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Production of eco-friendly clay bricks from municipal construction and demolition waste

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ABSTRACT

Although rapid urbanization has improved the quality of life by enabling the development of infrastructure, and buildings, it has also contributed to a significant increase in construction and demolition waste (CDW). Traditionally, most CDW has ended up in landfills and has not sufficiently valorized, exacerbating environmental degradation. Another repercussion of the building sector is the depletion of non-renewable resources, such as clay, to meet the extensive demands for building materials. Thus, this work proposes an effective solution for valorizing various types of CDW as an alternative raw material to produce valuable fired bricks. This paper evaluates the technological properties of bricks containing concrete waste (CW), ceramic waste (EW), and glass waste (GW). These wastes were analyzed using various techniques, including X-ray diffractometry, X-ray fluorescence, differential thermal analysis, and geotechnical testing. The results showed that incorporating CW into brick bodies notably reduced the density and flexural strength compared to the reference sample, leading to an increase in the rate of capillary water absorption. Therefore, the amount of waste concrete fines added to ceramic materials must be strictly controlled. However, the addition of GW and EW was more beneficial, with adequate water absorption and a significant improvement in flexural strength, reaching 14.9 MPa for marl and 20 MPa for clay. In summary, this research highlighted the possible use of CDW as a sustainable additive for clay bricks, presenting a practical solution to reduce the costs of the construction industry and tackle both environmental and resource-related issues.

Keywords: clay bricks, sustainable construction, thermal behaviour, flexural strength, construction and demolition waste, eco-friendly products.

INTRODUCTION

For centuries, clay has been widely used in a variety of sectors, particularly in building and civil engineering, due to its low cost and availability. Thus, clay-based bricks are among the most appreciated building materials. Currently, the annual global production of bricks has reached approximately 1,500 billion units (Zhang 2013). The traditional brick production generally uses clay, marl, or mixtures of clay and shale as raw materials, before the firing process (Wu et al., 2022; Wang et al., 2023; Nasri et al., 2019; Fadil-Djenabou, Ndjigui, and Mbey 2015). However, the overexploitation of these resources results in a shortage of these non-renewable raw materials, as their long geological formation time contrasts with their rapid and excessive consumption. Recently, the demand for clay-based bricks has outstripped market supply due to the rapid growth in urban populations, which has significantly increased the need for building materials and consequently raised construction and labor costs. For this reason, several countries have looking for technological solutions to mitigate economic fluctuations in the building and public works sector. For instance, some countries are discouraging the use of bricks made from clay and encouraging new environmentally-friendly building materials after noting an annual loss of several million cubic meters of clayey soil (Yang et al., 2014). Other countries have restricted the use of clay in particular fields for economic and logistical reasons (Monteiro and Vieira 2014; Chen et al., 2011).

In Morocco, the geological landscape is exceptional, characterized by a rich variety of clay deposits, particularly Miocene marls that shape a gentle hilly topography, and Cretaceous clays, which are of great interest in several areas. However, it has been proven that these clays, particularly marls, exhibit poor physical, geotechnical, and thermal properties, leading to an increased risk of dimensional defects and cracks in the final products (Nasri et al., 2019; El Yakoubi et al., 2006). This issue is compounded by the fact that the manufacturing process remains largely artisanal and semi-industrial to this day. In this context, most studies focus on improving the properties of these raw materials. Mesrar et al. 2018 investigated the characterization of Miocene marl from the Fez-Meknes region after doping it with various oxides, particularly Fe_2O_3, MnO_2, and Al_2O_3. The results indicated that the treated marl exhibited superior mechanical properties compared to the untreated marl. In recent years, studies have been conducted to evaluate the usability of industrial by-products and waste in brick manufacturing, in response to increasingly stringent environmental regulations regarding waste management and emissions. Achik et al. 2021 concluded that using pyrrhotite ash waste as a secondary raw material for fired brick bodies, at contents ranging from 10% to 50% by weight, reduces shrinkage and the amount of water required for paste formation up to 30%. Additionally, it increases both the flexural strength and bulk density of the bricks. Moumni et al. 2023 investigated the use of wheat straw (WS) and argan nut shell (ANS) at two different percentages (5 wt% and 10 wt%) to produce lightweight bricks. They observed a reduction in bulk density and thermal conductivity.

In parallel with the rapid acceleration of urbanization and the population growth discussed earlier, there is a notable increase in the amount of construction and demolition waste (CDW) generated globally each year. This rise in CDW contributes significantly to global environmental degradation. To the best of the authors' knowledge, no studies have yet explored the valorization of construction and demolition waste (CDW) in clay brick production. To date, only one study by Taha et al. 2017 has investigated a specific type of CDW – glass waste. Their findings demonstrated that incorporating up to 15% glass waste into the brick mixture improved flexural strength and reduced apparent density. This study aims to investigate the performance of fired bricks made from two primary types of Moroccan clay (C1 and C2), with the incorporation of various types of construction and demolition waste (CDW). This approach not only addresses extrusion-related issues, such as high plasticity, but also helps mitigate the overexploitation of natural clay resources. Finally, this research aims to provide a sustainable and promising solution to minimize the environmental impacts of waste disposal, a persistent challenge in the global industrial sector, particularly in low-income countries.

MATERIALS AND METHODS

Preparation of raw materials and brick samples

For brick manufacturing, waste materials and different clay samples were used as the raw materials. The waste materials were obtained from different disposal place of Fez-Meknes region, Morocco (Fig. 1).

The waste materials were initially subjected to drying, milling, and sieving. In the first stage, a crusher was employed to reduce the size of the waste materials, producing coarse fragments. Second, the fragments are put directly into the Los Angeles apparatus, operated for a few minutes with 11 steel balls. The output samples of the Los Angeles apparatus were finally sieved through 100 μm to obtain fine powder. Finally, the fine powder was stored in closed bags, until the mixing process (Fig. 2). describes the milling process of materials wastes.

The present study was conducted on two significant clay series from different regions of Morocco (Fig. 3). The clay sample (C1) was obtained from the 'Barrage Sidi Abderrahmane' site, located about 50 km east of the city of Safi, where several quarries are being exploited for various industrial applications. Another clay sample (C2) was collected from the Fez-Meknes region (Northern Morocco).

Several stages were followed in the elaboration of fired bricks. Clay bricks containing 0% waste

Figure 1. Municipal construction and demolition waste

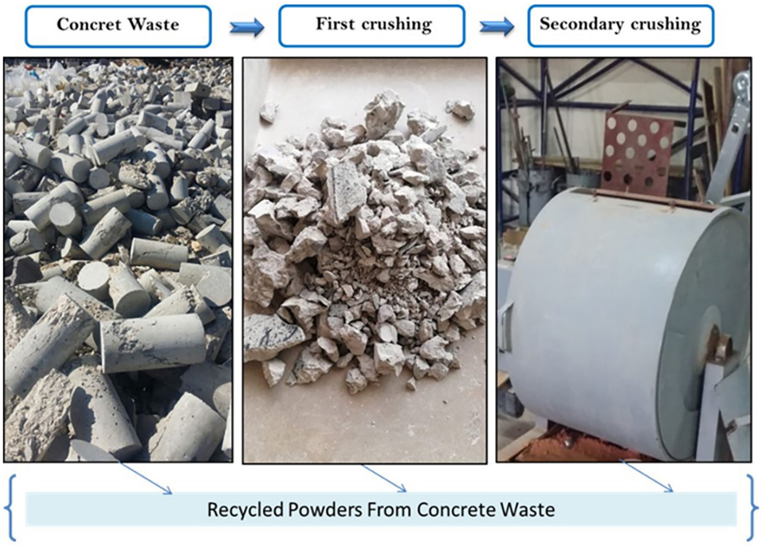
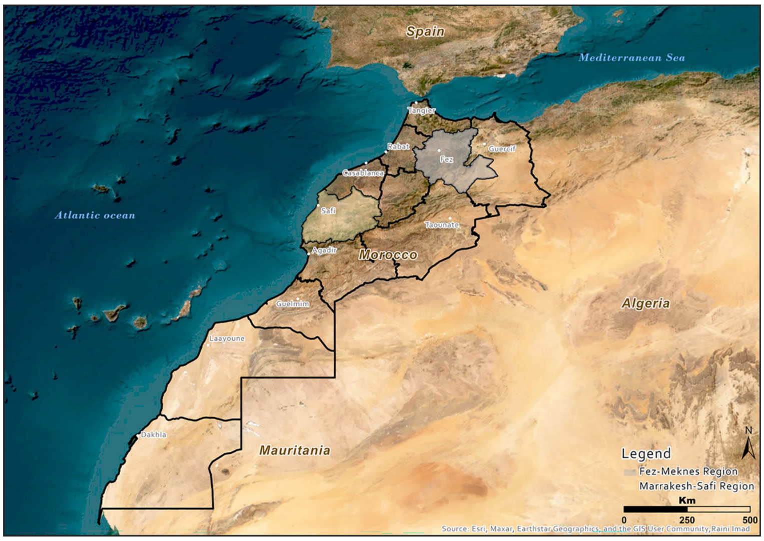


Figure 2. Overview of the recycling process of waste powders



Source: Esri, Maxar, Earthstar Geographics, and the GIS User Community,Raini Imad

Figure 3. Location map of raw material deposits

materials were prepared as a reference. These will be referred to as FB1 (0%) for clay from the Marrakech-Safi region, and FB2 (0%) for clay from the Fez-Meknes region. The clay brick containing concrete waste, ceramic waste, and glass waste, were labelled as FBC, FBE, and FBG. The mixture proportions of bricks specimens are shown in Table 1.

All raw materials were previously dried and grounded for brick manufacturing. The test samples were prepared by mixing waste materials and clay in 15% by weight. Further, water about 18–24% was added to reach a suitable plasticity for moulding. The mixing water is adjusted to ensure that the sample is in a plastic state, the paste can be shaped without cracks, or deformation in compliance with NM 13.1.007 [14]. A rectangular-shaped mold was used to make brick specimens with 80 mm × 40 mm × 15 mm dimensions. After shaping, the brick specimens were dried in ambient conditions until weight stabilization, and then oven-dried at 105 °C for 48 hours. Finally, the dried bricks were fired at 1000 °C for 2 hours in electrical furnace (Model B 150 Nabertherm) (Fig. 4).

Methods

Various tests on the raw materials and brick samples were performed to determine their performance. The mineralogical composition of samples was determined using the X-ray diffraction method (XRD), equipment with a PIXcel-3D detector from PANalytical and analyzed with X'Pert HighScore Plus software. For a more precise identification of the clay minerals present in our samples and their respective concentration, XRD on the oriented blade method was employed. Thermo-gravimetric analysis TGA in oxygen was used to investigate thermal behavior. Tests were

Table 1. Clay brick mixtures

Reference	C1(%)	C2(%)	CW(%)	EW(%)	GW(%)
FB1	100	0	0	0	0
FB1C	85	0	15	0	0
FB1E	85	0	0	15	0
FB1G	85	0	0	0	15
FB2	100	0	0	0	0
FB2C	85	0	15	0	0
FB2E	85	0	0	15	0
FB2G	85	0	0	0	15

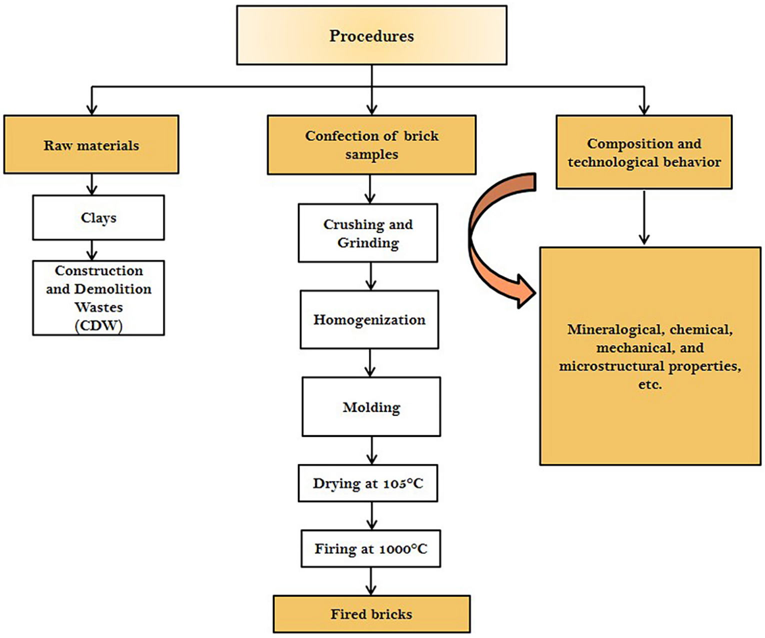


Figure 4. The experimental approach diagram for the manufacture of fired brick

conducted from ambient temperature to 1000 °C at a rate of only 10 °C/min. The chemical composition of the raw materials was assessed through X-ray fluorescence (XRF) analysis (Wavelength Dispersive Spectrometer – Axios type).

The ability of a soil volume to maintain its shape is directly influenced by its water content, which controls its consistency. In fact, as water content gradually decreases, soil generally passes through three states: liquid, plastic and solid. The plasticity index (PI) measures the soil's ability to be molded or deformed and is calculated as the difference between the liquid limit (LL) and the plastic limit (PL). The plasticity limit was determined in accordance with the NM 13.1.007 standard, according to the Casagrande method. Furthermore, various tests were conducted on bricks made with recycled powder from CDW, including flexural strength, loss on ignition, bulk density, and water absorption, following the methods outlined in ASTM C1161-13 and EN 772-21. The petrographic features (mineralogy and texture) of the fired samples were analyzed using polarized optical microscopy.

RESULTS AND DISCUSSIONS

Characterization of the raw material

Raw materials were characterized in terms of chemical, mineral, geotechnical, and thermal behavior. Table 2 shows the chemical composition in terms of oxide contents and the geotechnical properties of the studied raw materials. It showed that the major constituents of the studied clay (C1) are SiO_2, Al_2O_3 and Fe_2O_3, with respective contents 48.43%, 21.74% and 6.42%. The high Fe_2O_3 content (>3%) contributes to a deep red color in its raw state and suggests that reddish brick bodies could be achieved after firing at high temperatures. Moreover, since the concentration of SiO_2, Al_2O_3 are also significant in clay sample (C2), the CaO content is high (16.32%). This clay can be classified as a calcareous one since the amount of CaO is higher than 6% (Maniatis and Tite 1981).

In terms of the chemical composition of all studied wastes, the major components are SiO_2 and CaO. The high CaO content in the concrete waste can be attributed to the presence of natural limestone aggregates used in the formulation of the original concrete.

The results indicate that samples C1 and C2 have plasticity indices of 29%, and 35%, respectively. This suggests that both samples exhibit significant plasticity characteristics, typically associated with higher clay content in the soil. The waste materials are weakly hygroscopic and their low LOI indicate that they contain a minimal amount of volatile components.

The main phases of unfired clay powders were quartz, and phyllosilicates minerals (illite/muscovite, these two minerals cannot be distinguished from each other, and possibly the presence of kaolinite) (Fig. 5). This initial identification does not allow reliable detection of clay minerals, which has a significant influence on the final product's characteristics as well as its manufacturing process. For this reason, XRD was performed on the <2 µm fractions using the oriented mount method. The XRD spectrums obtained after air-dried, ethylene glycol saturated, and heat treated at 500 °C are shown in

Table 2. Chemical composition of the used raw materials

Properties	C1	C2	GW	EW	CW
SiO_2	48.43	38.08	69.7	64.99	11.2
Al_2O_3	21.74	13.67	1.72	19.67	3.10
MgO	2.72	3.65	3.59	1.41	10.86
CaO	3.88	16.32	6.81	2.77	34.24
Fe_2O_3	6.42	4.13	0.22	6.63	1.26
TiO_2	0.90	0.60	0.06	0.74	0.11
Na_2O	0.61	0.59	16.14	-	0.19
P_2O_5	0.15	0.21	0.23	-	0.05
K_2O	4.39	1.67	0.25	3.28	0.28
SO_3	0.20	0.14	0.24	-	0,95
LOI	10.02	20.70	0.86	1.04	37.57
Plasticity index (%)	29	35	-	-	-

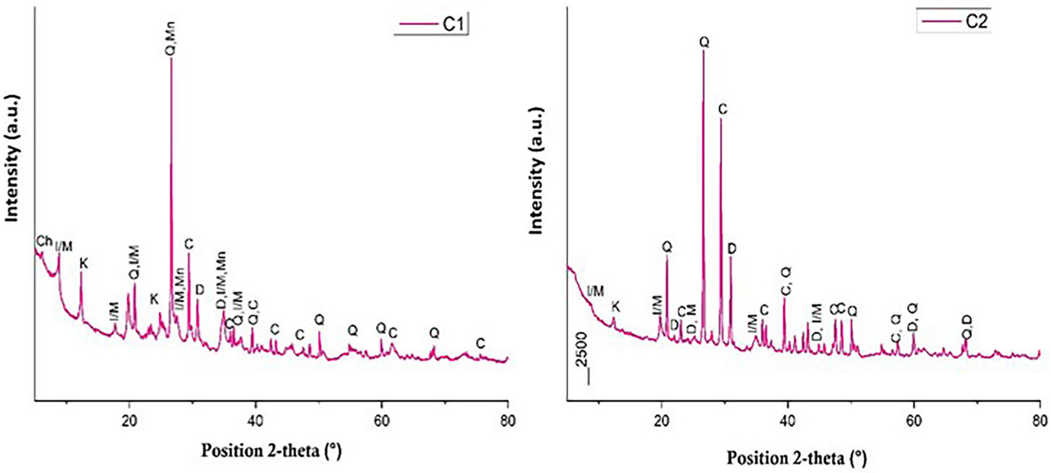


Figure 5. X-ray diffraction patterns of the raw clay samples. Ch – chlorite, I/M – illite/muscovite, K – kaolinite, D – dolomie, Q – quartz, C – calcite, Mn – montmorillonite.

Figure 6. The peaks corresponding to basal spacing d_{002}= 10 Å and d_{002}= 9.65 Å persist even after saturation with ethylene glycol and after calcination, which is related to the presence of illite (Maniatis and Tite 1981, Standarization, 2020). However, the peaks corresponding to basal spacing d_{001}=7.2 Å and $_{d001}$=7 Å disappear after heat treatment, confirms the presence of kaolinite (Duc 2020). The high amounts of K_2O (4.39%) content in C1 reflects the abundance of illite as shown in XDR results.

As seen from Figure 7, waste materials mainly consist of the quartz phase. Concrete waste has crystal phases of calcite and dolomite in addition there are some trace of portlandite minerals, which is released during cement hydration.

Figure 8 shows DSC and TGA curves for clay and CDW materials. The thermal behavior of C1 demonstrated that up to 250 °C, the trend of the TG curve shows that the compound has initially lost approximately 2.24% of its mass, the other part, however, resides at the increase in temperature, resulting in a relatively constant line (absence of reaction). The endothermic peaks observed at 145 °C and 200 °C, were caused by the removal of adsorbed water on the surface of the clay particles. Furthermore, peaks appeared between 450 °C and 700 °C, mainly related to the elimination of OH groups present in clay minerals (dehydroxylation). Rodriguez-Navarro et al., 2003, Mbey et al., 2021 noted that in the 400–600 °C temperature range, kaolinite and muscovite undergo significant changes in their structure. Another endothermic peak appeared at 765 °C, is essentially associated with the decomposition of carbonate phases. However, the exothermic peak observed at around 900 °C which does not correspond to a loss of mass, is linked to the formation of new crystalline phases such as anorthite, gehlenite, etc (Traoré, Kabré, and Blanchart

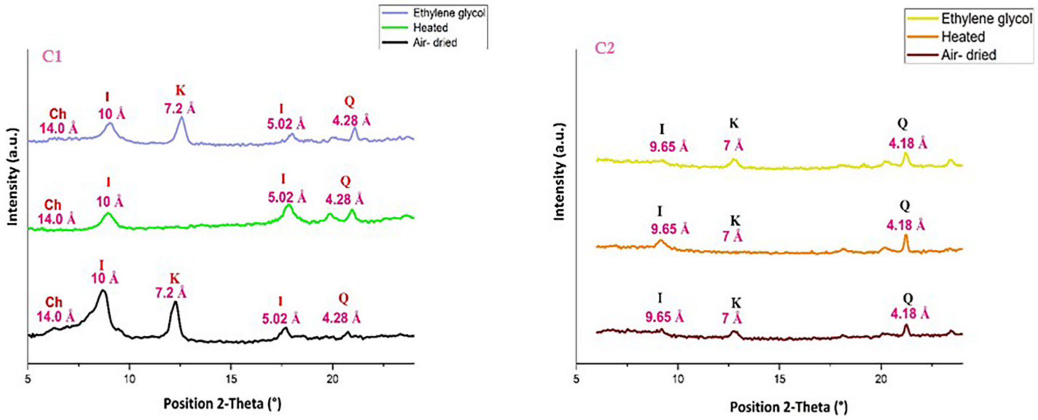


Figure 6. X-ray diffraction of the clayey fraction of C1 and samples under various conditions: Air-dried, ethylene glycol-saturated, and 500 C calcined. Q – quartz, Ch – chlorite, I – illite, K – kaolinite

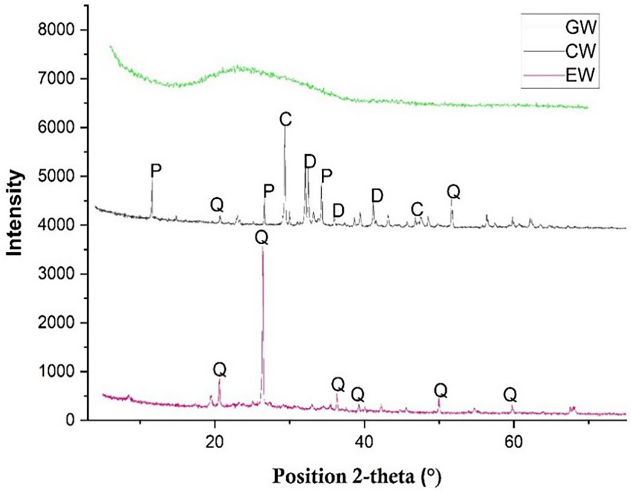


Figure 7. X-ray diffraction patterns of the wastes materials (GW, CW, EW). Q – quartz, K – kaolinite, I – illite.

2003). In Figure 8b, an endothermic peak appears at 55 °C, even before the sample reaches 100°C, accompanied by a mass loss of 3.48%, corresponds to the evaporation of the water. A higher mass loss of around 15.7% was observed at high temperatures (exceeding 450 °C), attributed to the dehydroxylation of clay minerals, calcite decomposition and CO_2 removal. In Figure 8(c,d), the TGA curve of the glass and ceramic waste showed no weight loss , as these are rigid materials. In Figure 8(c), the TGA curve of concrete waste showed significant weight loss due to the decomposition of ettringite, portlandite, and calcium carbonate.

Properties of the bricks products

Loss on ignition of brick specimens

Figure 9 shows the results of the loss on ignition (LOI) of the studied fired bricks. It can be seen that the LOI evaluated for C2-based fired bricks varies from 14% to 22.3%. This variation is less significant for C1-clay bricks. The increase in weight loss is generally linked to the elimination of organic matter by combustion and water by deshydration, as well as to the decomposition of certain clay minerals during firing (Bauluz et al. 2004, Bonet-Martínez et al. 2018).

In our case, it was found that the incorporation of concrete waste has a remarkable effect on LOI of the final products. The loss by calcination of FB1C and FB2C is mainly due to the dehydroxylation of portlandite ($Ca(OH)_2$), and the degradation of calcium carbonate ($CaCO_3$). However, addition of ceramic and glass waste decreases almost twice the LOI values when compared to the reference sample. Because, the LOI value of GW and EW (about 0.86%, 1%) is less than that of the clay material (about 22%, 10%). In general, the LOI values obtained are tolerable, since no cracks appeared on the bricks subjected to the experiment.

Water absorption of brick specimens

The durability performance of clay bricks is significantly influenced by their water retention capacity (Aouba et al. 2016). In fact, when water penetrates the brick, its weathering resistance and durability decrease. The results in Figure 10 show that the addition of concrete waste increases the water absorption of bricks regardless of the type of clay. This indicates that the bricks specimens contain a larger volume of voids compared to other bricks. These voids have an important impact on the water transport, which reflects their high water absorption coefficient.

Density of brick specimens

Figure 11 presents the density of the bricks incorporating different CDW. The density average values of the samples varied between 1.59 and 2g/cm^3 depending on the type of waste added. The high-density reduction was observed for FB1C and FB2C specimens compared with control bricks containing no waste additions. This indicates a substantial change in the bricks' texture and microstructure, due to the increased pore volume in the brick matrix generated during the combustion of the concrete waste. However, the density of fired bricks incorporating waste glass powder was higher than the other samples. This could be attributed to the high content of fluxing agents (K_2O +

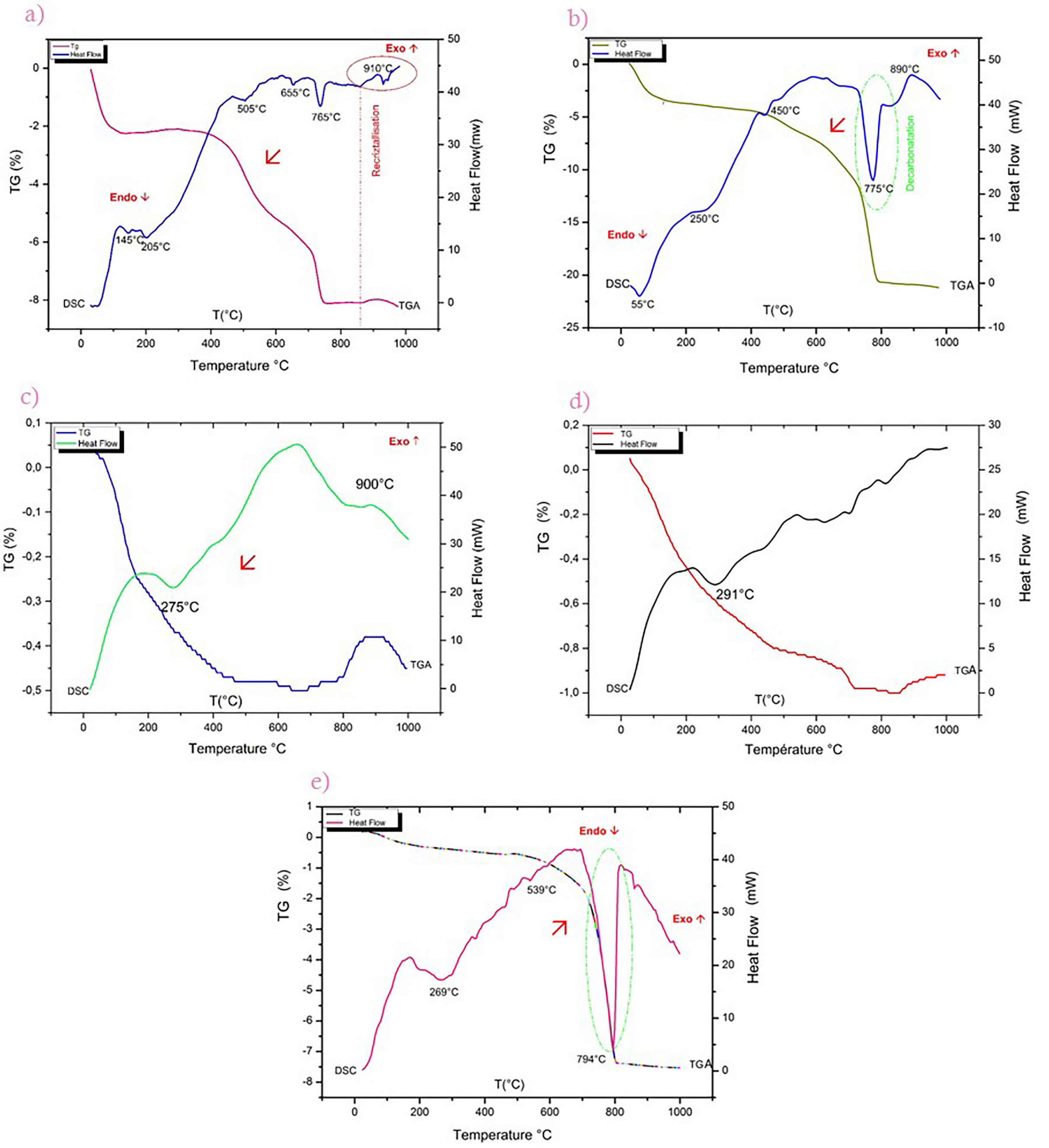


Figure 8. Thermal analyses of the studied clay samples. (a) C1; (b) C2; (c) GW; (d) EW; (e) CW

Na_2O> 16%), which facilitate fusion with the clay particles, thereby improving sintering, reducing pore count, and increasing material density. Furthermore, good quality of bricks has been shown to have average densities greater than 1.5 g/cm^3 (Quijorna et al. 2012). All the specimens of bricks designed using CDW are within the admissible.

Flexural strength of brick specimens

Flexural strength is a key factor in the manufacturing of clay bricks, particularly for those used in surface cladding or paving, where they are exposed to harsh environmental conditions and mechanical stress. Figure 12 shows the flexural strength results of burnt clay bricks incorporating various waste powders. Burnt clay bricks incorporating GW showed an increase in flexural strength of 14.6% for clay and 18% for marl, compared to the control brick specimens without CDW.

The lowest flexural strength values are attributed to the porous nature of the brick (FB2C), caused by the decomposition of carbonates and the release of CO_2 gas. This confirms that concrete fines powder undergoes significant weight loss during the

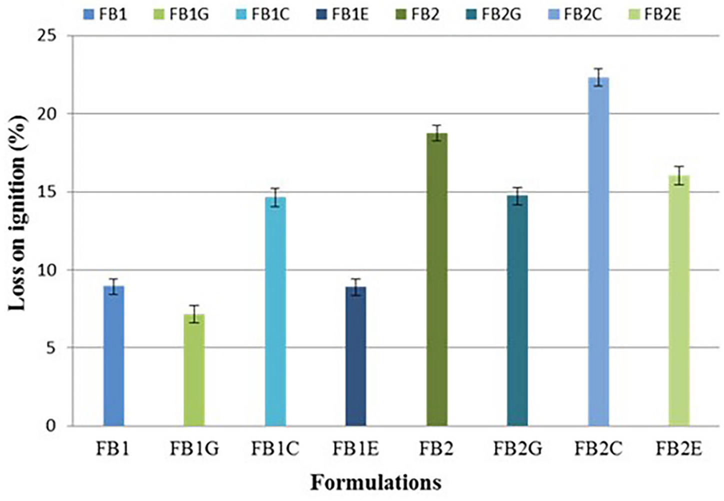


Figure 9. Loss on ignition of the elaborated materials

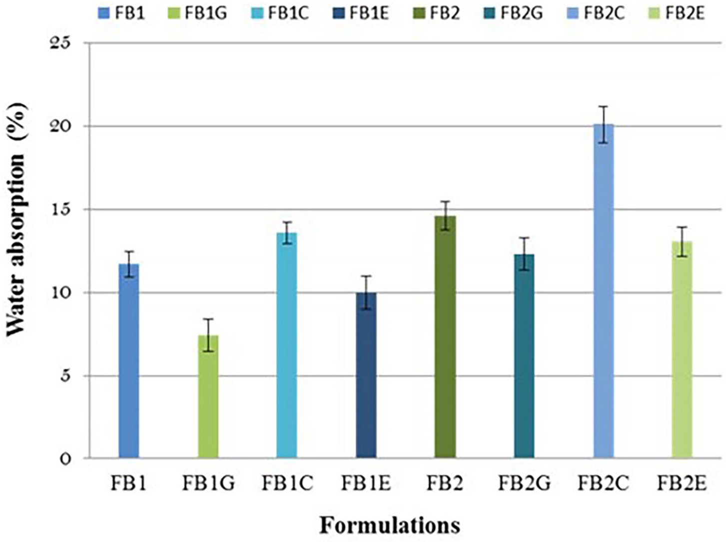


Figure 10. Water absorption of the elaborated materials

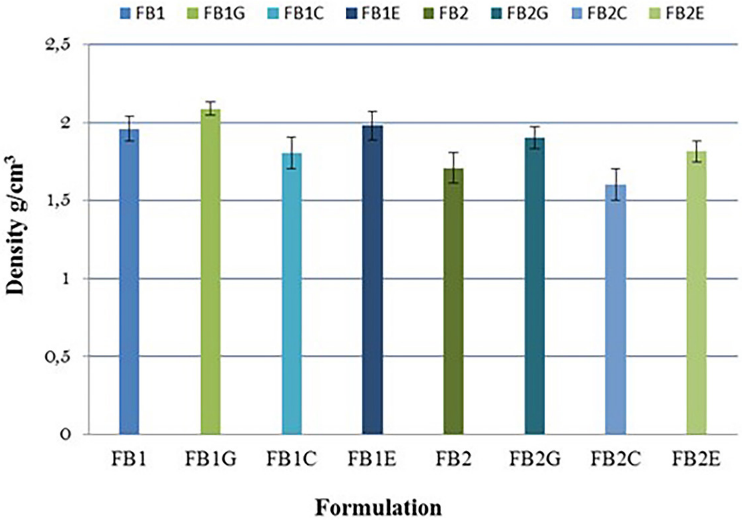


Figure 11. Density of the elaborated materials

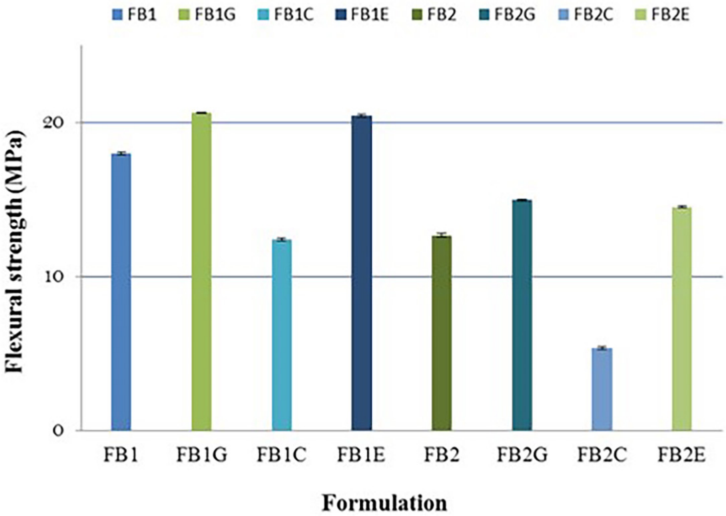


Figure 12. Flexural strength of the elaborated materials

firing process compared to other powder wastes, as observed in both types of clay used.

Brick texture by polarized optical microscopy

Figures 13 and 14 show the textural and microstructural features (e.g., pore abundance, grain size) of the brick as a function of CDW content. Under the microscope, the two groups of samples fired (FB1 and FB2) in the laboratory appear different from the textural point of view. Microscopic observations of FB2 revealed the presence of quartz grains, generally with angular to sub-angular shapes, identifiable by their gray to whitish tints and undulatory extinction under cross-polarized light (Fig. 13 a,b). These grains and small inclusions of manganese and iron oxides, identified by their black and red colors, are less abundant in the matrix of this brick sample than in FB1 (Fig. 13 c,d). The microstructural

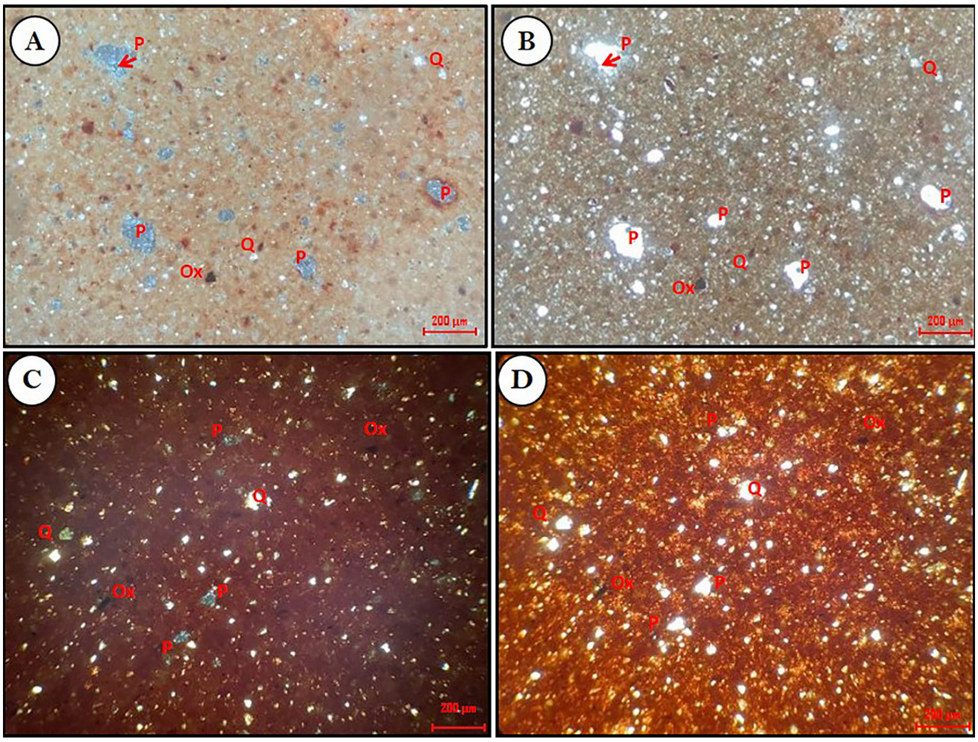


Figure 13. Photomicrographs of the fired brick's features under an optical microscope, A–B; FB2, C-D; FB1, P: pores, Q: quartz, Ox: oxides.

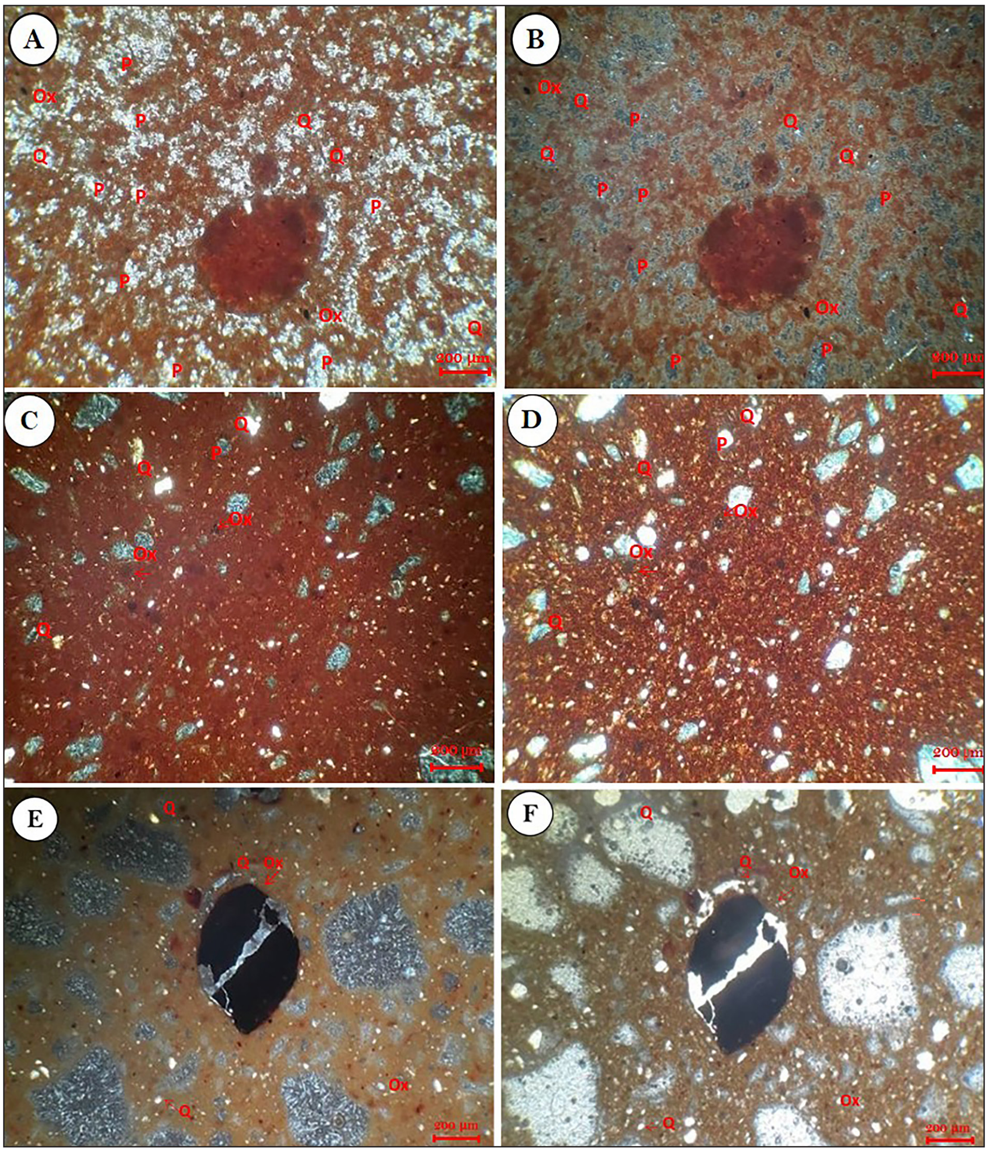


Figure 14. Photomicrographs of the fired brick's features under an optical microscope. A–B; FB2C, C–D; FB1G, E–F; FB2G P: pores, Q: quartz, Ox: oxides

analysis for the sample containing CW (Fig. 14 a, b) revealed a higher porosity due to the burning of portlandite. Calcite and dolomite-rich particles in the waste contributed to the formation of a porous structure during thermal treatment due to the release of CO_2. The pore sizes within this matrix range from approximately 20 µm to 150 µm and are irregular and lozenge-shaped. As seen in Fig. 14 (e, f), the waste glass powder acts as a filler, occupying the pores created during firing. In natural light, the matrix color of the FB1C samples is slightly darker than that of the other samples, due to the increased calcium concentration in the clay paste after the addition of fine concrete (calcium mass concentration is greater than 20%), which reduces the iron/manganese ratio and favors the formation of calcium ferrite (Milohin 2021).

CONCLUSIONS

This study constitutes a major scientific contribution to the understanding and characterization of construction and demolition waste (CDW), with a particular focus on clay materials from the provinces of Fez-Meknes and Marrakech-Safi. Furthermore, it promotes the valorization of local construction materials and contributes to the improvement of the quality of artisanal bricks produced.

- Chemical and mineralogical analyses demonstrate a high clay mineral content, along with distinct variations in CaO and Fe_2O_3 levels between the samples from Fez and Safi.
- The flexural strength of the reference marl bricks was 12.7 MPa, which decreased to 5.4 MPa after incorporating recycled powder from

concrete waste. Water absorption increased in parallel with the loss of ignion. This is due to the degradation of hydroxyl and carbonate that forms pores in the structure by releasing CO_2 gas. Microscopic analysis of FB2C confirms this finding.

- The highest density values were observed in the formulation containing 15% waste glass and 85% clay from the Marrakech-Safi region. This could be attributed to the presence of significant amounts of alkaline oxides, which act as flux agents and improve interparticle cohesion in the brick matrices.
- These results demonstrate the significant influence of both the composition of clay raw materials and the type of waste incorporated on the quality of brick products.
- Overall, these findings encourage the development of environmentally friendly brick materials using CDW. Specifically, the use of waste glass not only improves the density but also supports the development of more sustainable construction materials, contributing to waste recycling efforts and reducing environmental impact.

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