that the nature of the raw material, flux content, and firing temperature strongly influence ceramic materials' mechanical and physical properties. However, they highlight the lack of in-depth research into the impact of local feldspars and clays specific to the Hauts Bassins region in producing wall tiles adapted to market requirements. Furthermore, although thermal conductivity and mechanical strength are crucial parameters for the effectiveness of materials, the correlation between these parameters and porosity remains little studied.

This work thus fills a gap in the literature by proposing a method for manufacturing wall tiles that meet the requirements for mechanical strength, water absorption, and thermal conductivity by ceramic standards. The study establishes a correlation between the porosity of the tiles produced and their physico-mechanical properties, particularly thermal conductivity and compressive strength. Analyzing the properties of Burkina Faso clay at different firing temperatures provides a solid scientific basis for developing local ceramic tiles capable of meeting market needs while promoting a sustainable, self-sufficient ceramics industry in Burkina Faso.

2. Experimental

2.1. Raw clayey material

The raw clay used in this study was obtained from the locality of Kodeni, situated to the south of the town of Bobo-Dioulasso in the Hauts Bassins region of Burkina Faso (Fig. 1a). The geographical coordinates of the site are 11°10' Latitude North and 04°17' Longitude West. This raw material, referred to as KOD, is used by local people mainly to make building materials such as bricks and roof and wall coverings. Fig. 1b shows the Kodeni clay extraction site. This clay has been studied for its use in plastering [6].

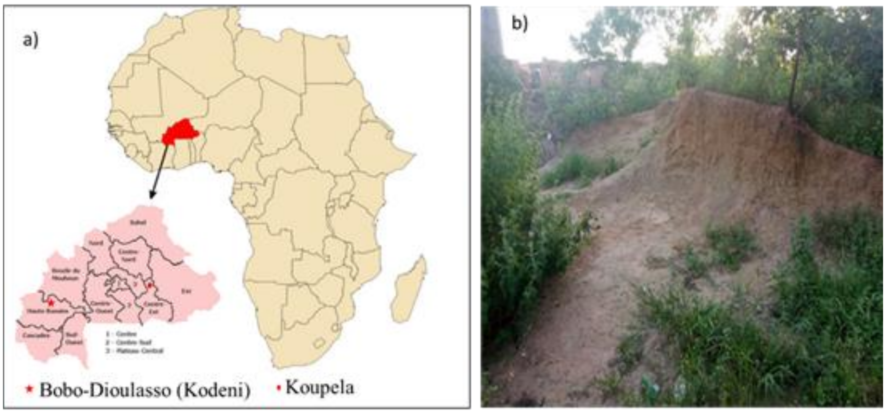

Fig. 1: a) Geolocation of raw materials sites; b) Kodeni clay site

This study studied the raw clay material used by Bamogo et al. 2020, 2022 [8, 9] for elaborating earthen plasters reinforced by dolomite lime.

The results of mineralogical (XRD, IR, DSC-ATG), geotechnical (grain size, methylene blue test, Atterberg limits), and chemical (ICP-AES) analyses obtained in the work of Bamogo et al. 2020 [8]. The coupling of chemical analysis, mineralogical analysis, and semi-quantitative calculations [10] revealed the presence of kaolinite (62 wt.%), quartz (31 wt.%), and goethite (3 wt.%). Geotechnical analysis (**Table 1**) classified the Kodeni soil as sandy-loam and water-sensitive [7].

Table 1. Geotechnical analysis.

Atterberg Limits			Methylene Blue Value (g/100g)	Particles Size Distribution			
Liquidity limit (WL) %	Plasticity limit (WP) %	Plasticity Index (PI) %		Clay (wt.%)	Silt (wt.%)	Fine sand (wt.%)	Coarse sand (wt.%)
44	21	23	1.43	40	10	34	16

2.2. Feldspar

Feldspar is an essential mineral used in the ceramics industry as a flux and degreaser, playing a key role in manufacturing processes. As a flux, it reduces the vitrification temperature of ceramic bodies, facilitating the fusion of silicate components [1]. This property is due to its chemical composition, which is rich in alkalis (sodium, potassium) that lower the temperature at which the ceramic material begins to vitrify [11]. Feldspar encourages the formation of a liquid phase during firing, improving the cohesion of mineral grains and giving ceramics increased density and a smooth surface.

At the same time, feldspar acts as a degreaser. It improves the plasticity of the clay by reducing its ability to contract during drying and firing, thereby limiting the formation of cracks or deformations. Feldspar, therefore, stabilizes the structure of the ceramic, making it easier to control the final dimensions of the product [12]. Its dual role as a flux and degreaser is vital in manufacturing ceramic products such as stoneware, porcelain, and earthenware, which helps produce resistant, durable, and aesthetically smooth materials.

The feldspar used in this study is of the potassic type with the chemical formula Si_3AlO_8K and an apparent density of 2.5. It comes from Koupela, a town in the Centre-East region of Burkina Faso (Fig. 1a).

2.3. Tiles manufacturing

The raw clayey material (KOD) and the natural feldspar were air-dried, ground, and sieved dry. Two granular classes were selected for the production of the slip:

- those passing through a 106 µm sieve, known as **class I**
- those passing through 150 µm sieves and retained on the 106 µm sieve, called **class II.**

The feldspars (Fig. 2a) were crushed and ground using the same mill to a particle size of 125 µm or less (Fig. 2b).

For the formulation of the specimens, two types of suspensions in well-defined proportions of material (clay + feldspar) and water (mass of water/mass of material = 1/2) were prepared. The composition of the raw material mixtures is given in Table 2.

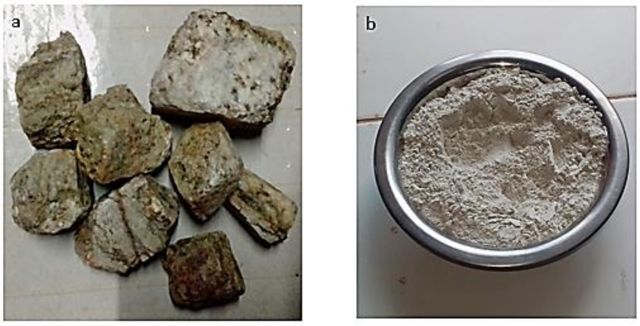

Fig. 2. a) Unground feldspar b) Ground feldspar

Table 2. Mass content of the various fractions.

Code	**Raw clayey material**			**Feldspar (wt.%)**
	class I (wt.%)	**class II (wt.%)**	**Total (wt.%)**	
F_0	75	25	100	0
F_1	56.25	18.75	75	25

Sodium carbonate was added at 0.35 wt.% [13] of dry matter as a deflocculant. The mixture was mixed until a homogeneous slip was obtained (Fig. 3).

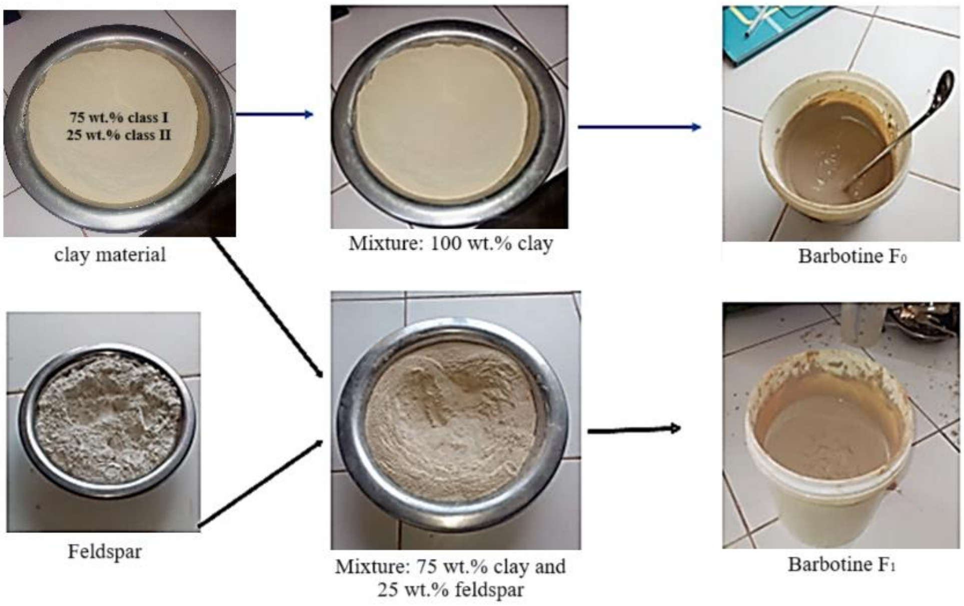

Fig. 3. Barbotine preparation

The specimens were shaped by casting. Casting enables the extraction of exact and reproducible shapes. It is one of the most widely used techniques for the mass production of pottery, although it was initially developed for fine pottery, mainly porcelain. Once the slip has been obtained, it is poured into rectangular plaster molds measuring (13×5×2) cm^3 (Fig. 4). After 48 hours, the specimens were removed from the molds, and the surfaces smoothed. A drying step was carried out before firing to obtain the ceramic product.

Before firing ceramics, removing the water used for shaping is necessary, especially when this quantity is large (as in the case of slip). Drying is a delicate transition stage involving extracting the water from the products. It is, therefore, essential to dry the pieces away from harmful conditions. You can even cover them with plastic sheeting to allow them to dry slowly, especially in very hot places.

The green tiles obtained are left to dry at room temperature (30±5) °C away from solar radiation for 72 hours. After drying, the specimens were placed in an oven at 40°C for 24 hours, 75°C for 24 hours, and 105°C for 24 hours [1, 13-15].

Sintering can be described as the change from a powdery compact to a coherent material under heat. During this transformation, the shape of the part is retained, but its volume generally decreases (shrinkage). The compact is consolidated by forming bonds between the grains; if fusion occurs during sintering, it can only be very localized to maintain the whole part's coherence.

The samples were fired at 1150, 1200, and 1250°C at a heating rate of 5°C/min, followed by a one-hour isothermal plateau at the desired temperature, and then allowed to cool to room temperature using the kiln's automatic cooling system. Fig. 5 shows tiles fired at different temperatures.

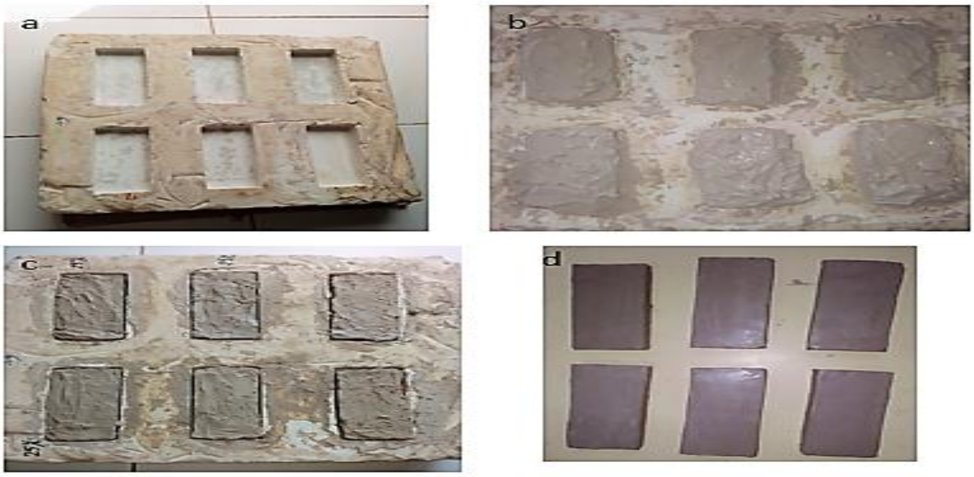

Fig. 4. a) Plaster mold b) Barbotine poured into the mold c) 48h after casting d) Test tubes removed from the mold

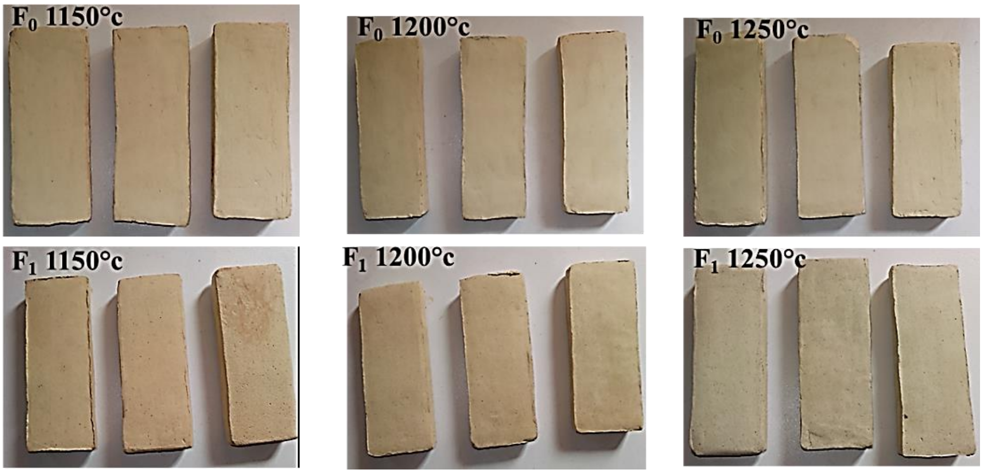

Fig. 5. F0 and F1 specimens baked at different temperatures

The sintering cycle is summarized in the following Fig. 6.

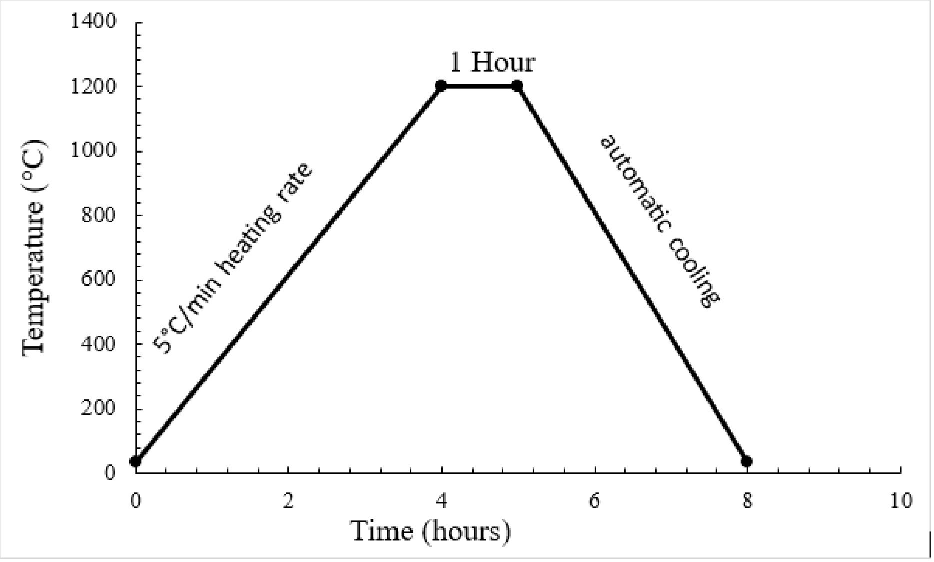

Fig. 6. Tile sintering cycle

2.4. Experimental methods

The oxide content was studied by inductively coupled plasma atomic emission spectrometry (ICP-AES). The Kodeni clay powder was ground beforehand (< 80 µm). This powder was melted with lithium metaborate ($LiBO_2$) to form beads. The beads were then dissolved in hydrofluoric (HF), nitric (HNO_3), or hydrochloric (HCl) acid. Loss on ignition was assessed after calcining the samples at 1000°C.

The loss on ignition, which is used to determine the organic content, was obtained by calcining the sample at a temperature of 1000°C. The loss on ignition (P) was calculated using Equation 1:

$$P = (M0-M1) x100 / M0 \qquad \text{Equation 1}$$

Where
M0: mass of the soil sample dried at 105°C
M1: mass of the soil sample after calcination at 1000°C

X-ray diffraction (XRD), differential scanning calorimetry coupled with thermogravimetric analysis (DSC/ATG), and Fourier Transform Infrared spectra were used to determine the mineralogical composition of the Kodeni clay.

The diffractometer used is a Siemens D5000 type equipped with a monochromatic lamp with a cobalt anti-cathode and using the line Kα (λ= 1.789 Å). DSC-ATG thermograms were carried out on a Netzsch SATA 449 F3 Jupiter with a temperature rise rate of 10°C/min to 1000°C.

The Fourier Transform Infrared spectra were obtained using a Perkin Elmer UATR 1 Frontier FT-IR spectrometer operating between 4000 and 550 cm^{-1}.

The size distribution of the soil mixtures was analyzed using two techniques: the coarser fraction (≥ 80 µm) was analyzed by wet sieving (NF P 94-056) [16], and the finer fraction (< 80 µm) using pipette analysis according to standard NF P 94-057 [17] (method based on measurement of the sedimentation time of solid particles in suspension in a solution of water mixed with sodium hexametaphosphate as a deflocculating agent).

The plasticity of the clay was determined by measuring the Atterberg limits according to standard NF P 94-051 [18]. The liquid limit (WL) was determined using the Casagrande cup, and the plasticity limit (WP) using the roll method. The plasticity index is derived from Equation 2:

IP=WL-WP Equation 2

The clayness of the sample was determined by the methylene blue test according to standard NF P 94 -068 [19].

Open porosity (ɳ) is the ratio between the volume of open pores and the external volume of the sample. The test consists of saturating the open porosity of the grains, making up the granular material with water using the boiling water impregnation method following standard ISO10545-3 **[20]**. Its value will be determined according to the following Equation 3 [21]:

ɳ(%) = (M2-M1)x100 / (M2-M3) Equation 3

Where
M1: Mass of the fired test specimens,
M2: Water-saturated mass of the baked test specimens,
M3: Hydrostatic mass of the fired test specimens.

In particular, this method of measuring porosity gives no information about the nature of the porosity: interconnected pores or cracks.

The density of fired specimens is measured by hydrostatic weighing. The sample of initial mass weighed after firing (M1) is completely immersed in water and weighed again (M3). It is then saturated with water and weighed (M2). The value of the apparent density is determined according to the following Equation 4 **[22]**:

d_a = M1 / (M2-M3) Equation 4

The thermal conductivity of the adobes was measured with a TR-1 probe (2.4 mm diameter and 10 cm length, working range between 0.1 and 4 $W.m^{-1}K^{-1}$) connected to the KD2 Pro Thermal Properties Analyser. The probe was inserted into a hole in the specimen to avoid contact with the air (C25W/P442, 1981). This method of measuring thermal conductivity is applicable to any water content in the clay matrix (Decagon, 2006) [23].

The compressive and flexural (AFNOR, NF P 15-451) [24] strengths are the mechanical properties which were carried out using a Controlab multifunction press with a speed of 0.5 mm/min and maximum load of 200 kN.

3. Results and Discussion

3.1. Physical characterization of tiles

3.1.1 Loss of mass and shrinkage on sintering

Fig. 6 shows the mass loss as a function of the baking temperature of the samples. For F0 formulations, this loss varies slightly between 7.3 and 7.9 wt.% between 1150°C and 1250°C. This variation can be explained by the combustion of organic matter and the evaporation of water by dehydration or dehydroxylation of the kaolinite during firing [25, 26]. For the F1 formulations, the mass loss remained almost constant (5.7 wt.%). This consistency suggests that the volatile compounds responsible for this loss were eliminated at temperatures below 1150°C. Previous studies, such as those by Rankin et al. (1987) [27] and Nahdi et al. (2001) [28], have established that a temperature of 1000°C is generally sufficient for the total elimination of volatile components. Samples from F0 formulations show a higher loss than those from F1, probably due to the chemical composition of the feldspars, which is poor in volatile elements.

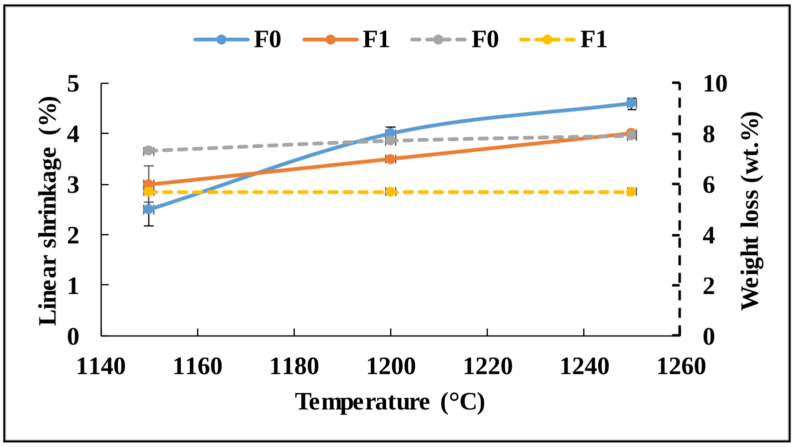

Fig. 7. Loss in mass and linear shrinkage during baking

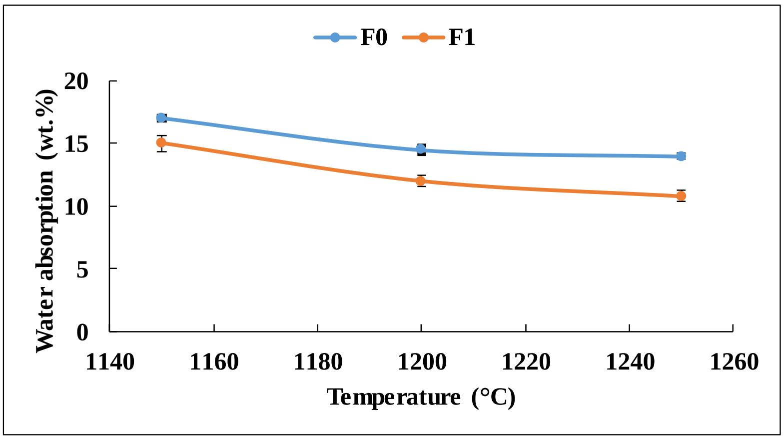

Fig. 8. Water absorption by tiles

Linear firing shrinkage, which reflects firing efficiency, is typically between 7 and 10% for materials such as aluminum silicates, kaolin, and fired clays [29]. This shrinkage is linked to eliminating interstitial water in the clay particles, causing the particles to move closer together and reduce volume. It also results from amalgamating cavities and forming a liquid phase at high temperatures [30]. Tile samples were fired at 1150°C, 1200°C and 1250°C. Firing shrinkage increased with temperature, but the addition of 25 wt.% feldspars reduced shrinkage from 1200°C, compared with samples without addition (Fig. 7). The shrinkage values observed, between 2.5 and 4.6% [31], are in line with international standards, making this material economically viable for industrial production.

3.1.2 Water absorption

Water absorption values are a key parameter in ceramic applications [29]. As shown in Fig. 8, tile water absorption decreases with increasing firing temperature. The F0 formulation decreases from 17 to 14 wt.%, while for the F1 formulation, it drops from 15 to 10.8 wt.%. 'This reduction is due to forming a liquid phase at high temperatures, filling the material's pores and enhancing densification, sealing and isolating adjacent pores. The surface tension and capillarity of the liquid encourage the pores to move closer together, reducing porosity. This leads to densification of the material, which in turn reduces its capacity to absorb water [11].

3.1.3 Open porosity and density

Fig. 9 shows the evolution of the open porosity of the F0 and F1 samples as a function of temperature. It is clear that porosity decreases with increasing temperature, from 26 to 23% for the F0 samples and 24.5 to 18.3% for the F1 samples.

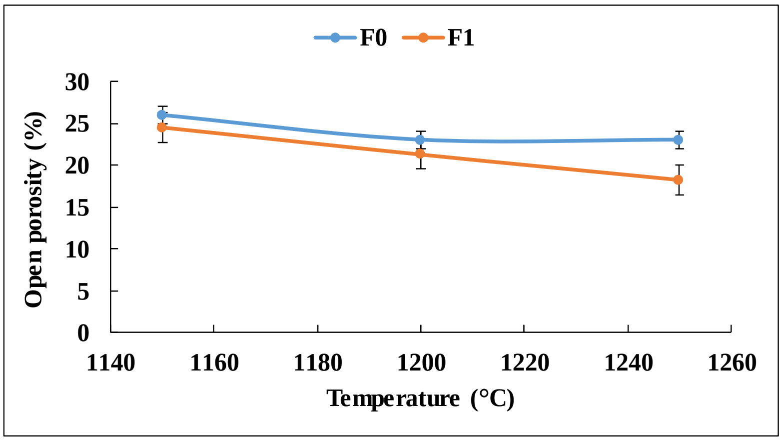

Fig. 9. Open porosity

This decrease is attributed to the densification of the material, facilitated by the formation of a liquid phase. During this formation, the surface tension and capillarity of the liquid bring the particles closer together, thus reducing porosity [32]. Densification also results from the formation of crystalline phases such as mullite and spinel, which replace porous metakaolinite at high temperatures [29, 33-35]. These pore-free phases help to reduce the porosity of the material. The formation of the glassy phase, induced by quartz during sintering, also promotes the crystallization of mullite [36], thus decreasing porosity. However, the porosity values remain relatively high, which could be due to the refractory nature of the material [37].

According to Blanchart's work on silicate ceramics, the open porosity of terracotta (bricks, tiles, decorative elements), after firing between 950°C and 1150°C, should be between 10 and 25% [38], corresponding to the results observed after firing at 1150°C in this study.

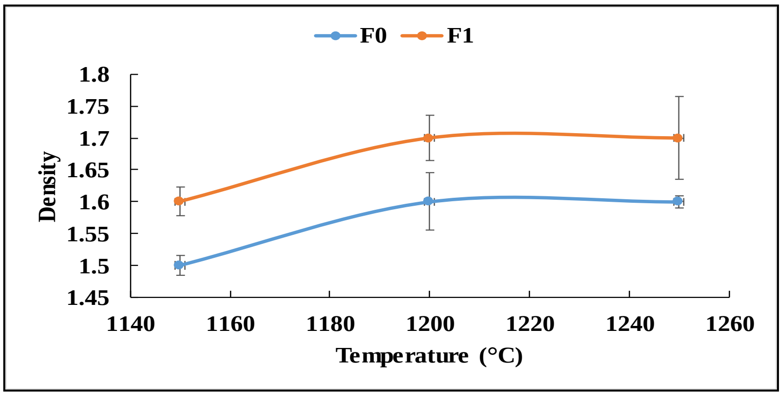

Fig. 10. Apparent density

Tile density depends on the density of the raw materials, the manufacturing method, and the firing temperature. An inverse correlation is observed between porosity and density: as density increases, the mechanical strength of the tiles increases, while water absorption decreases [39]. Fig. 10 shows that the density of the samples increases slightly with temperature. However, this densification remains limited due to the relatively high porosity and the small glassy phase formed [40]. The chemical composition of the clay, which is low in melting elements, also contributes to this low densification.

3.1.4 Thermal conductivity

Fig. 11 reveals that increasing the firing temperature increases the thermal conductivity of ceramic tiles. This relationship is explained by the opposite trend between thermal conductivity and porosity: as firing temperature increases, open porosity decreases, improving thermal conductivity [41]. This increase in conductivity is attributed to the continuous formation of mullite, a crystalline phase that promotes heat transfer in ceramic materials.

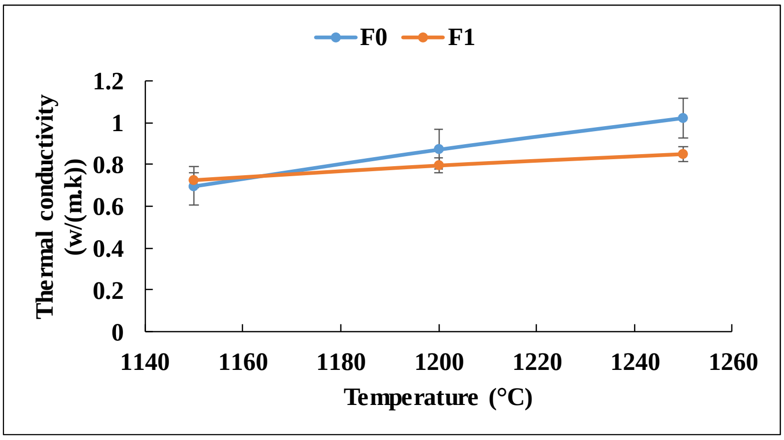

Fig. 11. Thermal conductivity

3.2. Mechanical characterization of tiles

The increase in flexural strength with temperature is shown in Fig. 12. This improvement is attributed to vitrification and the formation of mullite in the samples [42]. The mullite reinforces the glassy phase by creating an interlocking structure [43], which improves mechanical strength. Pialy et al., 2009 [44] have shown that the Al/Si spinel phase forms primary mullite and a low-viscosity liquid phase between 1100°C and 1200°C [44], which could account for the increase in flexural strength. However, above 1200°C, this strength decreases for the F1 formulation, making the material more brittle. According to the work of Gültekin, 2018 [45], the decrease in flexural strength is due to an increase in closed porosity, which is explained by a phenomenon of coalescence of the pores and their expansion under the effect of the pressure of the gases inside these pores (superheating phenomenon). The maximum flexural strengths recorded were 22.58 MPa at 1250°C for F0 and 25.69 MPa at 1200°C for F1, demonstrating the beneficial effect of feldspars, rich in alkaline oxides (K_2O, Na_2O), in reducing the densification temperature and improving the mechanical properties of ceramics.

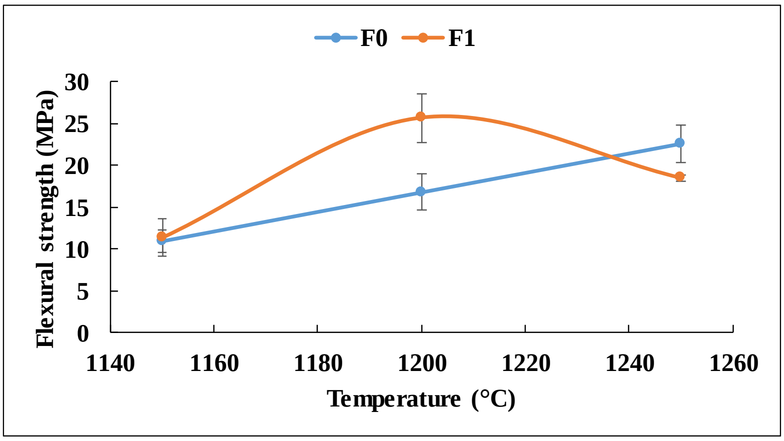

Fig. 12. Tile flexural strength

In addition, Fig. 13 shows that the simple compressive strength of fired samples also increases with temperature. This increase is due to the formation of a glassy phase, which densifies the material by reducing porosity, thus preventing crack formation and enhancing mechanical strength [29, 32, 36, 45]. However, the vitrification of the samples remained partial, with large, interconnected pores. This indicates that particle agglomeration and pore closure are not fully promoted due to a weak glassy phase during sintering, thus limiting the mechanical performance of the fired samples [42].

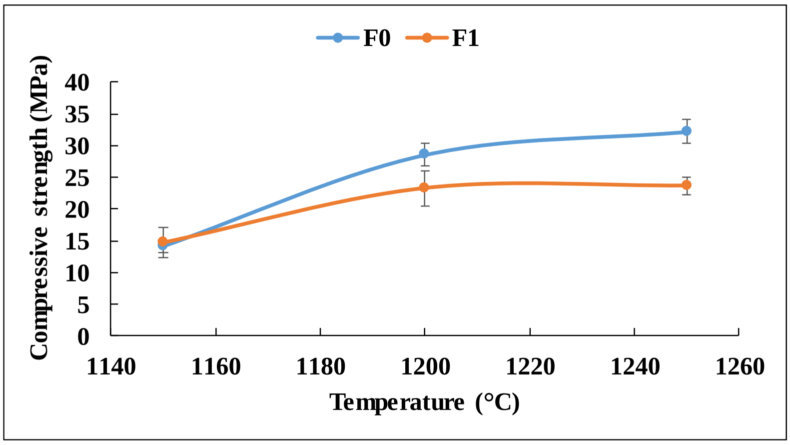

Fig. 13. Tile compressive strength

4. Conclusion

This study proposed an approach for manufacturing wall tiles from local Burkina Faso clay that meets ceramic standards' mechanical strength, water absorption, and thermal conductivity requirements. By exploring the physico-mechanical properties of KOD clay at different firing temperatures (1150°C, 1200°C and 1250°C), we have established a scientific basis for the development of ceramic tiles adapted to the local market and contributing to the emergence of a self-sufficient ceramic industry in Burkina Faso.

Chemical analyses revealed that KOD clay is a silico-aluminous clay, containing mainly kaolinite and quartz, with SiO_2 and Al_2O_3 contents of 60.79 wt.% and 24.36 wt.% respectively. Thermal and mineralogical analyses confirmed the characteristic transformations of these mineral phases during firing.

After formulation by casting and firing, the properties of the samples were evaluated. We observed a maximum flexural strength of 22.58 MPa at 1250°C for the F0 formulation and 25.69 MPa at 1200°C for the F1 formulation, which highlights the positive effect of feldspar (25 wt.%) on tile densification at relatively low temperatures.

Moreover, water absorption and open porosity decreased progressively over the studied temperature range, with values ranging from 17 to 10.8 wt.% for water absorption and 26 to 18.3% for porosity. Following ISO 13006, these tiles are classified in group III, making them suitable for wall use. The tiles obtained also have a low thermal conductivity (≤ 1 W/(m.K)), contributing to good thermal comfort and an internationally acceptable linear shrinkage, allowing optimum dimensional control and limiting deformation.

These results show that KOD clay, combined with 25 wt.% feldspar, is suitable for manufacturing quality wall tiles at an optimum firing temperature of 1200°C. Given the complexity of the phenomena involved during firing, particularly during sintering, further investigations will be needed to gain a deeper understanding of the interactions between the viscous phase and the other constituents of the mixture. To this end, scanning electron microscopy analysis is planned to study the evolution of the microstructure, morphology, and formation of the viscous phase as a function of firing temperature.

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