

Article

From conventional to eco-friendly firing approach for eco-bricks: physico-mechanical and thermal performance

Hanane Miri^{1,2} , Halima Rezqi¹, Hicham Nasri¹ , Amar Bakdid¹, Aboubakr El Hammouti³, Meriam El Ouahabi⁴ and Nathalie Fagel⁴ 

¹Laboratory of Applied Geosciences, Faculty of Sciences, Mohammed I University Oujda: Université Mohammed Premier Oujda, Morocco; ²Laboratoire Argiles, Géochimie et Environnements Sédimentaires (AGEs), Department of Geology, Faculty of Sciences, University of Liege, Liege, Belgium; ³Ecole Speciale des Travaux Publics du Batiment et de l'Industrie, France and ⁴Laboratoire Argiles, Géochimie et Environnements Sédimentaires (AGEs), Department of Geology, Faculty of Sciences, University of Liege: Université de Liege, Belgium

Abstract

The brick production industry faces increasing environmental pressure due to high energy demands during firing, necessitating the optimization of firing conditions. This study investigates an eco-friendly stepped firing process as a sustainable alternative to conventional direct heat treatment using clayey raw materials from the Ouled Mansour area, north-east Morocco. To evaluate this approach, raw materials were characterized using X-ray diffraction, X-ray fluorescence, infrared spectroscopy, simultaneous thermal analysis, Atterberg limits and particle-size distribution analysis. Brick specimens were then prepared and fired under both conventional and stepped heating processes. Their thermophysical properties (thermal conductivity, thermal diffusivity, porosity, water absorption and density) and compressive strength were assessed. Non-destructive tests (ultrasonic pulse velocity and Schmidt hammer tests) together with mineralogical and microstructural analyses were also performed. The stepped firing process reduces porosity and defects, thereby increasing the ultrasonic pulse velocity from 3197 to 3508 m s⁻¹ and improving compressive strength by up to 21%. Thermal conductivity and density slightly increase, from 0.57 to 0.58 W mK⁻¹ and from 1.60 to 1.62 g cm⁻³ at 770°C, respectively. The proposed eco-friendly firing process enhances the physico-mechanical performance of bricks while supporting their energy-efficient production, with potential reductions in energy consumption during both manufacturing and the building service life.

Keywords: Acoustic comfort; durability; Neogene clay; Ouled Mansour; thermal efficiency; ultrasonic testing

(Received 11 November 2025 UTC; revised 26 May 2026 UTC; Associate editor: Michele Dondi)

Bricks are among the most widely used construction materials worldwide, with an estimated annual production of 1.5 trillion units (Brown, 2024). The growing demand for bricks is driven by continuously increasing urbanization and socio-economic development. Recent studies indicate that the brick market is expected to register a compound annual growth rate exceeding 3% between 2024 and 2029 (Mordor Intelligence Research and Advisory, 2023). However, brick production is associated with high energy consumption, particularly during the manufacturing process. Additionally, the energy demand for heating and cooling in buildings is strongly influenced by the hygrothermal properties of clay bricks, which depend on their porosity, density and product

configuration (solid or hollow), as these parameters influence thermal conductivity and moisture-buffering capacity (Makrygiannis & Karalis, 2023; Hofheinz *et al.*, 2025).

In 2020, the building sector recorded 38% of global CO₂ emissions and 35% of energy consumption (Global Alliance for Building and Construction, 2020). Moreover, brick manufacturing consumes approximately 0.54–4.50 MJ of energy per kilogram of product, depending on the type of kiln and fuel used (Maithel & Heierli, 2008; Murmu & Patel, 2018). These figures highlight the urgent need to implement strategies to reduce energy demand, particularly through the optimization of construction materials (Global Alliance for Building and Construction, 2020).

Many studies have promoted sustainability in the building sector through the development of ecological bricks. For instance, Bruno *et al.* (2017, 2019) investigated the hypercompaction of bricks prior to firing, while Kung (1985) estimated optimal firing conditions by measuring the saturation coefficient and specific surface area. Extensive research (Cid-Falceto *et al.*, 2012; Oti & Kinuthia, 2012; El Fgaier *et al.*, 2015, 2016; Touolak *et al.*, 2015; González-López *et al.*, 2018; Ruiz *et al.*, 2018; Malkanthi *et al.*, 2020; Nagaraj *et al.*, 2014; Abid *et al.*, 2022) has focused on raw

Corresponding author: Hanane Miri; Email: hanane.miri@ump.ac.ma

Paper submitted to the special issue devoted to the ICC-2025

Cite this article: Miri H, Rezqi H, Nasri H, Bakdid A, El Hammouti A, El Ouahabi M and Fagel N (2026) From conventional to eco-friendly firing approach for eco-bricks: physico-mechanical and thermal performance. *Clay Minerals*, 1–16. <https://doi.org/10.1180/clm.2026.10053>

earth bricks, which are often well suited for thermal insulation (El Fgaier *et al.*, 2015; Giada *et al.*, 2019; Belarbi *et al.*, 2022). However, their environmental advantages may vary depending on the formulation and production process. In particular, the use of stabilizers such as cement or lime can significantly increase embodied energy and associated CO₂ emissions (Arduin *et al.*, 2022; Dai, 2026). Additionally, earth bricks may exhibit limited technological performance in terms of mechanical strength and water absorption, which can affect their durability. These materials are particularly vulnerable to water damage and tend to lose strength and dimensional stability over time (Murmur & Patel, 2018). Conversely, fired clay bricks are valued for their high technological performance, achieved through mineralogical and microstructural transformations during firing (Oti *et al.*, 2009; Gentilini *et al.*, 2014; Lachheb *et al.*, 2023). As thermal treatment is energy-intensive, optimizing firing conditions while ensuring adequate technological properties and hygrothermal performance is essential.

In Morocco, several studies have investigated the performance of clay bricks in various contexts, particularly in the development of eco-efficient materials. El Hammouti *et al.* (2022) examined the thermophysical properties of raw earth materials from Ouled Setout and Touissite in north-east Morocco, reporting thermal conductivities of 1.379 and 0.807 W mK⁻¹, respectively. Similarly, Boukili *et al.* (2021) studied a clayey material from Bensmim and concluded that, although it is unsuitable for brick manufacturing due to its weak mechanical properties, it exhibits high thermal performance, with thermal conductivity values ranging from 0.324 to 0.356 W mK⁻¹. El Hammouti *et al.* (2023) conducted a comparative study of fired and unfired clay bricks from four regions in northern Morocco. Their results showed that firing improved mechanical strength by 19–107% while reducing thermal conductivity by 21.6–52.0%. El Azhary *et al.* (2017) investigated the thermal performance of unfired clay bricks in buildings in Errachidia and showed that, with a thermal conductivity of 0.703 W mK⁻¹, these materials reduced indoor temperatures by ~5.1°C during the hottest periods. Finally, El-Yahyaoui *et al.* (2023) investigated unfired clay bricks incorporating diss fibres in the Taounate region and reported that increasing fibre content improved insulation performance but reduced compressive strength. These variations in thermal conductivity among Moroccan clay-based materials are primarily attributed to differences in the physical properties of the elaborated specimens, particularly porosity and density. Higher porosity generally corresponds to lower density and reduced thermal conductivity, as air-filled pores impede heat transfer through the material.

Previous studies (Cid-Falceto *et al.*, 2012; Oti & Kinuthia, 2012; Nagaraj *et al.*, 2014; El Fgaier *et al.*, 2015, 2016; Touolak *et al.*, 2015; El Azhary *et al.*, 2017; González-López *et al.*, 2018; Ruiz *et al.*, 2018; Malkanthi *et al.*, 2020; Boukili *et al.*, 2021; Abid *et al.*, 2022; El Hammouti *et al.*, 2022, 2023; El-Yahyaoui *et al.*, 2023) aimed at optimizing energy demand in brick production have primarily focused on raw earth bricks, which exhibit a lower environmental footprint and acceptable insulation performance. However, their limited technological and mechanical properties make fired clay bricks essential for ensuring durability, despite their higher energy consumption. Research efforts to optimize firing conditions remain limited. Additionally, the investigated methods have not considered the type of heat treatment used. Therefore, research investigating innovative approaches to adjusting the firing process is essential.

This study evaluates the effect of a stepped firing process as a sustainable alternative to conventional heat treatment for clay bricks. The approach involves systematically adjusting firing parameters, including key temperatures and dwell times, representing a novel strategy in the literature. The research investigates how this firing process influences brick properties, including compressive strength, density, porosity, water absorption, thermal conductivity, rebound hammer and ultrasonic pulse velocity (UPV) tests, along with their mineralogical and microstructural characteristics.

Geological context

The undulating Ouled Mansour plateau (Fig. 1) comprises low ridges separated by elongated depressions. It forms the southern boundary of the Saidia coastal plain and the northern limit of the Triffa plain (Laouina, 1990; Carneiro *et al.*, 2010). The Ouled Mansour hills consist of marly sediments, representing the main Neogene deposits in north-eastern Morocco, including those of Boudinar, Kert, Mellila-Nador and Kbdana (Houzay, 1975; Guillemin & Houzay, 1982; Barathon, 1989; Laouina, 1990; Kharim, 1991; Münch *et al.*, 2001; Carneiro *et al.*, 2010; Nasri *et al.*, 2016, 2019).

The Neogene in north-east Morocco was also marked by a tectonic extensional phase followed by a compressional phase (Barathon, 1989). The Ouled Mansour horst corresponds to a flexural uplift of sedimentary layers, which explains the lagoonal to shallow-marine nature of these deposits. The plateau surface rises eastward, overlooking the Kiss border valley by ~170 m, and westward towards hills bordering the Moulouya River. Maximum elevation reaches ~190 m (Barathon, 1989; Laouina, 1990). Neogene sedimentation in north-eastern Morocco began in the late Tortonian (Barathon, 1989; Kharim, 1991; Boubkari *et al.*, 2022), while Ouled Mansour marls are of Miocene and Pliocene age (Carneiro *et al.*, 2010). The deposit comprises blue/green marls near the top, overlain by green marls interbedded with yellow/brown calcareous sandstones, and basal conglomerates with rounded pebbles in soft, sandy or chalky cement (Grari *et al.*, 2019). Three representative green marl samples (S1, S2 and S3) were collected from the top, middle and bottom of the deposit, respectively, after removing the weathered surface layer.

Methods

Raw material characterization

X-ray diffraction (XRD) analyses were performed on bulk samples and orientated aggregates using a Bruker D8-Advance diffractometer with Cu-K α_1 radiation ($\lambda = 1.542 \text{ \AA}$) at the Department of Chemistry, University Mohammed First (Morocco), to determine the mineralogical composition. Bulk samples were prepared according to Moore & Reynolds (1997). Orientated aggregates were prepared from the <2 μm clay fraction through three preparations: air dried (AD), after solvation with ethylene glycol for 24 h (EG) and after heating at 500°C for 4 h (H). The obtained XRD traces were manually processed using the Joint Committee on Powder Diffraction Standards (JCPDS)–International Centre for Diffraction Data (ICDD) diffraction files and EVA® Bruker software. The quantitative estimation of the bulk and clay fraction mineralogy was performed by using TOPAS® Bruker software.

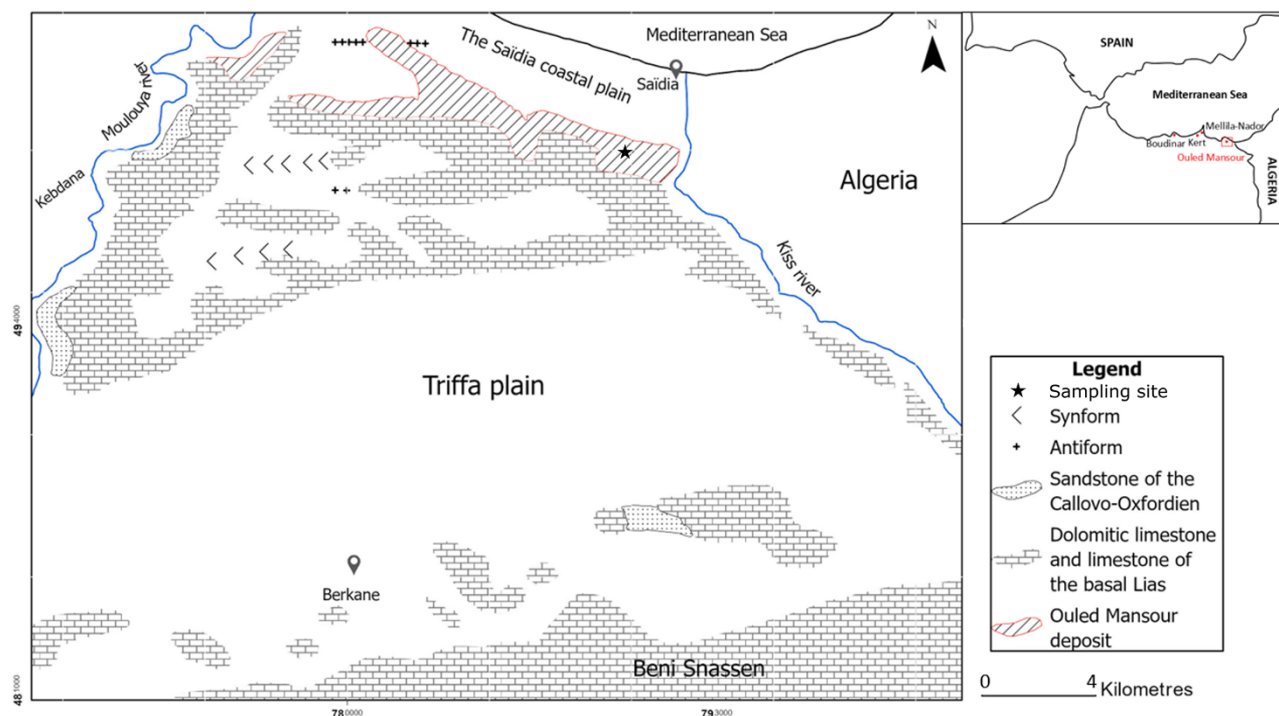


Figure 1. Simplified geological map of the study area (modified from Fetouani et al., 2008).

The chemical composition was determined by X-ray fluorescence (XRF) using a Thermo Fisher ARL Perform'X spectrometer after heating the samples at 1000°C for 2 h to determine the loss on ignition (LOI) at the Laboratory of Magmatic Petrology, University of Liege (Belgium).

Fourier-transform infrared (FTIR) spectroscopy was carried out using a Shimadzu FT-IR-8400S spectrometer in the range 400–4000 cm^{-1} at the Department of Chemistry, University Mohammed First (Morocco). Simultaneous thermal analysis (STA) was performed under atmospheric conditions using a TGA/DSC 3⁺ Mettler Toledo analyser up to 1200°C with a heating rate of 10°C min^{-1} (Laboratoire Argiles, Géochimie et Environnements Sédimentaires, University of Liege, Belgium).

The particle-size distribution analysis was performed using a Malvern Mastersizer 2000 laser diffraction analyser at the Department of Chemistry, University of Liege (Belgium). Approximately 1 g of bulk sample was suspended in distilled water and then introduced into the instrument, which operated at a rotation speed of 2000 rpm.

Atterberg limits, including the liquid limit (LL) and plastic limit (PL), were determined following the Casagrande method in accordance with the NF P 94-051 standard (AFNOR, 1993). The plasticity index (PI) was calculated as the difference between LL and PL at the Laboratory of Applied Geosciences, University Mohammed First (Morocco).

Brick preparation and characterization

The raw materials were initially mixed, ground and passed through a 1 mm sieve. The sieved material was then mixed with distilled water at 30 wt.% of the dry raw material to obtain a homogeneous and plastic paste. This paste was manually shaped into 50 × 50 × 50 mm³ cubic moulds. The preparation procedure is illustrated in Fig. 2.

The prepared specimens were first air-dried for 24 h and then dried at 70°C in a Binder E28 WTC oven until constant weight was achieved. The dried specimens were subsequently fired using direct and stepped processes at 770°C and 870°C in a Magmatherm MT 1100 furnace.

In the direct firing process, the temperature continuously increased to target temperatures of 770°C and 870°C, with a soaking time of 1.5 h (770D and 870D, respectively). In the stepped firing process, two intermediate steps were applied at 500°C and 700°C before reaching the maximum temperature (770S and 870S, respectively). The soaking time at each firing stage and at the target temperature was 30 min (Fig. 3). The heating rate for both firing processes was 2°C min^{-1} . In the direct process, firing is continuous without intermediate stages, and the materials were maintained for a longer period at high temperatures, in contrast to the stepped process, which helps to reduce energy consumption. For each firing process, 10 bricks were prepared and characterized, and the average values are reported.

The fired brick specimens were characterized for their microstructural, mineralogical, physical, thermal and mechanical properties. Non-destructive tests were also performed. Apparent porosity, water absorption and density were measured in accordance with the ASTM C373-88 standard (ASTM, 2006). Compressive strength was determined using a Controls Pilot Pro testing machine in accordance with EN 772-1 (AFNOR, 2015) at the Laboratory of Applied Geosciences, University Mohammed First (Morocco).

To evaluate the thermal insulation performance of the specimens, thermophysical characterization was conducted using the hot disk method according to ISO 22007-2 (ISO, 2008), at the Laboratory of Mechanics and Energy, University Mohammed First (Morocco). Thermal conductivity and thermal diffusivity were measured using a Transient Plane Source (TPS 2200) apparatus.



Figure 2. Preparation procedure of the specimens.

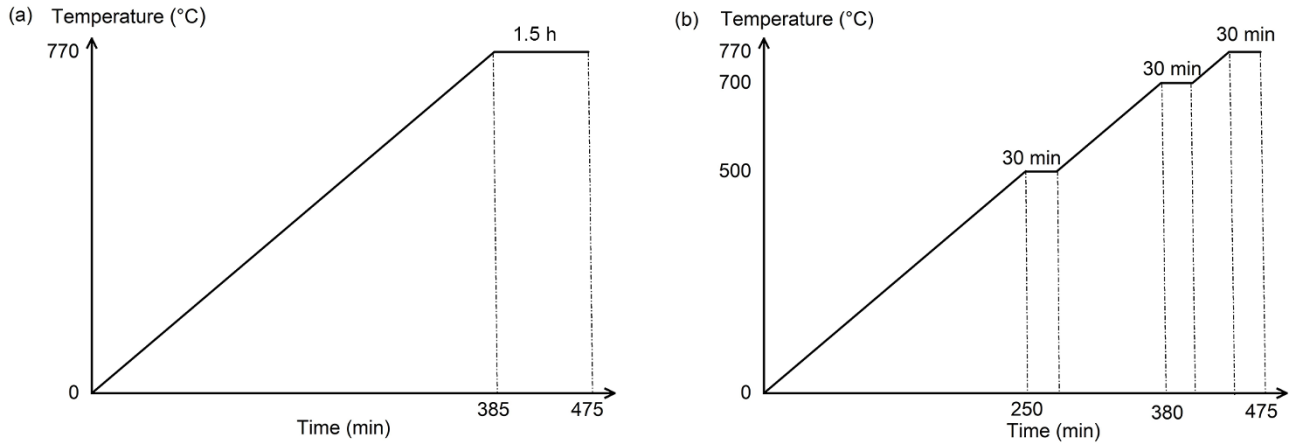


Figure 3. Schematic representation of the firing procedure at 770°C: (a) direct process and (b) stepped process.

Non-destructive characterization by UPV testing was performed using a Karl Deutsch 1085 ultrasonic flaw detector echograph equipped with a 2 MHz transducer, in accordance with the ASTM C597 standard (ASTM, 1998), at the Laboratory of Industrial and Engineering, University Mohammed First (Morocco). This method is based on the propagation of ultrasonic waves through a material to assess its durability. It enables the measurement of the UPV (m s^{-1}) and the detection of internal defects in specimens.

This method relies on the emission and reception of mechanical waves propagating through the material. Waves are emitted by a transducer, and the received signals are displayed as echograms on the equipment screen. UPV testing has been widely used to evaluate the quality of concrete for over 60 years (Naik *et al.*, 2003). It has also been applied to composites (Brancheriau, 2013; Rachidi *et al.*, 2019), steel (Bakdid *et al.*, 2016, 2019), wooden materials (Brancheriau, 2013), concrete (Bogas *et al.*, 2013), blocks and bricks (Korothe *et al.*, 1998; Sathiparan *et al.*, 2023), as well as in bearing defect detection in rotating machinery (Anouar *et al.*, 2017).

Defects were analysed through echograms displayed on the apparatus screen. Ultrasound velocity was calculated using Equation 1:

$$v = \frac{2e}{\Delta t} \quad (1)$$

where e is the specimen thickness (m) and Δt is the wave transit time (s).

Rebound hardness was assessed using a Schmidt hammer (type N) to determine the rebound value (R), following the ASTM C805 standard (ASTM, 1994), at the Laboratory of Applied Geosciences, University Mohammed First (Morocco). This non-destructive test, primarily used for concrete and rock, has been increasingly applied in brick hardness assessment (Debailleux, 2019). It measures the mean rebound value (R) of a sample, which reflects surface resistance to successive impacts from the hammer plunger tip (Aydin & Basu, 2005). This method provides an approximate estimate of the compressive strength of materials. It also allows monitoring of material quality and of the evolution of their performance after construction, as they are subjected to various degradation factors. While commonly applied to concrete (Shariati *et al.*, 2011; Jain *et al.*, 2013; Sanchez & Tarranza, 2015) and rocks (Aydin & Basu, 2005; Yagiz, 2009; Karaman & Kesimal, 2015), with established calibration diagrams for mechanical properties, its use in masonry remains limited (Debailleux, 2019; Brencich *et al.*, 2021; Gambilongo *et al.*, 2023). However, correlation equations have been developed to estimate brick compressive strength from rebound values (Brozovsky, 2014; Roknuzzaman *et al.*, 2017; Brencich *et al.*, 2021).

Mineralogical transformations during firing were monitored by XRD analysis at the Department of Chemistry, University Mohammed First (Morocco), and microstructure was examined using a scanning electron microscope (SEM; HIROX SH-5500P, 10 kV) at University Mohammed First (Morocco).

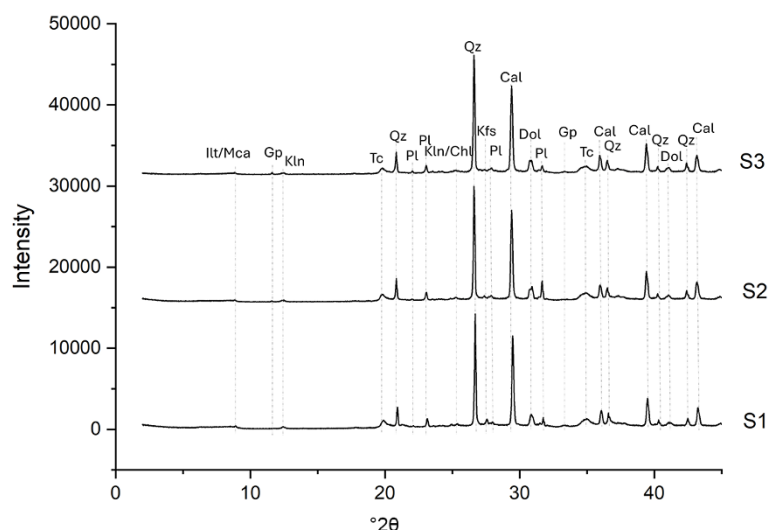


Figure 4. XRD traces of the raw materials. Cal = calcite; Chl = chlorite; Dol = dolomite; Gp = gypsum; Ill = illite; Kfs = K-feldspar; Kln = kaolinite; Mca = mica; Pl = plagioclase; Qz = quartz; Tc = total clay minerals.

Table 1. Mineralogical composition of the raw materials.

Mineral	Chemical formula	Reference card	Wt. %		
			S1	S2	S3
Quartz	SiO ₂	46-1045	25	27	29
Calcite	CaCO ₃	05-0586	33	35	35
Dolomite	CaMg(CO ₃) ₂	36-0426	4	4	3
K-feldspar	(K,AlSi ₃ O ₈)	19-0929	4	3	2
Plagioclase	(Na,Ca)(Si,Al) ₄ O ₈	9-0466	2	2	2
Gypsum	CaSO ₄ ·2H ₂ O	33-0311	1	1	1
Illite	(K,H ₃ O)(Al,Mg,Fe) ₂ (Si,Al) ₄ O ₁₀ ((OH) ₂ (H ₂ O))	26-0911	20	19	15
Kaolinite	Al ₂ Si ₂ O ₅ (OH) ₄	14-0164	4	4	5
Smectite	(Na,Ca) _{0.3} (Al,Mg) ₂ Si ₄ O ₁₀ (OH) ₂ ·n(H ₂ O)	29-1498	2	3	3
Vermiculite	(Mg,Fe,Al) ₃ (Al,Si) ₄ O ₁₀ (OH) ₂ ·4H ₂ O	16-0613	3	1	1
Chlorite	(Mg,Fe,Al) ₆ (Si,Al) ₄ O ₁₀ (OH) ₈	7-0076	1	1	3

Results and discussion

Raw material characterization

Mineralogical and chemical composition

The XRD traces show a similar mineralogical composition to the studied clayey samples (Fig. 4 & Table 1). The major phases include quartz (25–29 wt.%), calcite (33–35 wt.%) and dolomite (~4 wt.%). The principal clay minerals (Fig. 5 & Table 1) are illite (15–20 wt.%) and kaolinite (4–5 wt.%), with traces of smectite, vermiculite and chlorite (≤3 wt.%). The raw clay materials used in brick production are predominantly illitic and kaolinitic, with occasional traces of chlorite, whereas smectite is rarely present or occurs in limited amounts. Quartz and calcite are the most common accessory phases (El Yakoubi *et al.*, 2006; El Qandil, 2007; El Ouahabi *et al.*, 2014; Gharb & Ouazzani, 2014; Baghdad *et al.*, 2017; Laibi *et al.*, 2017; Tsozué *et al.*, 2017; Aghayev & Küçüküysal, 2018; Bomeni *et al.*, 2018; El Idrissi *et al.*, 2018; Nasri *et al.*, 2019; Kagonbé *et al.*, 2021; Rahou *et al.*, 2022).

The mineralogical composition controls the characteristics of clays, as each component undergoes specific transformations during firing. Each phase reacts differently based on firing conditions and interactions with other components. These transformations significantly influence the properties of the final product.

The chemical composition of the clay samples consists primarily of SiO₂ (39–40 wt.%), Al₂O₃ (10–12 wt.%) and CaO (14–16 wt.%; Table 2). The Fe₂O₃ ranges from 4 to 6 wt.%. The high contents of Al₂O₃ and SiO₂ are related to clay minerals and quartz, respectively.

The SiO₂/Al₂O₃ ratio exceeds 3 (average 3.61), which is within the typical range for common clays (2.85–4.09; Quiroga *et al.*, 2018). This ratio reflects the predominance of clay minerals (Souza *et al.*, 2005) and free quartz (Bennour *et al.*, 2015; Boussen *et al.*, 2016). The CaO and MgO contents are related to the presence of carbonates, particularly calcite and dolomite, which act as fluxes along with Na₂O₃ and K₂O, promoting the formation of a glassy phase (Kazmi *et al.*, 2017). In high concentrations, Ca and Mg may also delay the sintering process (Dondi *et al.*, 2014; Pardo *et al.*, 2018).

Iron oxides are responsible for the red colouration of ceramic pastes, originating from illite or chlorite, both of which may incorporate Fe cations (Kreimeyer, 1987; Molera *et al.*, 1998; Abajo, 2000). Previous studies indicate that clays containing more than 5 wt.% Fe₂O₃ typically fire red, whereas those with 1–5 wt.%, as in the studied samples (average Fe₂O₃ = 4.9 wt.%), tend to produce lighter colours (Murray, 2006; Dondi *et al.*, 2014; Jordán *et al.*, 2015; Domínguez *et al.*, 2016).

The infrared spectrum of the S3 sample is shown in Fig. 6, and it is presented as a representative example of the three studied sam-

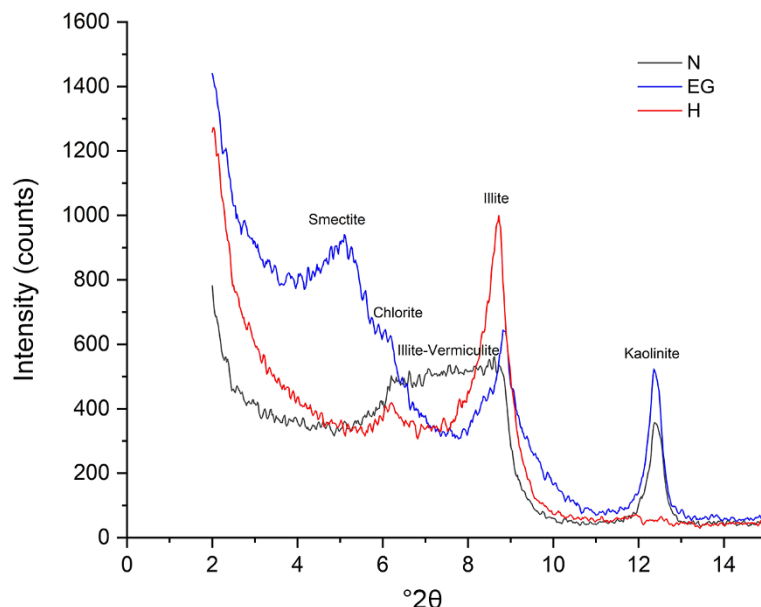


Figure 5. XRD traces of the orientated aggregates performed on sample S3. EG = ethylene glycol-solvated; H = heated at 500°C; N = natural (air-dried).

Table 2. Chemical composition of the raw clay materials (wt.%).

Oxide	S1	S2	S3
SiO ₂	39.42	39.33	39.57
Al ₂ O ₃	11.75	10.78	10.24
CaO	14.35	15.57	15.96
Fe ₂ O ₃	5.82	4.60	4.34
MgO	2.96	3.09	3.32
K ₂ O	1.72	1.36	1.62
Na ₂ O	1.06	1.29	0.96
TiO ₂	0.58	0.55	0.54
MnO	0.05	0.04	0.04
P ₂ O ₅	0.19	0.19	0.17
LOI	22.08	23.27	21.93
Total	99.98	99.05	98.69
SiO ₂ /Al ₂ O ₃	3.35	3.64	3.86

ples, all of which exhibited similar spectral trends. The most intense bands occur between 3612 and 3387 cm⁻¹, corresponding to OH stretching vibrations of the clay minerals. The band at 3612 cm⁻¹ is attributed to kaolinite, while that at 3387 cm⁻¹ relates to OH stretching of adsorbed water on clay minerals (Brindley *et al.*, 1986; Qtaitat & Al-Trawneh, 2005; Saikia & Parthasarathy, 2010).

The absorption near 981 cm⁻¹ corresponds to Al–Al–OH bending vibrations of the clay minerals (De Almeida Azzi *et al.*, 2016). The band at 1625 cm⁻¹ is attributed to the H–O–H bending vibration of water (Saikia & Parthasarathy, 2010). The bands at 1387 and 862 cm⁻¹ are assigned to the C–O vibrations of carbonates (Russell & Fraser, 1962). The bands at 793 and 400 cm⁻¹ correspond to Si–O stretching vibrations of quartz (Russell & Fraser, 1962; Saikia & Parthasarathy, 2010; De Almeida Azzi *et al.*, 2016). The band at 675 cm⁻¹ relates to Si–O–Si bending of clay minerals (Saikia & Parthasarathy, 2010). The band at 512 cm⁻¹ corresponds to Si–O–Al bending vibrations (Bich *et al.*, 2009; De Almeida Azzi *et al.*, 2016). The FTIR spectroscopy results are consistent with the XRD analysis and confirm the presence of clay minerals, quartz and carbonates as the main components of the studied clayey samples.

Physical properties

The grain-size distribution analysis classifies the studied samples as clayey silt (Shepard, 1954), with minor sand content (≤1 wt.%; Fig. 7 & Table 3). The clay fraction ranges from 46 to 49 wt.%, while the silt fraction varies from 50 to 53 wt.%. Minor variations in particle-size distribution are observed among the samples. The average values of clay, silt and sand are 48, 51 and 1 wt.%, respectively.

Grain-size distribution significantly influences material plasticity, affecting paste extrusion and shaping as well as permeability and porosity. According to McManus (1988), the raw materials exhibit low permeability and porosity, indicating desirable workability and consistency (El Idrissi *et al.*, 2018). Moreover, permeability and porosity are controlled by the Al₂O₃/SiO₂ ratio, with lower ratios corresponding to reduced permeability (Jarraya *et al.*, 2010). This aligns with the observed low Al₂O₃/SiO₂ values (0.86–0.89) in the studied samples.

The three samples S1, S2 and S3 exhibit a PI ranging from 28% to 34%, with a LL between 57% and 62% (Table 3). According to Holtz *et al.* (1981), these values classify the studied samples as highly plastic. Furthermore, the samples demonstrate optimal extrusion properties, in agreement with Bain (1987) (Fig. 7). The plastic behaviour of these samples is closely influenced by geological origin, genesis, crystal order, non-clay mineral content, organic matter, initial moisture content and, most importantly, particle-size distribution and mineralogical composition (Hajjaji *et al.*, 2010; Andrade *et al.*, 2011; El Ouahabi *et al.*, 2014; Moreno-Maroto & Azcárate, 2018; Moussi *et al.*, 2020).

Plastic clays typically contain either high amounts of low-plasticity clay minerals, including illite, chlorite and kaolinite, or low percentages of high-plasticity clay minerals such as smectite (Daoudi *et al.*, 2015). The studied samples contain significant amounts of low-plasticity clay minerals (>24%) associated with 2–3% smectite. Furthermore, the clay fraction exceeds 46%, which explains the observed plasticity. The samples exhibit suitable plasticity for brick manufacturing. Extremely plastic clays require substantial water to form workable pastes due to their internal moisture gradients (Souza

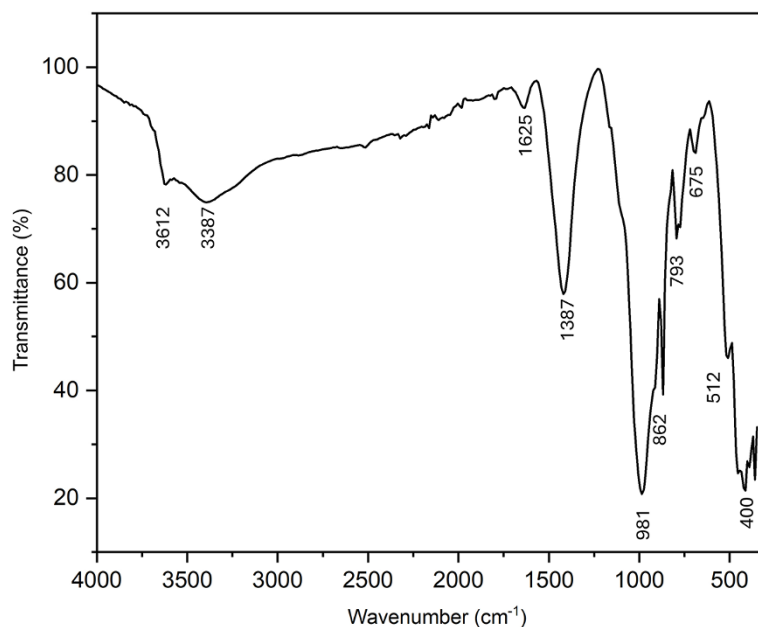


Figure 6. FTIR spectrum of the S3 sample.

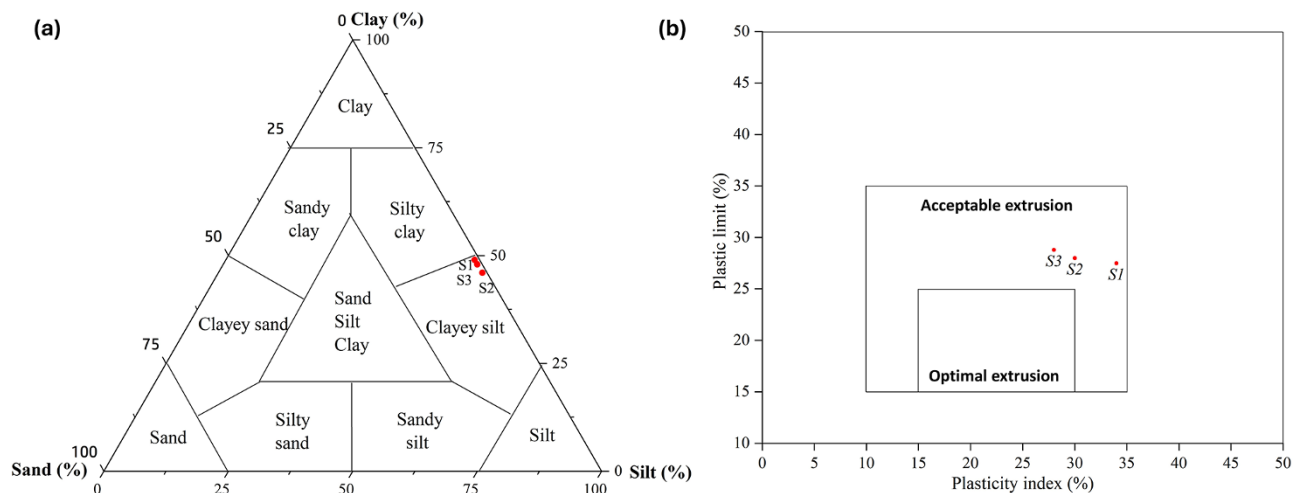


Figure 7. Projection of raw materials (a) on the Shepard diagram (Shepard, 1954) and (b) on a workability chart (Bain, 1987).

et al., 2013), potentially causing considerable shrinking and deformation during drying and firing (Pracidelli & Melchiades, 1997).

Thermal properties

The STA provides insights into the firing behaviour of the studied samples (Fig. 8), with S3 shown as a representative example, as all three samples exhibited similar trends. The STA curves display six distinct thermal events associated with weight loss. The first endothermic peak at 100°C is attributed to the removal of adsorbed water (Baran *et al.*, 2001; Ben Zaied *et al.*, 2015), accompanied by a weight loss of 3.5%. At ~500°C, kaolinite and illite dehydroxylation cause 9.4% weight loss (Jankula *et al.*, 2015). Between 700°C and 760°C, the decomposition of calcite accounts for a 6.2% mass loss, while the decomposition of dolomite at 830°C contributes an additional 0.5% weight loss (Trindade *et al.*, 2009; El Ouahabi *et al.*, 2014; Ben Zaied *et al.*, 2015; Bennour *et al.*,

Table 3. Grain-size distribution and Atterberg limits (wt.%) of the raw clay materials.

Sample	Clay	Silt	Sand	LL	PL	PI
S1	49	50	1.0	62	28	34
S2	46	53	0.9	58	28	30
S3	48	51	1.0	57	29	28

2015). Finally, the exothermic peak at 1170°C corresponds to high-temperature phase crystallization, with a 1% weight loss (Trindade *et al.*, 2009).

Characterization of bricks

Physical properties

The open porosity and water absorption results are presented in Fig. 9. Porosity values range from 26% to 31%, while water absorption varies between 17 and 21 wt.%. The lowest values are

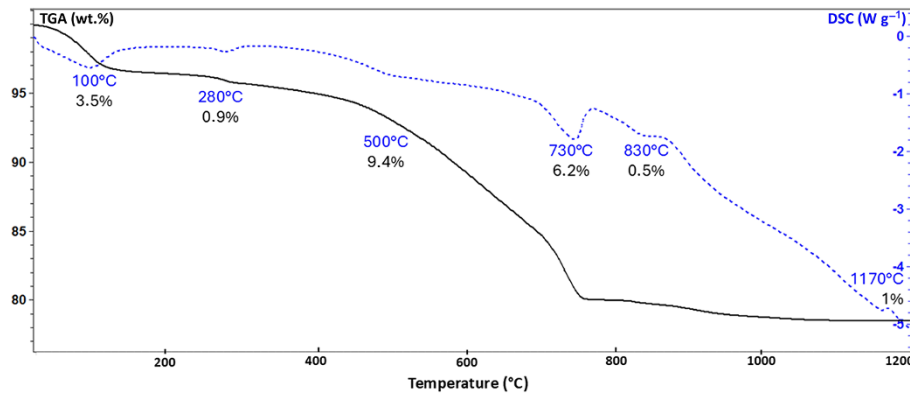


Figure 8. STA curves of sample S3. DSC = differential scanning calorimetry; TGA = thermogravimetric analysis.

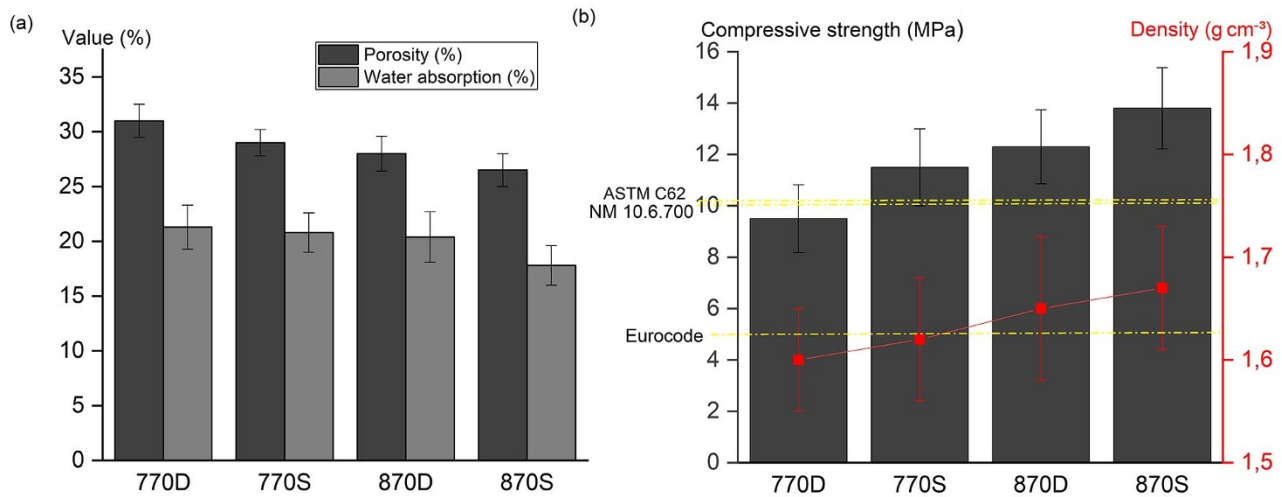


Figure 9. Physical and mechanical properties of the fired bricks: (a) porosity and water absorption; (b) bulk density and compressive strength.

observed in bricks fired using the stepped process up to 870°C (870S), whereas the highest values occur in bricks fired by direct heating at 770°C (770D).

Porosity and water absorption show minimal variation between direct and stepped firing processes, with a general decrease observed. For instance, at 770°C, porosity decreases from 31% in the direct process to 29% in the stepped process. Similarly, at 870°C, porosity reduces from 28% to 26% with the stepped firing, representing a reduction of 2%. Water absorption follows the same trend, as more porous bricks retain greater amounts of water. The stepped firing and higher temperatures reduce porosity and, consequently, water absorption by minimizing internal ducts and capillaries (Leiva *et al.*, 2016). Pores develop in the materials during the drying phase due to the loss of plasticity water and subsequently through dehydration during firing. The two intermediate firing steps at 500°C and 700°C contribute to reducing porosity. These stages are associated with the dehydroxylation of clay minerals and the decomposition of carbonates, which are key factors controlling reaction kinetics and the occurrence of new phases, as they release H₂O and CO₂, respectively (Duminuco *et al.*, 1998; Trindade *et al.*, 2009). During the 700°C firing stage, calcite decomposes gradually, providing sufficient time for the release of Ca, which subsequently reacts with other components, particularly SiO₂ and Al₂O₃, to form new phases. As a result, larger pores are partially filled, reducing their size, while smaller pores are completely filled. At 870°C in

the stepped process, two factors contribute to the further reduction of porosity: the increased temperature and the use of firing stages.

Water absorption directly affects brick durability, as higher absorption rates increase water infiltration, which gradually weakens the material over time. In facing and engineering bricks, excessive water absorption may also induce structural risks due to volumetric changes and stress generated during wetting–drying cycles (Mashiri *et al.*, 2015). Furthermore, water absorption provides an indication of the material's resistance to weathering. Water absorption for moderate weathering resistance should not exceed 22 wt.% (ASTM, 2012). Consequently, bricks from all firing processes are expected to withstand such weathering conditions.

Bulk density varies slightly from 1.60 to 1.67 g cm⁻³ (Fig. 9). Bricks densify with stepped firing and higher sintering temperatures, with 870S specimens exhibiting the highest density. Specimens fired at 770°C by direct heating are the least dense. Density values vary inversely with porosity and water absorption.

Brick densification results from reduced porosity and the formation of new phases. Densification minimizes voids, bringing particles closer together. Bulk density also depends on the nature, density and proportion of neoformed phases, with denser phases producing denser materials. Temperature is the primary factor affecting density, rather than the use of firing stages. Stepped heating maintains density without compromising brick lightness.

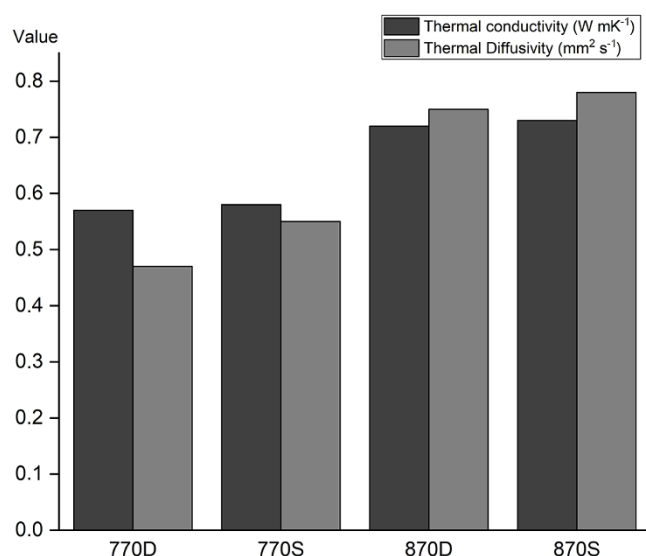


Figure 10. Thermal properties of the fired bricks.

Lightweight bricks improve building seismic performance and reduce transportation and labour costs (De Silva & Hansamali, 2019). Furthermore, they decrease the overall building weight, thereby reducing the required dimensions of structural elements such as beams and columns (Muñoz *et al.*, 2021).

Mechanical strength

Compressive strength ranges from 9.5 to 13.8 MPa (Fig. 9), with direct firing at 770°C yielding 9.5 MPa, increasing to 11.5 MPa with stepped firing. Compressive strength reaches 12 MPa at 870°C and peaks under stepped firing at 870°C. In Morocco, the mechanical resistance threshold is 10 MPa according to NM 10.6.700 standard (SNIMA, 2001), while ASTM C62 specifies 10.3 MPa for normal weathering (ASTM, 2012). All fired specimens except 770D meet these requirements. Additionally, all bricks satisfy the Eurocode minimum of 5 MPa for fired clay bricks.

Buildings should withstand both permanent (dead) loads from their own weight and operational (live) loads from occupancy. Stepped firing significantly improves mechanical strength, with 21% and 15% increases observed at 770°C and 870 °C, respectively. Higher firing temperatures increase strength by 26% and 20% for direct and stepped processes, respectively. The eco-friendly bricks produced by stepped firing exhibit adequate mechanical performance for unrestricted construction use.

Increased porosity and water absorption correlate with decreased density and mechanical strength. Pore-volume reduction and neoformed phase development during firing increase strength, rendering the bricks suitable as eco-friendly construction materials.

Thermal performance

The thermal characterization results (Fig. 10) show that 770D specimens exhibit the lowest thermal conductivity (0.57 W mK⁻¹) and thermal diffusivity (0.47 mm² s⁻¹). In contrast, 870S bricks display the highest values (0.73 W mK⁻¹ and 0.78 mm² s⁻¹, respectively).

Samples fired by the direct process exhibit similar thermal properties to those fired by the stepped process, although a slight increase is observed under stepped firing conditions. However, higher firing temperatures lead to increased thermal conductivity and diffusivity.

The obtained values align with the porosity and water absorption results. In general, the more porous the material, the lower its thermal conductivity. Air pores, with a thermal conductivity of 0.026 W mK⁻¹ (Smith *et al.*, 2013), reduce overall brick thermal conductivity. Mineralogical transformations occurring during firing also affect thermal insulation. As porosity develops due to the release of structural water from minerals such as kaolinite and illite, as well as the release of CO₂ during decarbonation (Nigay *et al.*, 2017), thermal conductivity is affected. The formation of new phases that fill the voids also plays a significant role, as each mineral exhibits specific thermal characteristics that may change during firing. For instance, kaolinite has a thermal conductivity of 2.8 W mK⁻¹ (Midtømme, 1998), which decreases to 0.39 W mK⁻¹ upon decomposition to metakaolinite above 500°C (Michot *et al.*, 2008). Illite and smectite exhibit thermal conductivities of ~2.8 W mK⁻¹, while the thermal conductivity of quartz ranges from 1.28 to 1.65 W mK⁻¹ (Abdulagatov *et al.*, 2000).

Thermal performance is inversely related to thermal conductivity and diffusivity. Therefore, bricks fired at 770°C under both direct (770D) and stepped (770S) processes exhibit the highest thermal efficiency, while stable thermal insulation properties are observed across all specimens. The stepped firing process can contribute to energy savings both during manufacturing and throughout the lifecycle of the bricks in buildings, improving thermal comfort while reducing overall energy consumption.

The values obtained in this study are lower than those for unfired solid clay bricks (0.77–1.07 W mK⁻¹) but higher than those for fired hollow clay bricks (0.19–0.40 W mK⁻¹), which have larger cavities that increase thermal transmittance (El Hammouti *et al.*, 2023).

Non-destructive testing

The UPV results for the tested brick specimens are summarized in Fig. 11. The lowest velocity is 3197 m s⁻¹ for the bricks fired at 770°C using the direct process (770D), increasing to 3246 m s⁻¹ with stepped firing (770S). The bricks 870D and 870S exhibit velocities of 3476 and 3508 m s⁻¹, respectively. Increasing firing temperature and stepped firing lead to higher UPV values, reflecting reduced porosity and cracks during sintering. In contrast, high open porosity reduced the interconnectedness of the solid structure, which in turn slows down ultrasonic pulse propagation (Jeong & Hsu, 1995).

UPV correlates positively with density and compressive strength (Bogas *et al.*, 2013; Sathiparan *et al.*, 2023) but negatively with water absorption (Korothe *et al.*, 1998). Anisotropy and the presence of anomalies within the material affect ultrasonic wave propagation, leading to attenuation and longer transit times (Brancheriau, 2013). The more compact the material, the denser and less porous it is, enabling faster wave transmission. In contrast, bricks with greater inhomogeneity dampen waves, resulting in longer transit times and reduced velocities.

The 770S and 870S brick specimens are more compact and exhibit lower porosity than the 770D and 870D bricks, which explains their higher UPV values. Compared with previous studies, the UPV values obtained in this study align with those reported by Korothe *et al.* (1998), at 2201–4383 m s⁻¹. They are higher than those reported for cement-stabilized earth blocks (270–2610 m s⁻¹; Sathiparan *et al.*, 2023) but lower than those reported for concrete (3600–5200 m s⁻¹; Bogas *et al.*, 2013).

Bricks with UPV values above 3500 m s⁻¹ are considered durable, while those with values below 1000 m s⁻¹ are considered non-durable (Korothe *et al.*, 1998). In this study, all tested bricks

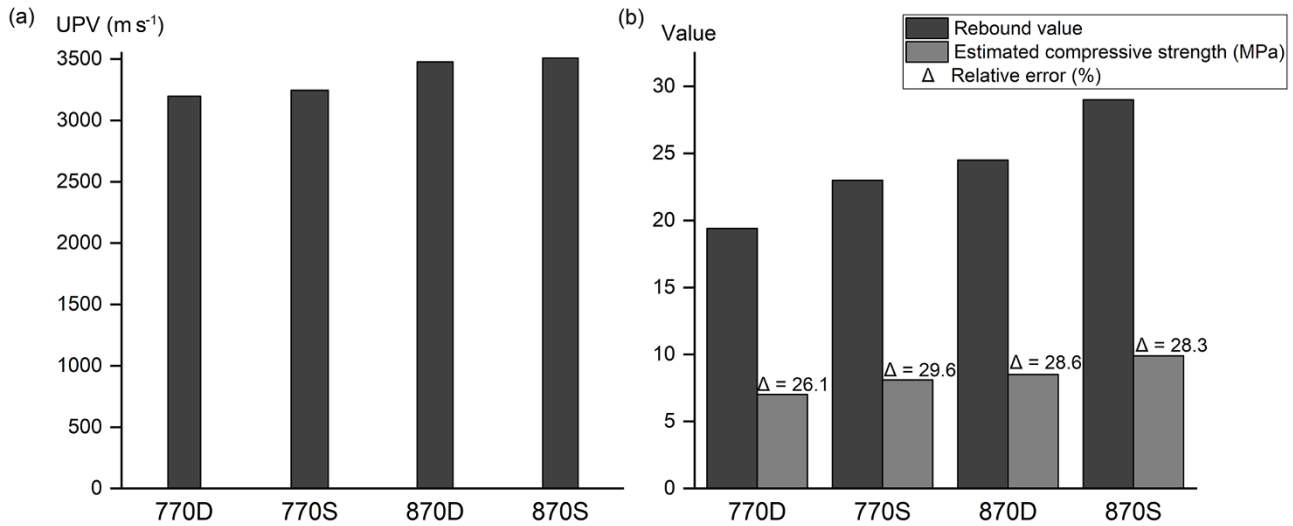


Figure 11. (a) UPV results and (b) rebound value and estimated compressive strength.

exhibit UPV values between ~ 3200 and 3510 m s^{-1} . 870S bricks, with UPV values exceeding 3500 m s^{-1} , represent the most durable specimens. The durability ranking is as follows: $870D > 770S > 770D$.

Ultrasonic waves have frequencies above 20 kHz, while audible sound ranges from 20 Hz to 20 kHz (Leighton, 2007). These two types of waves share the same nature and similar propagation behaviour but differ in frequency (Pompei, 2002). Accordingly, UPV can predict the sound transmission and acoustic insulation performance of brick materials. Sound transmission through walls within buildings can be reduced by using materials with lower UPV values. The bricks 770D and 870D are therefore expected to provide improved acoustic comfort. When sound waves encounter porous materials, they are damped within the pores, reducing external noise transmission.

Analysis of defects in the specimens was carried out through the examination of echographs (Fig. 12). Three peak types are identified: (1) peak A, corresponding to the excitation echo generated by transducer–specimen contact; (2) peak B, corresponding to the back-wall echo resulting from wave reflection at the opposite brick face; and (3) peak C, the defect echo, produced by material anomalies through which the wave is reflected upon encountering an obstacle (Krautkrämer & Krautkrämer, 1990).

Defect echoes exhibit varying signal intensities: the 770D signals are the most intense, whereas the 870S echoes are the most attenuated. Defect echoes in stepped process specimens are less pronounced than those in bricks from the direct process, consistent with their material properties. The relative amplitude of the echoes provides an indication of defect size (Brancheriau, 2013), with higher amplitudes corresponding to larger or more abundant pores.

The measured rebound values (R), the estimated compressive strength (CS) based on the equation reported in Brencich *et al.* (2021) and the corresponding error (%) relative to the measured values are presented in Fig. 11, calculated according to Equation 2:

$$\text{CS (estimated)} = 0.30R + 1.2 \quad (2)$$

Rebound number values range from 19.4 to 29.0, corresponding to estimated compressive strengths between 7.01 and 9.9 MPa. The stepped firing process produced 18% higher rebound values than

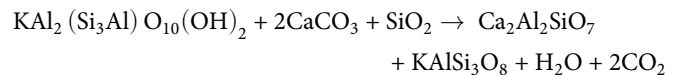
direct firing. This increased compactness increases brick hardness and resistance to the hammer plunger.

The rebound values found in this study exceed those reported in Roknuzzaman *et al.* (2017) but are lower than the values recorded in Debailleux (2019). The Schmidt hammer results for concrete show even higher values, reaching up to 30.5 (Kovler *et al.*, 2018), while earth-based mortar yielded lower values (11.9–25.9; Gambilongo *et al.*, 2023). The estimated compressive strengths are lower than those from standard mechanical testing (Fig. 11), with errors ranging from 26.1% to 29.6%. These results demonstrate the positive effects of stepped firing.

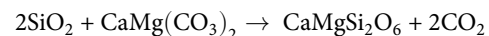
Mineralogical and microstructural evolution

The XRD traces of the fired specimens reveal the disappearance of calcite and dolomite, the transformation of clay minerals and the formation of new phases (diopside, hematite, plagioclase and gehlenite; Fig. 13). Quartz persists, as expected, up to 1100°C (Trindade *et al.*, 2009; El Ouahabi *et al.*, 2015). These mineralogical transformations are attributed to the reactions of SiO_2 and Al_2O_3 , derived from quartz and clay minerals, with CaO and MgO released during decarbonation of calcite and dolomite. The XRD results also indicate the presence of an amorphous phase, probably composed of residual calcite, dolomite and quartz that did not fully react during firing.

Gehlenite forms through the reaction of illite/mica, calcite and quartz as follows (Rathossi & Pontikes, 2010):



Diopside forms according to the following reaction (Cultrone *et al.*, 2020):



Pores form in the brick matrix through dehydration, dehydroxylation and subsequent decarbonation, which generates CO_2 . Decarbonation also releases CaO and MgO (Cultrone *et al.*, 2020), which react with SiO_2 and Al_2O_3 to form new phases. These newly formed phases partially fill pores, reducing porosity and water absorption. Consequently, the materials become denser, leading to increased mechanical strength and thermal conductivity while

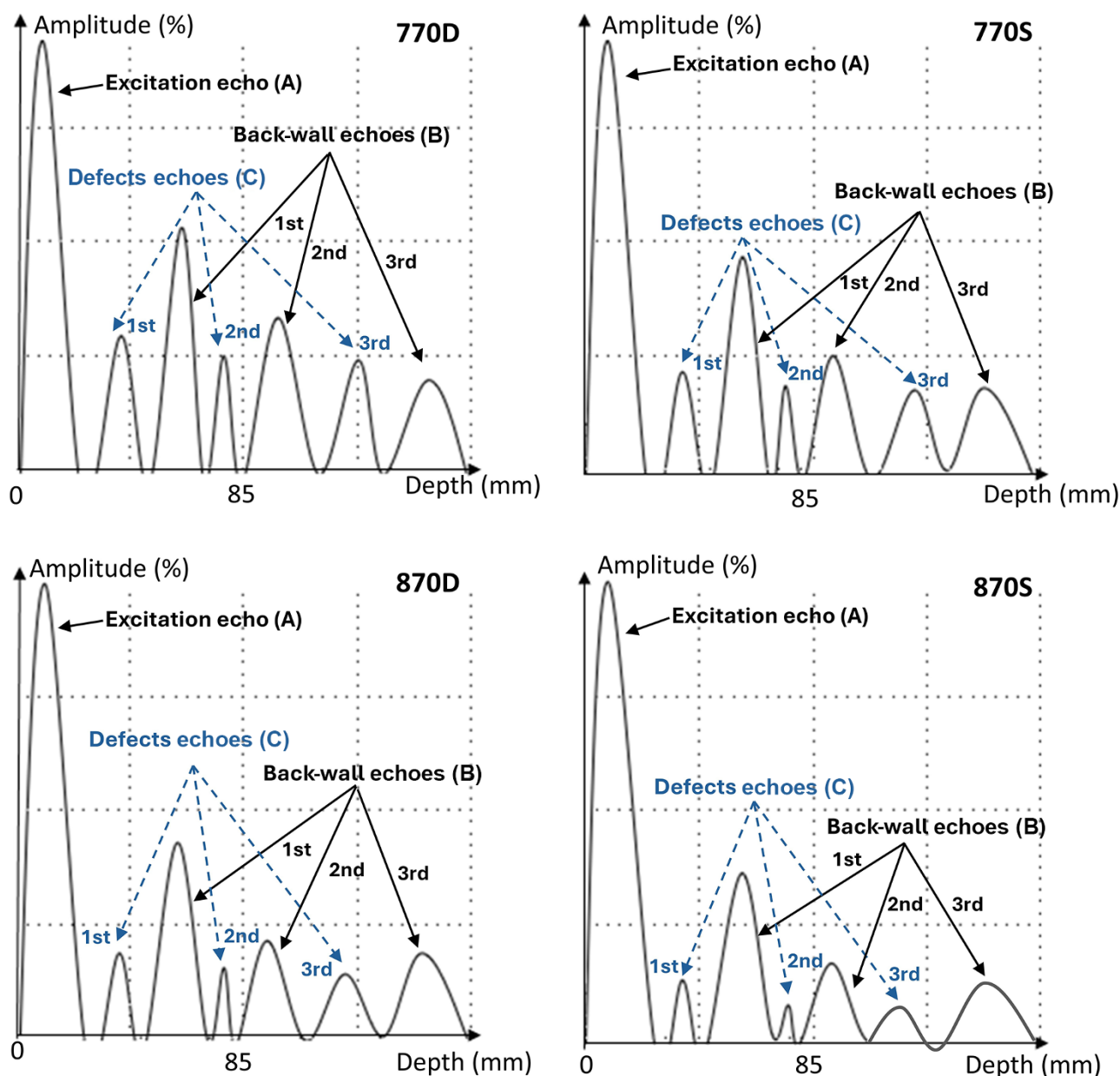


Figure 12. Echographs of the elaborated bricks.

minimizing defects and increasing UPV. The intensity of diopside, gehlenite and plagioclase peaks increases with rising temperature, improving brick properties. The decomposition of calcite is completed at $\sim 850^{\circ}\text{C}$ (Rodriguez-Navarro *et al.*, 2009), explaining the observed improvement at 870°C . The reduced intensity of the hematite peak is attributed to the presence of a significant amount of carbonates, which inhibit the formation of iron oxides (Maniatis *et al.*, 1981), contributing lighter brick colours. The abundance of fluxing agents in the studied clays, particularly CaO and MgO, lowers the melting temperature, promoting early densification and glassy phases (Boukili *et al.*, 2021). Consequently, calcareous clays improve these physical and mechanical properties (Kadir *et al.*, 2009).

SEM images reveal a homogeneous and porous structure regardless of firing process (Fig. 14). However, stepped firing significantly reduces pore size, as newly formed phases partially

fill pores, in line with the previously discussed brick properties. The direct firing process improves insulation performance by increasing porosity and water absorption, while the stepped firing slightly improves durability by increasing compactness and reducing defects.

Summary and conclusions

Clays from the Ouled Mansour area, north-east Morocco, were characterized and valorized for the production of eco-friendly fired bricks. An innovative firing process based on firing stages was investigated as an alternative to conventional direct firing. In the direct firing process, the temperature was continuously increased until reaching the target temperatures (770°C and 870°C), at which point the bricks were soaked for 1.5 h. In the stepped firing process, the temperature was first raised to 500°C and held for 30 min, then

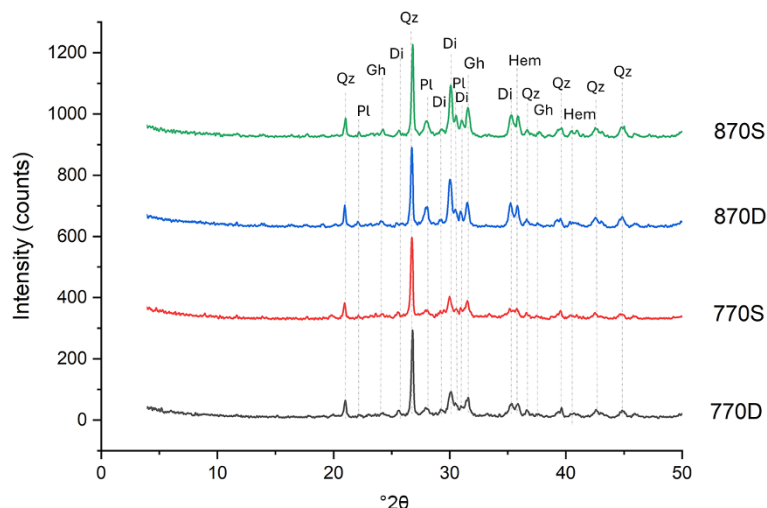


Figure 13. XRD traces of the brick specimens. Di = diopside; Gh = gehlenite; Hem = hematite; Pl = plagioclase; Qz = quartz.

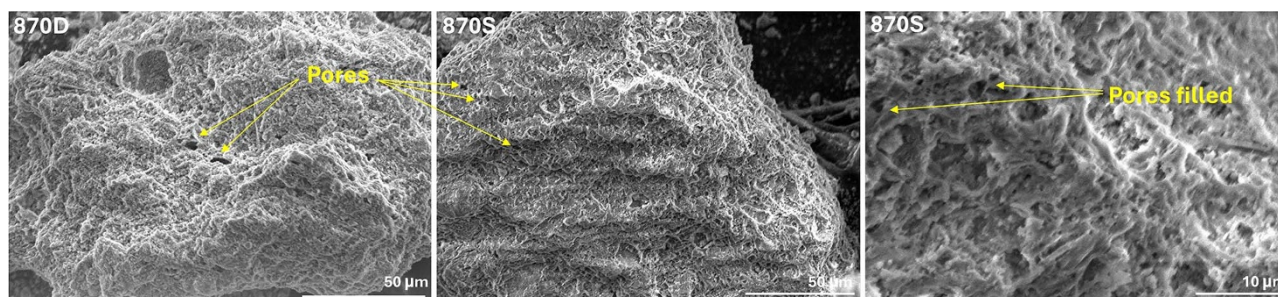


Figure 14. SEM images of 870D and 870S brick specimens.

increased to 700°C with a soaking time of 30 min. Finally, the bricks were soaked at the target temperatures (700°C and 800°C) for an additional 30 min.

The raw materials mainly consist of quartz, carbonates and clay minerals (illite, kaolinite, chlorite and smectite). These materials exhibit an adequate grain-size distribution and plasticity, making them suitable for brick manufacturing.

The stepped firing process slightly improved brick properties: compressive strength increased, while water absorption and open porosity decreased. Non-destructive tests provided valuable insights. Schmidt hammer measurements indicated higher rebound values for bricks fired using the stepped process at 770°C and 870°C. Ultrasonic tests revealed that materials with numerous defects exhibited lower UPV, which may improve acoustic insulation.

Mineralogical transformations during firing stages drive microstructural changes that determine brick properties. Thermal conductivity and diffusivity remained nearly constant across the firing processes, indicating that stepped firing maintains insulation performance. Among the tested processes, stepped firing at 770°C (770D) proved most ecological due to its lower energy consumption.

The Ouled Mansour Neogene marl deposit exhibits significant potential for brick manufacturing, supporting economic and industrial development in north-east Morocco. The stepped heat treatment offers an eco-friendly alternative capable of reducing energy consumption at both the industrial scale and during the service life of the building by promoting thermal comfort.

Acknowledgements. The authors acknowledge the Centre National pour la Recherche Scientifique et Technique (CNRS) in Morocco for the PhD Associate Scholarship PASS programme. We also acknowledge the Erasmus+ exchange programme. Hanane Miri thanks Professor Bachir El Kihel for his valuable help with ultrasonic testing.

Competing interests. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Declaration of generative AI and AI-assisted technologies in the writing process. During the preparation of this work, the authors used AI-based tools to assist with language refinement and style. All scientific content and interpretations remain the authors' own. After using the AI-based tools, the authors reviewed and edited the content as needed and take full responsibility for the publication.

References

- Abajo M.F. (2000) *Manual sobre fabricación de baldosas, tejas y ladrillos*. Bernalmar, Barcelona, Spain, 360 pp.
- Abdulagatov I.M., Emirov S.N., Tsomaeva T.A., Gairbekov K.A., Askerov S.Y. & Magomedova N.A. (2000) Thermal conductivity of fused quartz and quartz ceramic at high temperatures and high pressures. *Journal of Physics and Chemistry of Solids*, **61**, 779–787.
- Abid R., Kamoun N., Jamoussi F. & El Feki H. (2022) Fabrication and properties of compressed earth brick from local Tunisian raw materials. *Boletín de la Sociedad Española de Cerámica y Vidrio*, **61**, 397–407.
- AFNOR (1993) *NF P 94-051*. AFNOR, Paris, France, 15 pp.

- AFNOR (2015) *NF EN 772. Méthodes d'essai des éléments de maçonnerie – Partie 1 : détermination de la résistance à la compression*. AFNOR, Paris, France, 14 pp.
- Aghayev T. & Küçükuysal C. (2018) Ceramic properties of Uşak clay in comparison with Ukrainian clay. *Clay Minerals*, **53**, 549–562.
- Andrade F.A., Al-Qureshi H.A. & Hotza D. (2011) Measuring the plasticity of clays: a review. *Applied Clay Science*, **51**, 1–7.
- Anouar B.A.E., Elamrani M., Elkihel B., Delaunois F. & Electronique L. (2017) A comparative experimental study of ultrasound technique and vibration analysis in detection of bearing defect. Presented at 13th édition du congrès de mécanique (CMM), Oran, Algeria, 11–14 April.
- Arduin D., Caldas L.R., Paiva R.d.L.M. & Rocha F. (2022) Life cycle assessment (LCA) in earth construction: a systematic literature review considering five construction techniques. *Sustainability*, **14**, 13228.
- ASTM (1994) *ASTM C805, Standard Test Method for Rebound Number of Hardened Concrete*. ASTM, West Conshohocken, PA, USA, 4 pp.
- ASTM (1998) *ASTM C597, Standard Test Method for Pulse Velocity through Concrete*. ASTM, West Conshohocken, PA, USA, 4 pp.
- ASTM (2006) *ASTM C373-88, Standard Test Method for Water Absorption, Bulk Density, Apparent Porosity, and Apparent Specific Gravity of Fired Whiteware Products*. ASTM, West Conshohocken, PA, USA, 2 pp.
- ASTM (2012) *ASTM C62, Standard Specification for Building Brick (Solid Masonry Units Made from Clay or Shale)*. ASTM, West Conshohocken, PA, USA, 4 pp.
- Ayadin A. & Basu A. (2005) The Schmidt hammer in rock material characterization. *Engineering Geology*, **81**, 1–14.
- Baghdad A., Bouazi R., Bouftouha Y., Bouabsa L. & Fagel N. (2017) Mineralogical characterization of Neogene clay areas from the Jijel basin for ceramic purposes (NE Algeria – Africa). *Applied Clay Science*, **136**, 176–183.
- Bain J. (1987) Composition and properties of clays used in various fields of ceramics. *Ceramic Forum International*, **62**, 536–538.
- Bakdid A., El Kihel B., Delaunois F. & Nougauoi A. (2016) Technique de contrôle de la soudure par la méthode d'ultrason multi-éléments. Presented at: 10th Conférence Internationale: Conception et Production Intégrées, Tangier, Morocco, 2–4 December.
- Bakdid A., El Kihel B., Nougauoi A. & Delaunois F. (2019) Three-dimensional characterization of weld defects in a steel material. *Journal of Engineering and Applied Sciences*, **14**, 1928–1932.
- Baran B., Ertürk T., Sarikaya Y. & Alemdaroğlu T. (2001) Workability test method for metals applied to examine a workability measure (plastic limit) for clays. *Applied Clay Science*, **20**, 53–63.
- Barathon J.J. (1989) *Bassins et littoraux du Rif oriental (Maroc): évolution morphoclimatique et tectonique depuis le néogène supérieur*. PhD thesis, University of Poitiers, Poitiers, France.
- Belarbi Y.E., Sawadogo M., Poullain P., Issaadi N., Hamami A.E.A., Bonnet S. & Belarbi R. (2022) Experimental characterization of raw earth properties for modeling their hygrothermal behavior. *Buildings*, **12**, 648.
- Ben Zaied H.F., Abidi R., Slim-Shimi N. & Somarin A.K. (2015) Potentiality of clay raw materials from Gram area (northern Tunisia) in the ceramic industry. *Applied Clay Science*, **112–113**, 1–9.
- Bennour A., Mahmoudi S., Srasra E., Boussen S. & Htira N. (2015) Composition, firing behavior and ceramic properties of the Sejnène clays (northwest Tunisia). *Applied Clay Science*, **115**, 30–38.
- Bich C., Ambroise J. & Péra J. (2009) Influence of degree of dehydroxylation on the pozzolanic activity of metakaolin. *Applied Clay Science*, **44**, 194–200.
- Bogas J.A., Gomes M.G. & Gomes A. (2013) Compressive strength evaluation of structural lightweight concrete by non-destructive ultrasonic pulse velocity method. *Ultrasonics*, **53**, 962–972.
- Bomeni I.Y., Njoya A., Ngapgue F., Wouatong A.S.L., Yongue Fouateu R., Kamgang Kabeyene V. & Fagel N. (2018) Ceramic with potential application of Ngwenfon alluvial clays (Noun, west Cameroon) in building construction: mineralogy, physicochemical composition and thermal behaviour. *Construction and Building Materials*, **182**, 493–503.
- Boubkari L., Achalhi M., Raji O., Ouabid M., Bodinier J.L., El Kati I. & El Messbahi H. (2022) Neogene basins in Eastern Rif of Morocco and their potential to host native sulphur. *All Earth*, **34**, 90–106.
- Boukili G.E., Lechheb M., Ouakarrouch M., Dekayir A., Kifani-Sahban F. & Khaldoun A. (2021) Mineralogical, physico-chemical and technological characterization of clay from Bensmim (Morocco): suitability for building application. *Construction and Building Materials*, **280**, 122300.
- Boussen S., Sghaier D., Chaabani F., Jamoussi B. & Bennour A. (2016) Characteristics and industrial application of the Lower Cretaceous clay deposits (Bouhedma Formation), southeast Tunisia: potential use for the manufacturing of ceramic tiles and bricks. *Applied Clay Science*, **123**, 210–221.
- Brancheriau L. (2013) *Caractérisation acoustique et ultrasonore des produits bois et composites*. PhD thesis, Université Montpellier II, Montpellier, France.
- Brencich A., Dawid L., Matysek P., Orban Z. & Sterpi E. (2021) Compressive strength of solid clay brickwork of masonry bridges: estimate through Schmidt hammer tests. *Construction and Building Materials*, **306**, 124494.
- Brindley G.W., Kao C.C., Harrison J.L., Lipsicas M. & Raythatha R. (1986) Relation between structural disorder and other characteristics of kaolinites and dickites. *Clays and Clay Minerals*, **34**, 239–249.
- Brown A. (2024) Bricks: a review of sustainability and toxicity issues. Pp. 179–194 in: *Sustainability and Toxicity of Building Materials* (E.K. Petrović, M. Gjerde, F. Chicca and G. Marriage, editors). Elsevier, Amsterdam, The Netherlands.
- Brozovsky J. (2014) Determine the compressive strength of calcium silicate bricks by combined non-destructive method. *The Scientific World Journal*, **2014**, 1–5.
- Bruno A.W., Gallipoli D., Perlot C. & Mendes J. (2017) Mechanical behaviour of hypercompacted earth for building construction. *Materials and Structures/Matériaux et Constructions*, **50**, 1–15.
- Bruno A.W., Gallipoli D., Perlot C. & Mendes J. (2019) Optimization of bricks production by earth hypercompaction prior to firing. *Journal of Cleaner Production*, **214**, 475–482.
- Carneiro J.F., Boughriba M., Correia A., Zarhloule Y., Rimi A. & Houadi B.E. (2010) Evaluation of climate change effects in a coastal aquifer in Morocco using a density-dependent numerical model. *Environmental Earth Sciences*, **61**, 241–252.
- Cid-Falceto J., Mazarrón F.R. & Cañas I. (2012) Assessment of compressed earth blocks made in Spain: international durability tests. *Construction and Building Materials*, **37**, 738–745.
- Cultrone G., Javier F. & Rosua C. (2020) Growth of metastable phases during brick firing: mineralogical and microtextural changes induced by the composition of the raw material and the presence of additives. *Applied Clay Science*, **185**, 105419.
- Dai S. (2026) A state-of-the-art review of the life cycle assessment of rammed earth building construction. *Energy and Buildings*, **350**, 116643.
- Daoudi L., Knidiri A., El Boudour El Idrissi H., Rhouta B. & Fagel N. (2015) Role of the texture of fibrous clay minerals in the plasticity behavior of host materials (Plateau du Kik, western High Atlas, Morocco). *Applied Clay Science*, **118**, 283–289.
- De Almeida Azzi A., Osacký M., Uhlík P., Čaplovičová M., Zanardo A. & Madejová J. (2016) Characterization of clays from the Corumbataí formation used as raw material for ceramic industry in the Santa Gertrudes district, São Paulo, Brazil. *Applied Clay Science*, **132–133**, 232–242.
- De Silva S.G.H.M.J. & Hansamali E. (2019) Eco-friendly fired clay bricks incorporated with porcelain ceramic sludge. *Construction and Building Materials*, **228**, 116754.
- Debailleux L. (2019) Schmidt hammer rebound hardness tests for the characterization of ancient fired clay bricks. *International Journal of Architectural Heritage*, **13**, 288–297.
- Domínguez E., Dondi M., Etcheverry R., Recio C. & Iglesias C. (2016) Genesis and mining potential of kaolin deposits in Patagonia (Argentina). *Applied Clay Science*, **131**, 44–47.
- Dondi M., Raimondo M. & Zanelli C. (2014) Clays and bodies for ceramic tiles: reappraisal and technological classification. *Applied Clay Science*, **96**, 91–109.
- Duminuco P., Messiga B. & Riccardi M.P. (1998) Firing process of natural clays. Some microtextures and related phase compositions. *Thermochimica Acta*, **321**, 185–190.
- El Azhary K., Lamrani A., Raefat S., Laaroussi N., Garoum M., Mansour M. & Khalfaoui M. (2017) Improving energy efficiency using unfired clay enve-

- lope of housing construction in the south Morocco. *Journal of Materials and Environmental Sciences*, **8**, 3771–3776.
- El Boudour El Idrissi H., Daoudi L., El Ouahabi M., Collin F. & Fagel N. (2018) The influence of clay composition and lithology on the industrial potential of earthenware. *Construction and Building Materials*, **172**, 650–659.
- El Fgaier F., Lafhaj Z., Brachelet F., Antczak E. & Chapiseau C. (2015) Thermal performance of unfired clay bricks used in construction in the north of France: case study. *Case Studies in Construction Materials*, **3**, 102–111.
- El Fgaier F., Lafhaj Z., Chapiseau C. & Antczak E. (2016) Effect of sorption capacity on thermo-mechanical properties of unfired clay bricks. *Journal of Building Engineering*, **6**, 86–92.
- El Hammouti A., Charai M., Mezrhah A., Nasri H. & Karkri M. (2022) Effect of the nature of clayey soils (eastern Morocco) on the thermophysical properties of bricks. *Materials Today: Proceedings*, **60**, 321–327.
- El Hammouti A., Charai M., Channouf S., Horma O., Nasri H., Mezrhah A. et al. (2023) Laboratory-testing and industrial scale performance of different clays from eastern Morocco for brick manufacturing. *Construction and Building Materials*, **370**, 130624.
- El Ouahabi M., Daoudi L. & Fagel N. (2014) Mineralogical and geotechnical characterization of clays from northern Morocco for their potential use in the ceramic industry. *Clay Minerals*, **49**, 35–51.
- El Ouahabi M., Daoudi L., Hatert F. & Fagel N. (2015) Modified mineral phases during clay ceramic firing. *Clays and Clay Minerals*, **63**, 404–413.
- El Qandil M. (2007) *Recherche et valorisation des matériaux de constructions et des argiles industrielles dans les provinces nord centrales du Maroc; possibilités d'exploitation et problèmes environnementaux*. PhD thesis, Université Mohammed V, Agdal, Morocco.
- El-Yahyaoui A., Manssouri I., Lehleh Y., Sahbi H. & Limami H. (2023) Effect of Diss fibers on the mechanical and thermophysical characteristics of unfired clay bricks for use as construction material. *Innovative Infrastructure Solutions*, **8**, 196.
- El Yakoubi N., Aberkan M. & Ouadia M. (2006) Use potentialities of Moroccan clays from the Jbel Kharrou area in the ceramic industry. *Comptes Rendus – Geoscience*, **338**, 693–702.
- Fetouani S., Sbaa M. & Vanclooster M. (2008) Assessing ground water quality in the irrigated plain of Triffa (north-east Morocco). *Agricultural Water Management*, **95**, 133–142.
- Gambilongo L., Barontini A., Silva R.A. & Lourenço P.B. (2023) Evaluation of non-destructive techniques for mechanical characterisation of earth-based mortars in masonry joints. *Construction and Building Materials*, **392**, 131960.
- Gentilini C., Franzoni E., Graziani G. & Bandini S. (2014) Mechanical properties of fired-clay brick masonry models in moist and dry conditions. *Key Engineering Materials*, **624**, 307–312.
- Gharb B.D.U. & Ouazzani A.E. (2014) Evaluation de la qualité industrielle des argiles fibreuses de Bled Rmel. *European Scientific Journal*, **10**, 217–231.
- Giada G., Caponetto R. & Nocera F. (2019) Hygrothermal properties of raw earth materials: a literature review. *Sustainability*, **11**, 5342.
- Global Alliance for Buildings and Construction (2020) *Global Status Report for Buildings and Construction: Towards a Zero-emission, Efficient and Resilient Buildings and Construction Sector*. Global Alliance for Buildings and Construction, Nairobi, Kenya, 79 pp.
- González-López J.R., Juárez-Alvarado C.A., Ayub-Francis B. & Mendoza-Rangel J.M. (2018) Compaction effect on the compressive strength and durability of stabilized earth blocks. *Construction and Building Materials*, **163**, 179–188.
- Grari A., Chourak M., Boushaba F., Cherif S. & Alonso E.G. (2019) Numerical characterization of torrential floods in the plain of Saïdia (north-east of Morocco). *Arabian Journal of Geosciences*, **12**, 1–19.
- Guillemin M. & Houzay J. (1982) *Le Néogène post-nappes et le Quaternaire du Rif nord-occidental. Stratigraphie et tectonique des bassins de Melilla, du Kert, de Boudinar et du piedmont des Kbdana*. Etudes géologiques sur la chaîne du Rif: III. Pays édition: Inconnu, Paris, France, 238 pp.
- Hajjaji W., Hachani M., Moussi B., Jeridi K., Medhioub M., López-Galindo A. et al. (2010) Mineralogy and plasticity in clay sediments from north-east Tunisia. *Journal of African Earth Sciences*, **57**, 41–46.
- Hofheinz A., Walker R., Purcell C.E. & Kinnane O. (2025) The hygrothermal properties of historic bricks: case study of traditional brick construction material in Ireland. *Building and Environment*, **270**, 112491.
- Holtz R.D., Kovacs W.D. & Sheahan T.C. (1981) *An Introduction to Geotechnical Engineering*. Prentice-Hall, Englewood Cliffs, NJ, USA, 733 pp.
- Houzay J.P. (1975) *Géologie du bassin de Boudinar (Rif oriental, Maroc)*. PhD thesis, Université Paris VI, Paris, France.
- ISO (2008) *ISO 22007-2, Determination of thermal conductivity and thermal diffusivity – Part 2: Transient plane heat source (hot disc) method*. International Organization for Standardization, Geneva, Switzerland, 20 pp.
- Jain A., Kathuria A., Kumar A., Verma Y. & Murari K. (2013) Combined use of non-destructive tests for assessment of strength of concrete in structure. *Procedia Engineering*, **54**, 241–251.
- Jankula M., Hulan T., Štubňa I., Ondruška J., Podoba R., Šin P. et al. (2015) The influence of heat on elastic properties of illitic clay Radobica. *Journal of the Ceramic Society of Japan*, **123**, 874–879.
- Jarraya I., Fourmentin S. & Benzina M. (2010) Adsorption de cov par un matériau argileux tunisien organo-modifié. *Journal de la Société Chimique de Tunisie*, **12**, 139–149.
- Jeong H. & Hsu D.K. (1995) Experimental analysis ultrasonic attenuation in carbon composites. *Ultrasonics*, **33**, 195–203.
- Jordán M.M., Meseguer S., Pardo F. & Montero M.A. (2015) Properties and possible ceramic uses of clays from lignite mine spoils of NW Spain. *Applied Clay Science*, **118**, 158–161.
- Kadir A.A., Mohajerani A., Roddick F. & Buckeridge J. (2009) Density, strength, thermal conductivity and leachate characteristics of light-weight fired clay bricks incorporating cigarette butts. *World Academy of Science, Engineering and Technology*, **53**, 1035–1040.
- Kagonbé B.P., Tsozué D., Nzeukou A.N. & Ngos S. (2021) Mineralogical, physico-chemical and ceramic properties of clay materials from Sekandé and Gashiga (North, Cameroon) and their suitability in earthenware production. *Heliyon*, **7**, e07608.
- Karaman K. & Kesimal A. (2015) A comparative study of Schmidt hammer test methods for estimating the uniaxial compressive strength of rocks. *Bulletin of Engineering Geology and the Environment*, **74**, 507–520.
- Kazmi S.M.S., Abbas S., Nehdi M.L., Saleem M.A. & Munir M.J. (2017) Feasibility of using waste glass sludge in production of ecofriendly clay bricks. *Journal of Materials in Civil Engineering*, **29**, 04017056.
- Kharim Y.E. (1991) Sédimentologie et palynologie du Néogène du bassin de Boudinar. Implications paléogéographiques et paléoclimatiques (Rif Nord-Oriental, Maroc). *Documents des Laboratoires de Géologie*, **117**, 3–153.
- Koroth S.R., Fazio P. & Feldman D. (1998) Evaluation of clay brick durability using ultrasonic pulse velocity. *Journal of Architectural Engineering*, **4**, 142–147.
- Kovler K., Wang F. & Muravin B. (2018) Testing of concrete by rebound method: Leeb versus Schmidt hammers. *Materials and Structures*, **1**, 1–10.
- Krautkrämer J. & Krautkrämer H. (1990) The pulse-echo method; design and performance of a pulse-echo flaw detector. Pp. 167–221 in: *Ultrasonic Testing of Materials* (J. Krautkrämer & H. Krautkrämer, editors). Springer, Berlin, Germany.
- Kreimeyer R. (1987) Some notes on the firing colour of clay bricks. *Applied Clay Science*, **2**, 175–183.
- Kung J. (1985) Firing optimization of clay bricks. *Ceramic Engineering and Science Proceedings*, **6**, 1582–1586.
- Lachheb M., Youssef N. & Younsi Z. (2023) A comprehensive review of the improvement of the thermal and mechanical properties of unfired clay bricks by incorporating waste materials. *Buildings*, **13**, 2314.
- Laibi A.B., Gomina M., Sorgho B., Sagbo E., Blanchart P., Boutouil M. & Sohounhloué D.K.C. (2017) Caractérisation physico-chimique et géotechnique de deux sites argileux du Bénin en vue de leur valorisation dans l'éco-construction. *International Journal of Biological and Chemical Sciences*, **11**, 499–510.
- Laouina A. (1990) *Le Maroc nord oriental: Reliefs modelés et dynamiques du calcaire*, 1st edition. Publications du Rectorat de l'Université Mohammed Premier, Oujda, Morocco, 245 pp.
- Leighton T.G. (2007) What is ultrasound? *Progress in Biophysics and Molecular Biology*, **93**, 3–83.
- Leiva C., Arenas C., Alonso-Fariñas B., Vilches L.F., Pecoño B., Rodríguez-Galán M. & Baena F. (2016) Characteristics of fired bricks with co-combustion fly ashes. *Journal of Building Engineering*, **5**, 114–118.

- Maithel S. & Heierli U. (2008) *Brick by Brick: The Herculean Task of Cleaning Up the Asian Brick Industry*. Swiss Agency for Development and Cooperation (SDC), Bern, Switzerland, 132 pp.
- Makrygiannis I. & Karalis K. (2023) Optimizing building thermal insulation: the impact of brick geometry and thermal coefficient on energy efficiency and comfort. *Ceramics*, **6**, 1449–1466.
- Malkanthi S.N., Balthazaar N. & Perera A.A.D.A.J. (2020) Lime stabilization for compressed stabilized earth blocks with reduced clay and silt. *Case Studies in Construction Materials*, **12**, e00326.
- Maniatis Y., Simopoulos A. & Kostikas A. (1981) Moessbauer study of the effect of calcium content on iron oxide transformations in fired clays. *Journal of the American Ceramic Society*, **64**, 263–269.
- Mashiri M.S., Vinod J.S., Sheikh M.N. & Tsang H.H. (2015) Shear strength and dilatancy behaviour of sand–tyre chip mixtures. *Soils and Foundations*, **55**, 517–528.
- McManus J. (1988) Grain size determination and interpretation. Pp. 63–85 in: *Techniques in Sedimentology* (M. Tucker, editor). Blackwell Scientific Publications, Oxford, UK.
- Michot A., Smith D.S., Degot S. & Gault C. (2008) Thermal conductivity and specific heat of kaolinite: evolution with thermal treatment. *Journal of the European Ceramic Society*, **28**, 2639–2644.
- Middtømme K. (1998) Thermal conductivity of selected claystones and mudstones from England. *Clay Minerals*, **33**, 131–145.
- Molera J., Pradell T. & Vendrell-Saz M. (1998) The colours of Ca-rich ceramic pastes: origin and characterization. *Applied Clay Science*, **13**, 187–202.
- Moore D.M. & Reynolds R.C. (1997) *X-Ray Diffraction and the Identification and Analysis of Clay Minerals*, 2nd edition. Oxford University Press, Oxford, UK, 378 pp.
- Mordor Intelligence Research and Advisory (2023) *Marché de briques – Taille et tendances de l'industrie*. Mordor Intelligence Research and Advisory, Hyderabad, India.
- Moreno-Maroto J.M. & Alonso-Azcárate J. (2018) What is clay? A new definition of 'clay' based on plasticity and its impact on the most widespread soil classification systems. *Applied Clay Science*, **161**, 57–63.
- Moussi B., Hajjaji W., Hachani M., Hatira N., Labrincha J.A., Yans J. & Jamoussi F. (2020) Numidian clay deposits as raw material for ceramics tile manufacturing. *Journal of African Earth Sciences*, **164**, 103775.
- Münch P., Roger S., Cornée J.J., Saint Martin J.P., Féraud G. & Moussa A.B. (2001) Restriction des communications entre l'Atlantique et la Méditerranée au Messinien: Apport de la téphrochronologie dans la plate-forme carbonatée et le bassin de Mellilla-Nador (Rif nord-oriental, Maroc). *Comptes Rendus de l'Académie des Sciences – Série IIa: Sciences de la Terre et des Planètes*, **332**, 569–576.
- Muñoz P., Letelier V., Muñoz L., Bustamante M.A. & Gencel O. (2021) The combined effect of bottom ashes and cellulose fibers on fired clay bricks. *Construction and Building Materials*, **301**, 124307.
- Murmu A.L. & Patel A. (2018) Towards sustainable bricks production: an overview. *Construction and Building Materials*, **165**, 112–125.
- Murray H.H. (2006) Introduction. Pp. 1–6 in: *Applied Clay Mineralogy* (G.W. Brindley, editor). Developments in Clay Science 2. Elsevier, Amsterdam, The Netherlands.
- Nagaraj H.B., Sravan M.V., Arun T.G. & Jagadish K.S. (2014) Role of lime with cement in long-term strength of compressed stabilized earth blocks. *International Journal of Sustainable Built Environment*, **3**, 54–61.
- Naik T.R., Malhotra V.M. & Popovics J.S. (2003) The ultrasonic pulse velocity method. Ch. 8 in: *Handbook on Nondestructive Testing of Concrete*, 2nd edition. CRC Press, Boca Raton, FL, USA.
- Nasri H., Elhammouti K., Azdimousa A., Achalhi M. & Bengamra S. (2016) Calcimetric and sedimentometric characterization of clay deposits in the Neogene Boudinar basin (north eastern Rif, Morocco): implication on the eustatic and hydrodynamic evolution of the basin and economic interest. *Journal of Materials and Environmental Science*, **7**, 859–870.
- Nasri H., Azdimousa A., El Hammouti K., El Haddar A. & El Ouahabi M. (2019) Characterization of Neogene marls from the Kert Basin (northeast Morocco): suitability for the ceramics industry. *Clay Minerals*, **54**, 379–392.
- Nigay P.M., Cutard T. & Nzihou A. (2017) The impact of heat treatment on the microstructure of a clay ceramic and its thermal and mechanical properties. *Ceramics International*, **43**, 1747–1754.
- Oti J.E. & Kinuthia J.M. (2012) Stabilised unfired clay bricks for environmental and sustainable use. *Applied Clay Science*, **58**, 52–59.
- Oti J.E., Kinuthia J.M. & Bai J. (2009) Engineering properties of unfired clay masonry bricks. *Engineering Geology*, **107**, 130–139.
- Pardo F., Jordan M.M. & Montero M.A. (2018) Ceramic behaviour of clays in central Chile. *Applied Clay Science*, **157**, 158–164.
- Pompei F.J. (2002) *Sound from Ultrasound: The Parametric Array as an Audible Sound Source*. PhD thesis. Massachusetts Institute of Technology, Cambridge, MA, USA.
- Pracidelli S. & Melchiades F.G. (1997) Importância da composição granulométrica de massas para a cerâmica vermelha. *Cerâmica Industrial*, **2**, 31–35.
- Qtaitat M.A. & Al-Trawneh I.N. (2005) Characterization of kaolinite of the Baten El-Ghoul region/south Jordan by infrared spectroscopy. *Spectrochimica Acta – Part A: Molecular and Biomolecular Spectroscopy*, **61**, 1519–1523.
- Quiroga M.I.F., Giraldo-Gómez G.I. & Sanabria-González N.R. (2018) Characterization of Colombian clay and its potential use as adsorbent. *The Scientific World Journal*, **2018**, 1–11.
- Rachidi R., Elkihel B., Delaunois F. & Deschuyteneer D. (2019) Effectiveness of phased array focused ultrasound and active infrared thermography methods as a non-destructive testing of Ni-WC coating adhesion. *Nondestructive Testing and Evaluation*, **34**, 205–220.
- Rahou J., Rezqi H., El Ouahabi M. & Fagel N. (2022) Characterization of Moroccan steel slag waste: the potential green resource for ceramic production. *Construction and Building Materials*, **314**, 125663.
- Rathossi C. & Pontikes Y. (2010) Effect of firing temperature and atmosphere on ceramics made of NW Peloponnese clay sediments. Part I: reaction paths, crystalline phases, microstructure and colour. *Journal of the European Ceramic Society*, **30**, 1841–1851.
- Rodriguez-Navarro C., Ruiz-Agudo E., Luque A., Rodriguez-Navarro A.B. & Ortega-Huertas M. (2009) Thermal decomposition of calcite: Mechanisms of formation and textural evolution of CaO nanocrystals. *American Mineralogist*, **94**, 578–593.
- Roknuzzaman M., Hossain B., Mostazid I. & Haque R. (2017) Application of rebound hammer method for estimating compressive strength of bricks. *Journal of Civil Engineering Research*, **7**, 99–104.
- Ruiz G., Zhang X., Edris W.F., Cañas I. & Garijo L. (2018) A comprehensive study of mechanical properties of compressed earth blocks with pozzolanic stabilization. *Construction and Building Materials*, **173**, 19–30.
- Russell J.D. & Fraser A.R. (1962) Infrared methods. *Physics Today*, **15**, 70–72.
- Saikia B.J. & Parthasarathy G. (2010) Fourier transform infrared spectroscopic characterization of kaolinite from Assam and Meghalaya, northeastern India. *Journal of Modern Physics*, **1**, 206–210.
- Sanchez K. & Tarranza N. (2015) Reliability of rebound hammer test in concrete compressive strength estimation. *International Journal of Advances in Agricultural & Environmental Engineering*, **1**, 198–202.
- Sathiparan N., Jayasundara W.G.B.S., Samarakoon K.S.D. & Banujan B. (2023) Prediction of characteristics of cement stabilized earth blocks using non-destructive testing: ultrasonic pulse velocity and electrical resistivity. *Materialia*, **29**, 101794.
- Shariati M., Ramli-Sulong N.H., Mohammad Mehdi Arabnejad K.H., Shafigh P. & Sinaei H. (2011) Assessing the strength of reinforced concrete structures through ultrasonic pulse velocity and Schmidt rebound hammer tests. *Scientific Research and Essays*, **6**, 213–220.
- Shepard F.P. (1954) Nomenclature based on sand–silt–clay ratios. *Journal of Sedimentary Research*, **24**, 151–158.
- Smith D.S., Alzina A., Bourret J., Nait-Ali B., Pennec F., Tessier-Doyen N. et al. (2013) Thermal conductivity of porous materials. *Journal of Materials Research*, **28**, 2260–2272.
- SNIMA (2001) *NM 10.6.700-2001*. Service de Normalisation Industrielle Marocaine, Rabat, Morocco, 21 pp.
- Souza A.E., Teixeira S.R., Santos G.T.A. & Longo E. (2013) Addition of sedimentary rock to kaolinitic clays: influence on sintering process. *Cerâmica*, **59**, 147–155.
- Souza G.P., Sousa S.J.G., Terrones L.A.H. & Holanda J.N.F. (2005) Mineralogical analysis of Brazilian ceramic sedimentary clays used in red ceramic. *Cerâmica*, **51**, 382–387.

- Touolak B.T., Nya F.T., Haulin E.N., Yanne E. & Ndjaka J.M. (2015) Compressed bricks made of Makabaye and Pitoaré clay: implementation and production. *Advances in Materials Physics and Chemistry*, **5**, 191–204.
- Trindade M.J., Dias M.I., Coroado J. & Rocha F. (2009) Mineralogical transformations of calcareous rich clays with firing: a comparative study between calcite and dolomite rich clays from Algarve, Portugal. *Applied Clay Science*, **42**, 345–355.
- Tsozué D., Nzeugang A.N., Mache J.R., Loweh S. & Fagel N. (2017) Mineralogical, physico-chemical and technological characterization of clays from Maroua (Far-North, Cameroon) for use in ceramic bricks production. *Journal of Building Engineering*, **11**, 17–24.
- Yagiz S. (2009) Predicting uniaxial compressive strength, modulus of elasticity and index properties of rocks using the Schmidt hammer. *Bulletin of Engineering Geology and the Environment*, **68**, 55–63.