

Improving Rheological and Mechanical Properties of Non-plastic Clay soil using Bentonite Additions: Suitability for Building Application

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Abstract

The manufacturing of conventional construction materials is one of the primary sources of CO_2 emissions worldwide. The exploitation of locally available materials can be a viable alternative for sustainable development. Recently, earth has attracted the attention of the researchers since it offers good hygrothermal comfort with a low carbon footprint. However, the extraction of raw materials, as well as transportation and construction, consume a significant amount of energy. In order to minimize the economic and environmental impact of transporting clay materials, clayey materials from nearby deposits should be used in the building-related ceramic industry. Following this vision, the present study aims to develop an innovative scientific methodology for adjusting the physicochemical composition of any clay soil to make it appropriate for construction applications. The realized research was carried out on unexploited clayey soil extracted from Bensmim village (Morocco). Another clay sample from "Extrabrick" brick manufactory was also used as a reference since it produces high-quality bricks. Raw material's physicochemical and geotechnical properties were determined. Results demonstrated that the clayey part of Bensmim soil is mainly composed of illite and kaolinite. Extrabrick, on the other hand, contains kaolinite and a considerable amount of smectite. The principal oxides found in the studied clay soils are SiO_2 (57.33–59.6 wt%), Al_2O_3 (11.08–23.40 wt%), and Fe_2O_3 (3.63–4.56 wt%). CaO content in Extrabrick clay is approximately 11%. Hence it is negligible in Bensmim clay. Grain size analysis and Atterbergs limits showed that Extrabrick sample is characterized by high plasticity related to its high clay amount and the presence of smectite clay. Bensmim, on the other hand, has low plasticity, considering the significant content of sand and the lack of swelling clays in its clay fraction. Based on the conducted tests, Bensmim clay was confirmed to be an unsuitable raw material for clay bricks production. This is due to its low plasticity resulting from its significant sand content, low clay fraction, and absence of swelling clay. Therefore, improving the plasticity of Bensmim clay was taken as a critical factor to enhance the properties of this clay. Different percentages of bentonite, which is known for its high plasticity, ranging from 0-10%, were added to study the effect of this addition on the characteristics of Bensmin clay. The rheological and mechanical tests showed that increasing the percentage of bentonite has a beneficial effect on the properties of Bensmim clay bricks. In fact, the addition of 10% bentonite showed an increase in the yield stress, viscosity, and the mixture exhibited a rheological behavior similar to the reference sample. The founded results were fitted to Herschel-Bulkley classical. The findings suggest that the addition of bentonite decreases the flow index value and increases the consistency index of Bensmim clay. Furthermore, the compressive strength showed a value of 5.3 MPa, and 8.2 MPa for the brick without additive, and the brick with 10% bentonite, respectively. However, the reference sample showed a value of 8.8 MPa.

Keywords: *Clay bricks, sustainability, clay characterizations, rheological properties, compressive strength.*

1. Introduction

Buildings and their construction represent 36% of worldwide energy use and 39% of energy-related CO_2 emissions annually, according to the United Nations Environment Program [1]. Furthermore, according to the Moroccan Agency for Energy Efficiency, the construction industry is one of the most energy-intensive sectors in Morocco, consuming up to 33% of total energy, with commercial structures representing 7% and residential buildings accounting for 26%. Emissions from buildings are often measured as a combination of two factors. The first is "operational carbon emissions," which are generated during lighting, heating, and cooling on a daily basis. Globally, building operations account for around 28% of emissions each year. The second factor is "the embodied carbon of a building," which refers to the quantity of carbon emitted during the manufacturing of construction materials, transportation to construction sites, and the building process. The embodied carbon accounts for 25% of a building's total lifecycle carbon emissions [2].

The use of locally available materials can be a good option for sustainable development. Recently, earth has gained more interest as a construction material thanks to its abundance and low environmental impact [3]–[5]. In Morocco, clay is an abundant raw material with a wide range of structures and compositions [6]. Sadly, its exploitation still insufficient and poor [7]. As a result, the Moroccan government imports clay materials from other countries, namely Italy and Spain [8]. For economic and logistical reasons, clayey materials from nearby deposits should be used in the building-related ceramic sector.

According to Fabri the physical and chemical characterizations and quality control of each clayey soil are critical for the technical performance of local products [9][10]. Several research studies were done on the characterization of clayey soil from different Moroccan deposits, as well as their potential in the clay brick industry [11]–[14] [3–7]. For instance, El Ouahabi et al. [15] assessed the suitability of clay material from Meknes and Tetouan cities as industrial raw materials in a variety of clay products such as bricks, refractories, and ceramic tiles. The findings revealed that the raw clays from Tetouan and Meknes are suitable for producing clay products, either with or without additives, depending on the kind of clay products. Another study by El Ouahabi et al. [16] aims to analyze the mineral composition, grain-size distribution, and geotechnical qualities (primarily plasticity) of Moroccan clays to document the clay assemblage's spatial distribution and assess their possible use in industrial applications. Based on found results, authors proposed a search focused on evaluating the utilization of these raw resources as ceramic raw materials in the local ceramic industry on a semi-industrial scale. Furthermore, Lahcen et al. [17]examined five clayey soil samples from two quarries in Morocco's Amezmiz region to see if they might be used as raw materials in different ceramic applications. The findings revealed that two of the studied clayey materials have suitable properties for the manufacturing of structural ceramics. However, more plastic clay should be added to adjust the workability of the three remaining clays.

Several studies have investigated the impact of raw clay materials' physicochemical and mineralogical properties on the final product's performance. For instance, Ten et al. [19] studied the effect of raw material mineralogy on the mechanical and thermal performance of fired products. the obtained findings revealed that large quartz grains have a negative impact on brick's mechanical properties.. Vasic et al. [18] studied two natural clays with distinct mineralogy (montmorillonite and hydromica). Authors of this study determined all significant factors that describe behavior during molding and drying, as well as the quality of burnt bricks. Finding showed that montmorillonite clay bricks require a longer firing period than hydromica clay bricks, and they exhibit higher compressive strength. In the work of Gualtieri et al. [20], thermal performances of bricks produced from various Italian clays were evaluated and related to various raw material parameters (mineralogicy, organic matter, and granulometry). According to the findings, the grain size and mineralogy of raw materials have an impact on the thermal conductivity.

Bensmim is a mountainous region in the Middle Atlas situated about 6 km from Ifrane city, Morocco. This region is known for its cold weather in the winter. The severe cold affects the population and makes living hard in such conditions. Consequently, this isolated and poor village is desperate for affordable housing with decent thermal properties. The cheap, natural, and affordable raw material in this region is clay. Unfortunately, when employed in its raw state, this clay was found to be unsuitable as a potential raw material for the clay brick industry.

From the perspective of sustainable development of the region, this study aims to improve the properties of this unexploited clay and make it suitable for clay brick production. For comparison purpose, authors used another clay sample exploited in the production of clay bricks; this clay produce bricks with high quality. Autors compared and contrasted between the physicochemical composition of these two clays and studied its effect on the quality of fired clay product. Conducted tests showed that Bensmim clay is not suitable for clay brick manufacturing due to its weak plasticity. Therefore, different percentages of bentonite, which is known for its high plasticity, ranging from 0-10% were added to the Bensmim sample, and the effect of this addition on the performance of BS was studied.

The exploitation of the local clay resource of this region in the production of building materials has many beneficial impacts; Clay-based materials will be produced locally with similar features and lower costs than the imported ones. Thus, the cost and carbon footprint of material transportation is minimized.

2. Material and methods

2.1. Studied raw materials

In this study we used an unexploited clayey soil (BS) taken from Bensmim village located in the Middle Atlas near Ifrane city. Whereas the reference clay sample came from the quarry of Extrabrick, a brick factory in Meknes city. Because of its high plasticity, this clay is usually mixed with 20% of sand before being used in the clay brick industry. This formulation (EB) was considered as a reference in the current study since it produces high-quality bricks. Raw clays were first cleaned, dried at a temperature of 105 °C, grounded using LOS ANGELES machine, and finally sieved at 500µm. In order to ameliorate the physicochemical and mechanical characteristics of Bensmim sample, different percentages of bentonite were added. The bentonite used in this study is a commercial clay supplied from the foundry laboratory of ENSAM, Meknes. This type of clay is used as a binder for foundry sand in molds production.

2.2. Raw material characterizations

Raw materials mineralogical composition was examined by X-ray diffraction using Brüker D5000 automated diffractometer, using CuK radiation (λ = 1.5406Å). The experiments were performed following the clay analysis standard protocol and as previously presented in the work of Boukili et al. [7]. The chemical composition was determined by using "Axion" X-ray fluorescence spectrometer 1kW wavelength dispersion. Thermo-gravimetric analysis TGA in oxygen was used to investigate thermal behavior. Tests were conducted from ambient temperature to 900°C at a rate of only 5°C/min. The plasticity limit was obtained in accordance with the standard (NF P 94-051), and the Casagrande apparatus was used to determine the liquidity limit (NF P 94-052-1).

2.3. Rheological measurements

Rheological characterization of the studied samples was carried out using MCR rheometer from Anton Paar, equipped with a temperature-controlled water bath and connected to a vane geometry. This geometry was chosen to avoid slipping on the measuring system walls and prevent sedimentation. All rheological tests were performed at a temperature of 20 °C±0.1.

The clay powders were dispersed under stirring in distilled water at a concentration of 63 wt.%. Next, suspensions were pre-sheared at a constant shear rate of 200 $\dot{\gamma}$ during the 60 s to eliminate any memory effect. Prior to the measurements, the samples were kept at rest for 600 seconds under the measuring geometry to allow the material to restore its initial structure. This operation is repeated before each test.

2.4. Clay bricks preparation

First, raw materials were dried at 105 °C in the lab oven until constant mass. Then, raw clay was crushed using Los Angeles apparatus (<500µm) (Fig.1). Next, brick specimens (clay samples and 35 wt% of water) were prepared and homogenized for 5 minutes at a 95 rpm steady-state pace, using CONTROLS automatic electric mixer (Fig.1). Next, brick samples were formed under 6.5MPa using a hydraulic press machine. Molds were prepared in two shapes: a rectangular mold of 16x4x4cm for mechanical testing and a square mold of 12x12x2cm for thermal testing.

Figure 1. Sieved clay samples: a) BS clay, b) Bentonite clay, c) EB.

The specimens were demolded after three days to enhance global drying. They were then dried on a lab stove at 105°C until they achieved constant mass. Next, the surface of the fired samples is smoothened with the help of abrasive paper. Finally, the dried samples were fired in Extrabrick manufactory kiln (750–850°C) for 24h.

Four sets of bricks were made with varying percentages of bentonite ranging from 3% to 10% (Table.1). We made three brick specimens for each composition to conduct a statistical calculation.

Table 1. Composition of specimens.

Reference	*BS clay (%)*	*EB clay (%)*	*Bentonite (%)*
0% bentonite	100	0	0
3% bentonite	97	0	3
6% bentonite	94	0	6
10% bentonite	90	0	10
Ref (EB)	0	100	0

2.4. Bricks characterizations

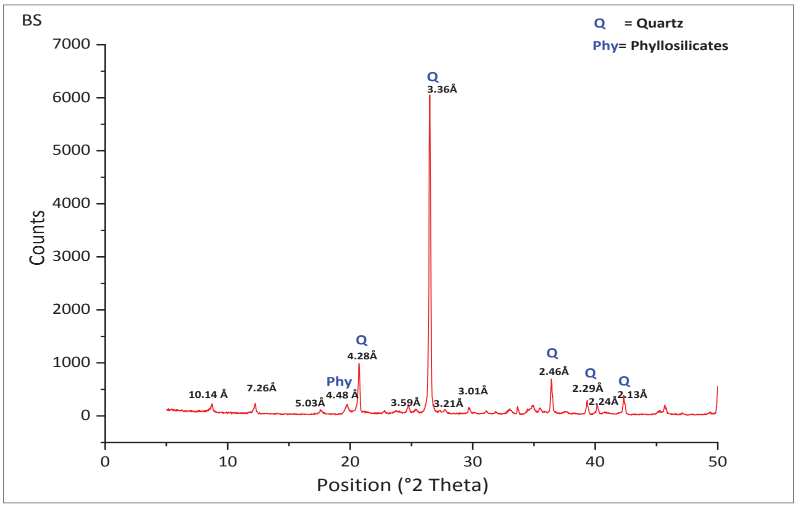
Compression strength testings were carried out according to NM EN 772-1-2015 standards (cubic samples of standard dimensions 4×4×16cm). These tests were performed by Controls compression analysis device with a capacity of 100kN and a speed of 0.1MPa/s.

3. Results and discussion

*3.1.***C***haracterization of raw materials*

3.1.1. Mineralogical composition

Clay's mineral composition has a significant influence on the final product's characteristics as well as its manufacturing process. Fig.4 represents the obtained XRD spectrum of the bulk studied clay samples. We observe that the EB sample is mainly composed of quartz, calcite, and phyllosilicates (possibly kaolinite, illite, and smectite). However, quartz, hematite Fe_2O_3, and phyllosilicates (probably illite, and kaolinite) are the phases found in BS clay. Clay minerals cannot be clearly detected in the bulk sample's spectrums. For this reason, we performed XRD analysis on oriented aggregate [23], [26].



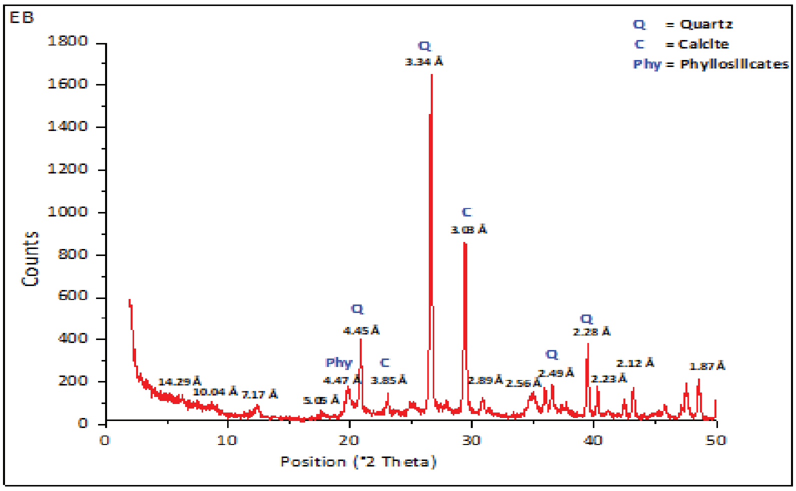


Figure 4: Difractogram of BS and EB clays.

Figs. 5 represents the XRD spectrums of the clayey proportion of the clay specimens under three conditions: air-dried, heat-treated at 550 °C, and ethylene glycol saturated. According to the obtained results, kaolinite (d≈7.2 Å) and illite (d≈10 Å) are the main minerals present in BS clay [22].

The disappearance of the peak around 7Å when the sample was calcined at 550°C confirms the existence of kaolinite (transformation of kaolinite into amorphous metakaolinite) [23]. However, the existence of illite is confirmed by the unchanged peak near 10 Å after ethylene glycol saturation [24].

The mineral composition of EB sample is represented in Fig.5 and shows that this sample consists mainly of illite, kaolinite and smectite. In fact, smectite group is distinguished by the expanding behavior in the existence of ethylene glycol [25]. We observe in Fig.5 that the peak at 14 Å, which overlaps with the chlorite peak, has been shifted to 18.23, confirming the presence of smectite [25].

The mineral composition of bentonite clay was also performed by X-ray diffraction analysis (Fig.6). The obtained diffractogram shows the typical spectrum of standard bentonite [26]. The identified phases were quartz (d=4.06Å), (d=3.03Å), montmorillonite (smectite) (d=15Å), (d=2.51Å) and calcite (d=3.78Å), (d=2.89Å) [26].

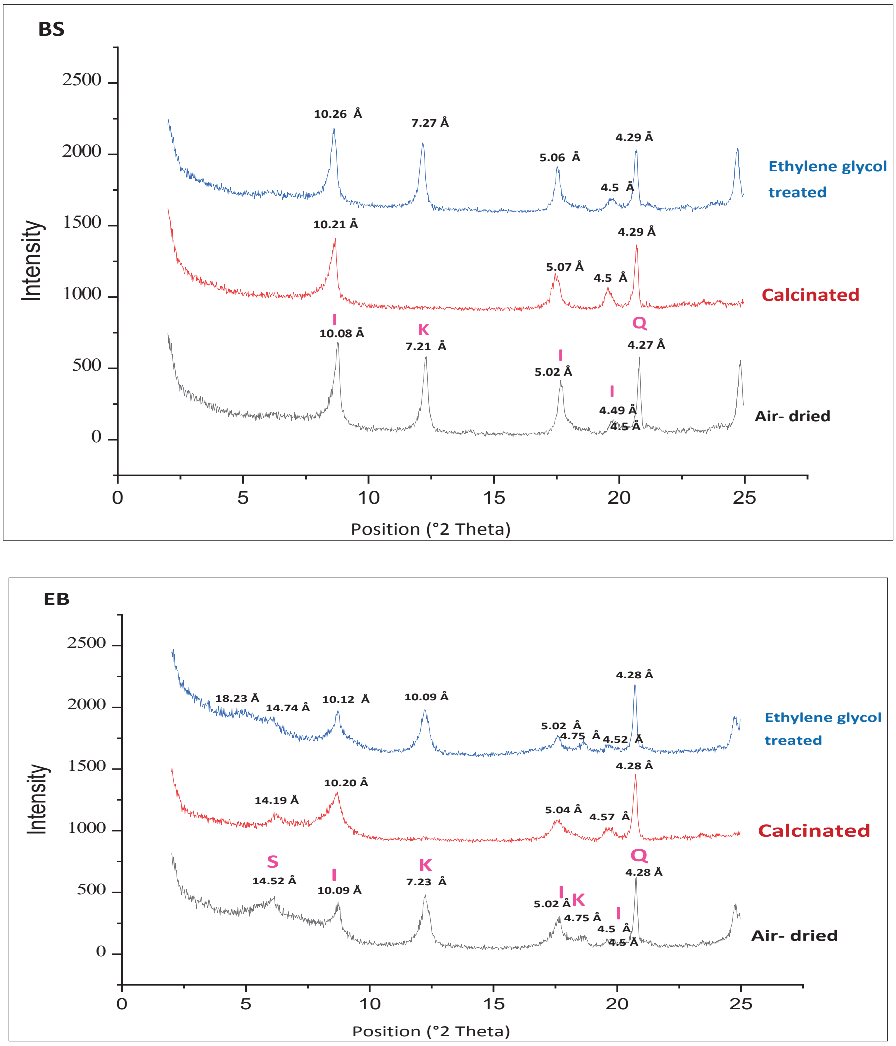


Figure 5: X-ray diffraction of the clayey fraction under various conditions: Air-dried, ethylene glycol-saturated, and 500°C calcined.

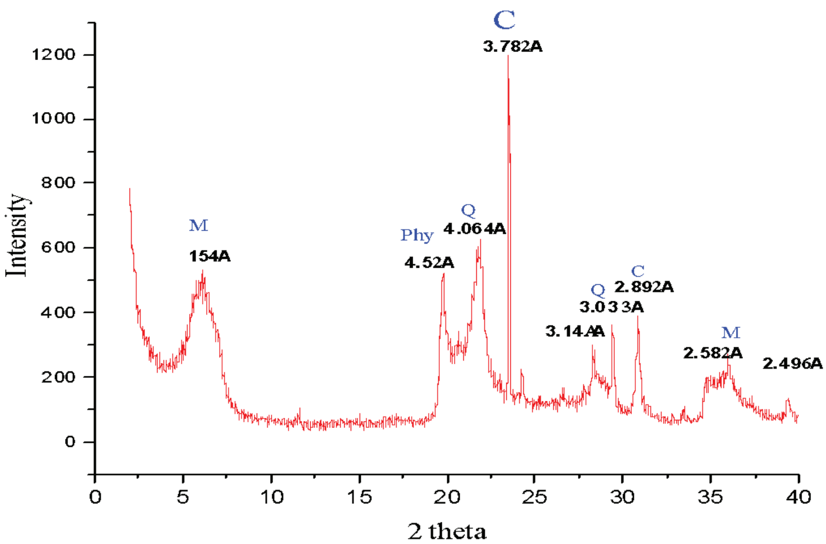


Figure 6. X-Rays diffraction spectrum of Bentonite clay.

3.1.2. Chemical composition

The chemical composition of the clays used in this study is shown in Table 2. We can notice that BS clay is composed of SiO_2 (59.60%), Al_2O_3 (23.40%), K_2O (3.63%), small amounts of Fe_2O_3 (3.63%), and CaO (2.77%). Whereas it was found that SiO_2 (57.33%), Al_2O_3 (11.08%) and CaO (10.61%) are the most abundant oxides in EB clay sample. The other oxides, such as MgO (0.97%), and P_2O_5 (0.46%) show just some traces in both samples.

Table 2. X-ray fluorescence results of the studied clays.

Oxide (%)	SiO_2	Al_2O_3	Fe_2O_3	K_2O	CaO	MgO	TiO_2	P_2O_5	SO_3	Na_2O_3	L.O.I
BS clay	59.60	23.40	3.63	2.53	2.77	0.97	0.13	0.46	-	-	5.34
EB clay	57.33	11.08	4.56	1.76	10.61	2.18	0.57	0.16	0.19	0.94	10.61
Bentonite	60	15.9	6	2.9	3.6	2.2	0.8	0.03	0.80	0.2	7.8

The abundance of SiO_2 and Al_2O_3 in both BS and EB is a beneficial finding since these oxides provide mechanical strength to the bricks, limiting shrinkage, and help maintain the brick shape during molding [27]. However, the high iron concentration (Fe_2O_3) in BS clays permits this clay sample to be classified as ferruginous clay, which explains its intense red color [7].

Furthermore, the presence of K_2O in BS clay suggests that this clay is illite-rich and confirms XRD findings. On the other hand, it is observed that CaO is abundant in EB sample (10.61%). This value permits this clay to be classified as calcareous (CaO > 6%). In contrast to the BS sample that contains only 2.77% by weight of CaO [28]. The obtained results of loss on ignition upon heat treatment at 1050°C show that EB specimens represent a high level (11.82%). However, BS clay presents only 6% of mass loss. This difference can be explained by the calcium carbonate amount, clay minerals content, and nature, as well as the presence of organic matter. This will be covered in further detail in the next section using TGA/DTA analysis

Table.2 illustrates also the chemical composition of bentonite clay. Results suggest that it contains around 60% of SiO_2, mostly generated from smectite clay and quartz minerals. The presence of MgO and CaO involves the substitution in octahedral positions of Mg^{2+} and Ca^{2+} for Al^{3+} ions and allows classifying this bentonite as Ca-Bentonite [22] [29].

3.1.3. Thermogravimetric behavior

Figure 6 represents the TGA/DTA results of the studied samples. We can observe that BS clay shows a total mass loss of 2.8%. The loss is progressive up to 600 °C due to absorbed water evaporation and organic matter combustion. In this stage, other reactions may also take place during this phase as well, and they are associated with the dehydration evaporation of chemically combined water (between clay layers) [30]. Finally, the slight mass loss observed up to 650°C may be related to calcium carbonate decomposition and the elimination of CO_2, as shown in equation 1, the low intensity of this mass loss (0.46%) is in accordance with XRF results [7], [31].

$$CaCO_3 \rightarrow CaO + CO_2 \qquad (1)$$

BS sample losses of 3.24 % of its total mass. This low value may be attributed to the lack of swelling clay minerals and the low calcium carbonate content (According to XRF and XRD analysis).

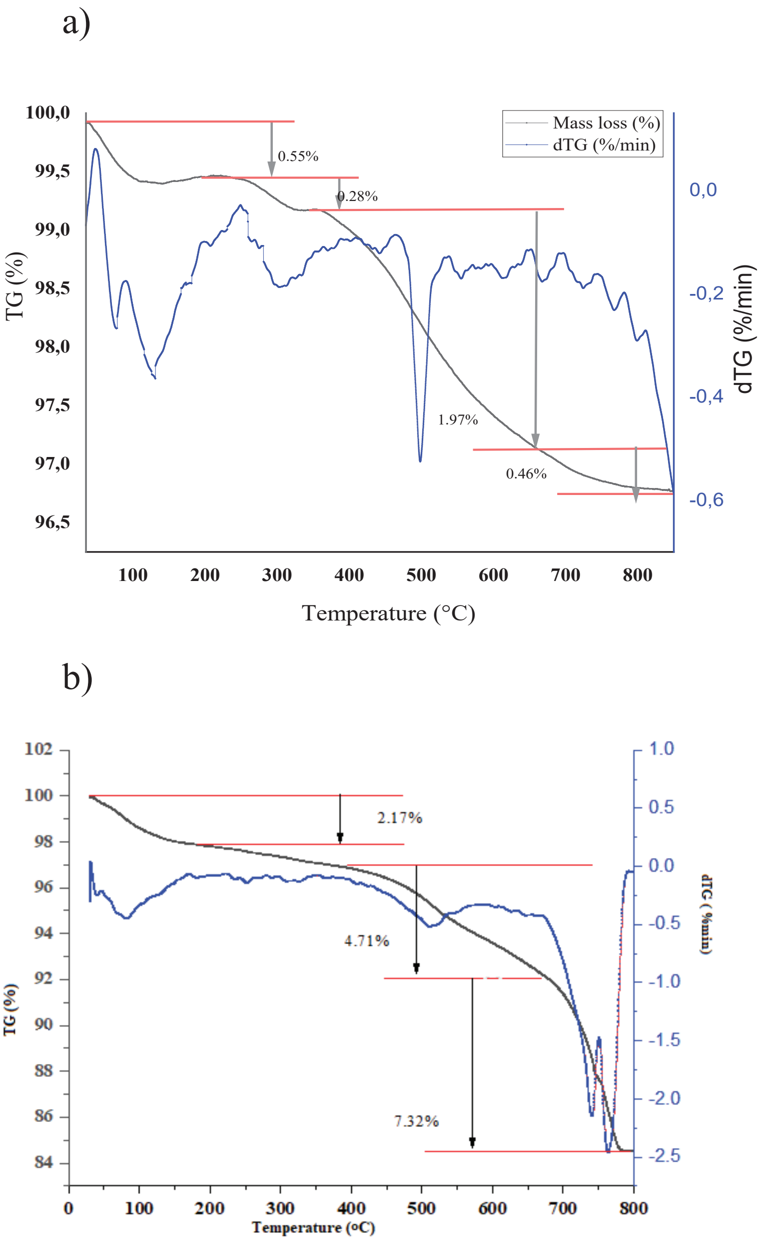


Figure 6: Thermogravimetric behavior of: a) BS clay, b) EB clay.

However, the EB sample shows a different behavior as shown in Fig.6.b. The soft peak observed at 64.87°C corresponds to the evaporation of the water [27], [32]. The second mass loss occurring between 400-650°C characterizes the dehydroxylation of clay minerals and the α-quartz→β-quartz transition [33]. Overall, smectite and vermiculite are dehydroxylated approximately at 670°C [39], while illite and kaolinite are dehydroxylated around 500°C. This dehydroxylation results in a 4.71% weight loss. Finally, an intense peak occurred near 700°C (7.32%) , which may be associated with calcite dissociation and CO_2 removal [40]–[42]. These obtained results are in line with the XRD analysis.

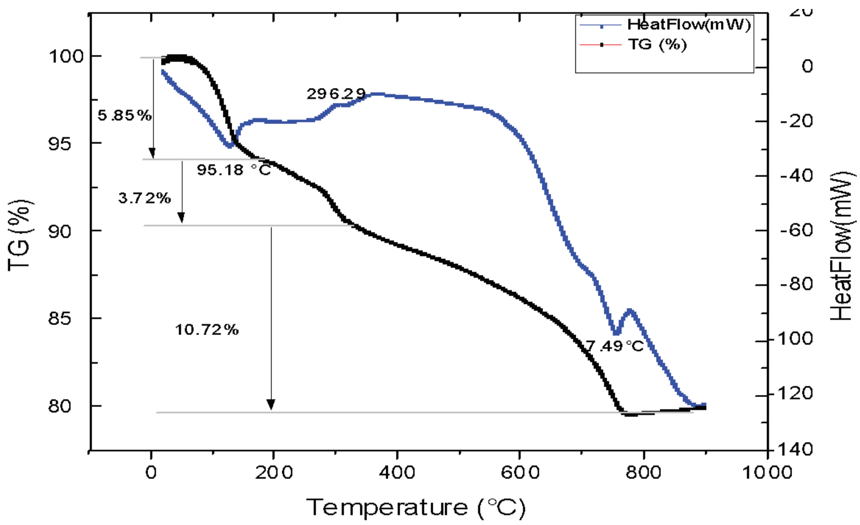


Figure 7: Thermogravimetric behaviour of bentonite.

The Thermogravimetric analysis of bentonite clay sample are represented in Fig.7. It is observed that this sample represents three significant mass losses:

1. Between 50 and 200 ºC, we observe a mass loss of 5.58 % related to dehydration of clay minerals, in which the clay loses the adsorbed water on its surface and the bonded water within its layers [18]. This large weight loss is due to the clay's swelling nature and the strong moisture affinity of bentonite clays [31], [35].
2. The mass loss of 3.42% detected between 200 and 300ºC may be attributed to the evaporation of adsorbed water retained between the basal planes of the lattice structure [31].
3. The mass loss of 10.72% observed between 300ºC and 750ºC could be related to dehydroxylation of smectite in bentonite and calcite decomposition [7], [31].

The bentonite sample lost 20.29% of its initial mass; this significant mass loss may be related to the presence of calcium carbonate and swelling clays.

3.1.4. Grain size analysis

As demonstrated in Fig.8, the grain size of the studied clay samples shows a significant difference. They have a clay content (< 2 µm) that ranges from 17 to 40%, a silt content (2-60 µm) from 25 to 60%, and sand content (>60 µm) from 0 to 62.14%. Expressly, BS clay contains the highest sand (58%), an important silt fraction (25 %), and as a result, the lowest clay fraction (17%). However, the EB sample is characterized by high clay content (39.4%), 36.8% of silt, and the lowest sand portion (23.37%). On the other hand, the texture of bentonite sample is different. It is characterized by the abundance of silt (60%) and clay (40%) and the absence of sand.

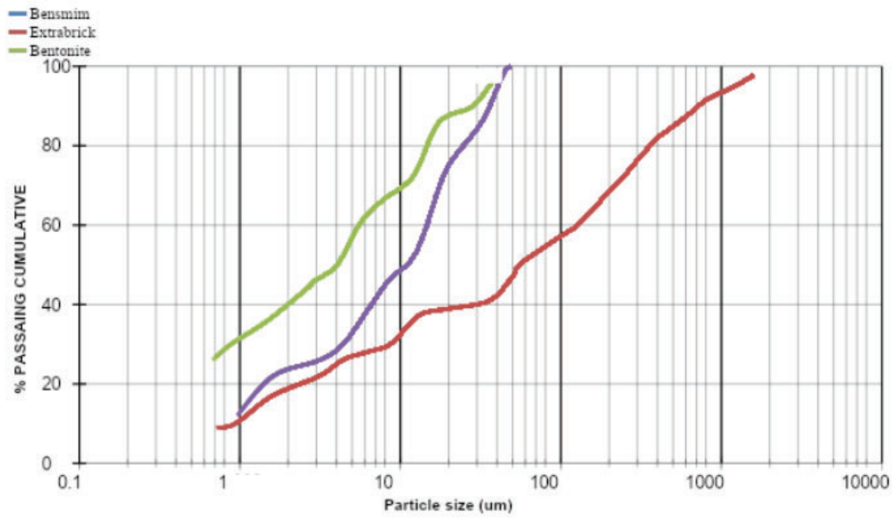


Figure 8. Grain size distributions of clay samples

Table 3 Granulometric analysis of the studied samples

	Clay fraction (%)	Silt fraction (%)	Sand fraction (%)
BS clay	17	25	58
EB clay	38	41	21
Bentonite	40	60	0

3.1.5. Atterberg's limits

From the obtained results in Table 4, we can clearly notice a huge difference between the obtained values for the studied clays. The plasticity index of the studied samples is 16%, 19%, and 131% for BS, EB, and bentonite samples, respectively. According to Barba et al. [38] and Händle [39], the plasticity index is directly associated with the sample's physical properties. Specifically, the grain size distribution and the sample's mineralogical composition (type of clay mineral, the proportion of swelling minerals, etc.) [40]. Therefore, the weak plasticity of the BS sample is related to its low clay fraction, the absence of expandable clay, and the dominance of quartz. However, EB sample is considered plastic clay because of its large clay content and the presence of smectite. Finally, the bentonite sample represents very high plasticity, because of its large montmorillonite content (smectite group) and the absence of sand.

Atterbergs method is widely used in the construction field to determine the plastic behavior of materials. However, the results obtained exhibit low precision. The perfect characterization of the behavior of a plastic mass can only be performed by determining its different rheological parameters (yield stress, viscosity, limit deformation without rupture) [41]. This will be discussed in detail in the following section.

Tableau 4. Plastic limit, Liquid limit, and plasticity index of the studied materials.

	Plastic limit (%)	Liquid limit (%)	Plasticity index (%)
BS clay	22	37	15
EB	33	52	19
Bentonite	191	60	131

3.2. Amelioration of the properties of clay bricks by bentonite

Taking into account all of the examined characteristics, BS clay was determined to be unsuitable as a raw material for brick manufacturing [15][18]. This is attributed to its weak plasticity resulting from its low clay content, lack of swelling clay, and significant sand content, The plasticity of clay pastes can be related to their behavior in different manufacturing process stages before firing (mixing, molding, drying, transport, etc.) [37]. This is possible because the properties of the clay mineral that determine plastic behavior (particle-size distribution, specific surface area, mineralogy, etc.) also determine the properties of the final product in its solid state (mechanical strength, shrinkage permeability, compactness, etc.) [22][37]. Because of the existence of these empirical relationships, plasticity has become a typical parameter in formulating and adjusting clay compositions, in which materials of varying plasticity are mixed until the optimal mixture is formed.

Following this vision, improving the plasticity of Bensmim clay was taken as a key factor to improve the properties of this clay. Different percentages of bentonite, which is known for its high plasticity, ranging from 0-10%, were added to BS sample, and the effect of this addition on the properties of BS was studied.

3.3. *Effect of Bentonite addition on rheological characteristics of Bensmim*

Rheology is a field of research that aims to characterize the flow and deformation of materials using stress and shear rate fundamental principles. The rheological behavior of clay materials is critical for quality control because it allows the user to identify the viscoelastic state characteristics of clay bricks by correlating shear stresses and shear rates. Moreover, the fresh state performance of clay bricks is not only crucial for proper brick molding and shaping but also for its hardened state properties. With this focus, rheological experiments were used to study the bentonite addition effect on the performance of BS samples at a microscopic level.

3.4. Flow curve and yield stress

As demonstrated in 3.1.1 section, studied samples contain a proportion of swelling clays, "montmorillonite". In a very dilute solution, these colloidal clay particles form a gel. The elasticity of the gel increases with time because of the building up of the structure of the sample. The initial status of the sample has consequently a crucial importance in having reproducible results [42][43][44]. For this reason, the samples were submitted to a strong pre-shear at a constant shear rate of 200 $\dot{\gamma}$ during the 60s, then left at rest for 600 seconds to enable the sample to reestablish, at least partially, its initial structure. This procedure is repeated before the start of each rheological experiment.

We applied an increasing shear rate of 0 to 200 $\dot{\gamma}$ over 600s to the studied materials, and the shear stress versus shear rate is presented in Figure 9. The obtained flow curves highlight that all the studied samples are characterized by yield stress, so for the flow to occur, stress higher than yield stress should be applied to the sample (below this value, flow is not possible) [45][46], and viscosities that vary with strain over time.

From the obtained curves, we notice three distinguished states:

1. The first zone is characterized by yield stress (elastic deformation of the sample). This behavior can be related to the swelling properties of the clay minerals, and the forces of interaction between particles (such as Van der Waals forces, which are responsible for the formation of flocs and aggregates). These forces control the cohesion of the system, leading to a strong three-dimensional structure. Hence, this structure can be broken only under shear stress above the yield stress value [47].
2. The second zone corresponds to quick fluidization, resulting from the succession of bond ruptures and deformation of particle aggregates.
3. The last zone, delimited by an inflexion point of the flow curve, corresponds to shear-thinning behavior of the inert particles.

The observed behavior places the studied clays in the category of time-dependent fluids that show thixotropic and plastic properties. In other words, when they are subjected to stress less than the yield stress, their viscosities are so high that they cannot flow, and they behave solidly. However, the sample structure is destroyed above this limit, and they gradually lose their solid character.

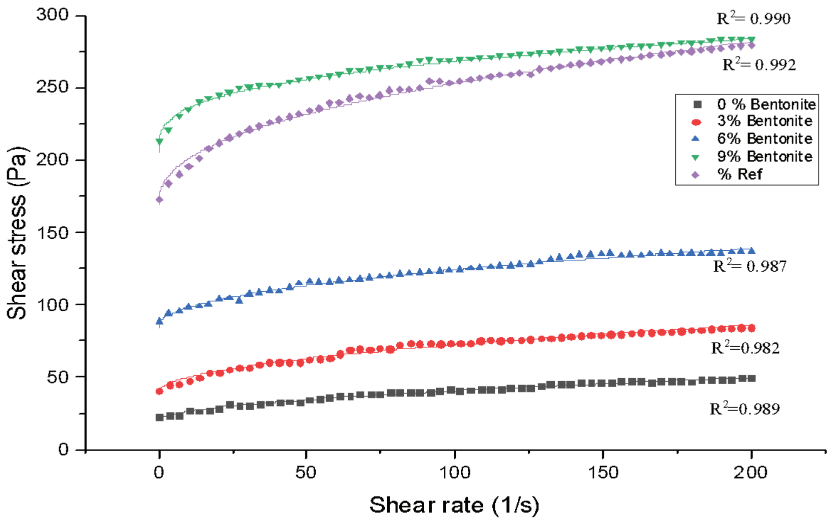


Figure 9. Flow curve of the studied samples

It is clear from the curves represented in figure 10 that the addition of bentonite increases the yield stress of BS clay and makes BS soil's behavior closer to EB sample. In fact, BS clay represents a very low yield stress (20Pa), followed by the sample containing 3% of bentonite (30MPa), the sample containing 6% of bentonite (90MPa), and finally sample containing 10% of bentonite (160MPa). However, Ref sample represents the highest value (206Pa).

This can be explained by the swelling clays' effect on the rheological behavior of clay samples; BS sample is very rich in sand, and its clayey fraction is mainly composed of illite. Illite is a non-expandable clay known for its low plasticity and low water interaction. The reason behind this is related to the strong bonding of its tetrahedral and octahedral sheets (resulting from Van Der Waals forces and potassium ions K+) [22]. Consequently, the suspension adopts a rheological behavior close to the dispersing fluid (Water). On the contrary, EB sample is characterized by the abundance of clay minerals and the presence of smectite. Smectite group is distinguished by its high plasticity and ability to form a solid network known as house of card structure (gel) [45][46]. This network is created by the presence of the electric double layer on the faces and edges of the clay particles formed by the absorbed water. Thus, an amount of energy is needed to break the bonds responsible for this three-dimensional network of the particles (yield stress) [46].

The addition of bentonite to BS clay affects its behavior and makes it closer to EB sample since the bentonite suspensions display high values of yield stresses and forms a gel due to the swelling nature and electrostatic interaction between clay platelets of montmorillonite (smectite group) present in bentonite [48]. Similar behavior was found in the work of Khaldoun et al. [43].

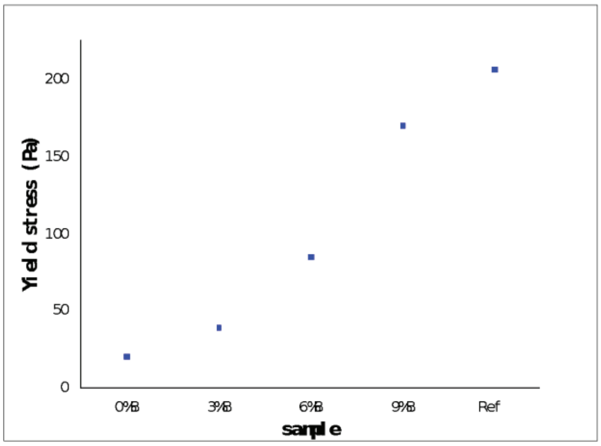


Figure 10. Effect of bentonite addition on the yield stress of samples.

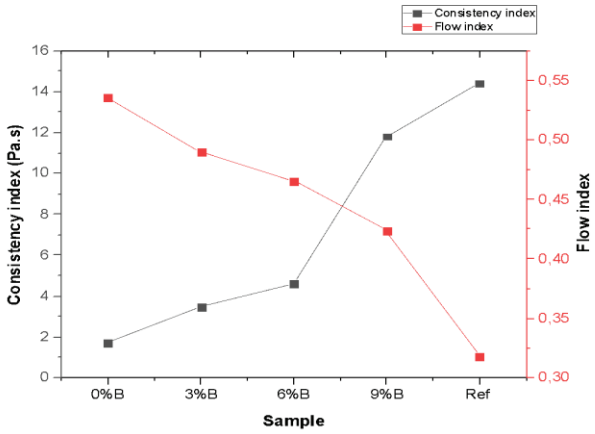


Figure 11. Effect of bentonite addition on consistency index and flow index

The obtained data were correlated to the Herschel-Bulkley classical model of with correlation coefficients R^2 between 0.98 and 0.99 for all suspensions:

$$\tau = \tau_0 + k\gamma^n$$

Where: τ_0: Yield stress in Pa.

k: The consistency index in Pa.s^n.

n: The flow index.

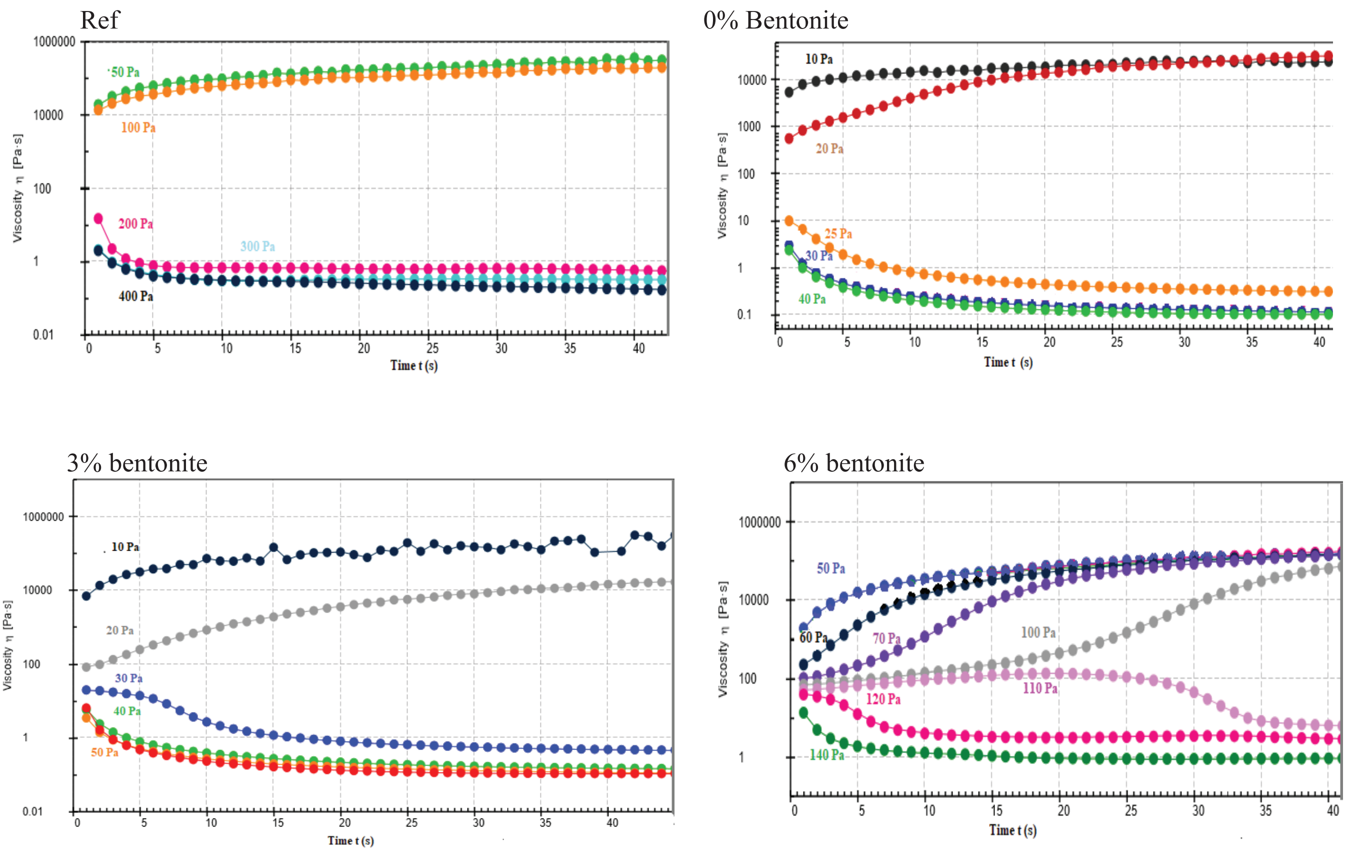
The fitted parameters of Herschel-Bukley model of the different studied samples are presented in Figs 10 and 11. We can observe that the addition of bentonite decreases the flow index value n and increases the consistency index K. This can be explained by the ability of the swelling clays to form a three-dimensional structure resulting from the strong interactions occurring in the presence of water. These interactions increase the suspension n's viscosity. Consequently, the consistency (k) increases, and the flow in dispersing medium becomes more difficult [49][50]. This is translated, in Figure 11, by a decrease in the flow index (n).

3.1.1. Effect of bentonite on the viscosity of clay mixture

The viscosity is a material property representing its capability to resist the shear applied. A constant shear stress is imposed on the sample, and we follow the viscosity variation as a function of time. The results obtained are represented in figure 12. Tests at different stress levels show the sensitivity of the studied samples to variations in stress. It can be observed that when relatively low stresses are applied, the viscosity of the material increases with time until it eventually stops flowing. However, above a certain value of applied stress, the apparent viscosity, which was initially relatively high, gradually decreases to a constant value, indicating that an equilibrium state has been reached. This leads to the so called viscosity bifurcation for a critical stress value.

Results showed that the minimum stress to be applied so the mixture viscosity starts decreasing is 200 Pa, 140 Pa, 70 Pa, 30 Pa, and 25 Pa, respectively for Ref (EB sample), 10% bentonite, 6% bentonite, 3% bentonite, and 0% bentonite. It is also observed that Ref sample requires the highest critical stress, and the addition of bentonite to Bensmim clay increases this critical stress. This behavior is characteristic of clays swelling clays, namely bentonite, and reflects the building up of the random house-of-cards structure: a fragile colloidal gel in which the clay platelets are edge-to-face, creating a space filling structure [51]. This structure of clay particles confers the macroscopic elasticity to clay suspensions. The elasticity increases continuously in time. This is what we call the aging behavior of swelling clays.On the other hand, spectacular liquefaction of the material happens for stress that is only slightly higher than critical stress. This can be explained by the rupture of the bonds between particles when the hydrodynamic forces become greater than the cohesive forces between particles [51]. This rupture progressively reduces the quantity of water trapped by the network and makes the particles "slide" against each other thus the apparent viscosity of the suspension decreases [50]. The viscosity increases as the bentonite percentage increases and becomes closer to the reference sample viscosity. This may be related, as we previously mentioned, to the inner properties of bentonite clays known by their high plasticity and ability to form a strong network structure (gel) [50]. These interactions increase the cohesion of particles, and thus the flow is slow.

Similar behavior has been observed in the work of Khaldoun et al. [43] that studied the rheological behavior of a laboratory clay made by mixing sand and different percentage of bentonite clay in saltwater, in order to find the mixture that reproduces the behaviour of a natural quicksand from Irane.



10% bentonite

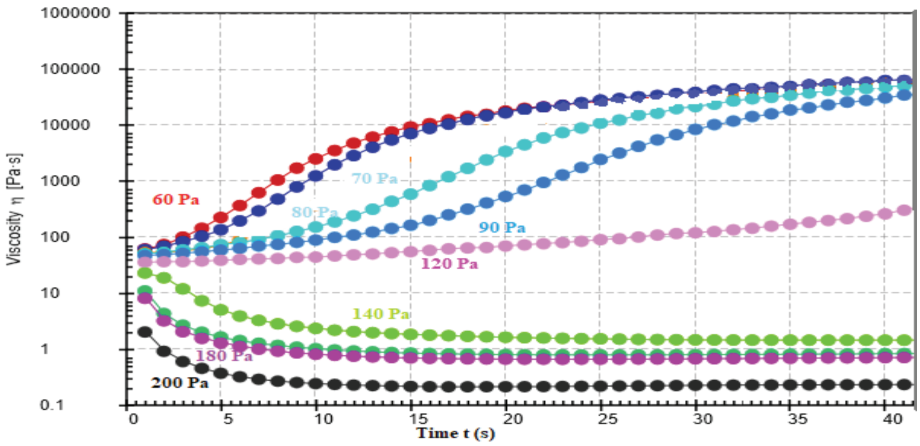


Figure 12. Viscosity bifurcation experiment of the studied samples.

3.8. Compressive strength

Compressive strength is one of the most significant indexes for building materials. It ensures engineering efficiency and determines whether materials are suitable for load-bearing or non-load-bearing walls [20]. Table 5. illustrates the variation of the compressive strength of BS clay with different bentonite concentrations (0%, 3%, 6%, and 10%), and EB clay used as a reference in this study.

According to the results, the compressive strength of bricks has increased by around 24 % with an addition of 10 % of bentonite. The compressive strength went from 5.3 Mpa to 8.2 Mpa for 0S sample and 10S sample, respectively. However, EB samples shows a high compressive strength value of 8.8Mpa. The weak compressive strength of Bemsmim samples is related to their low amount of clay percentage in them. In other words, the clayey fraction that works as a binder in the material is low. Consequently, the brick's cohesion is poor, and as a result, the compressive strength is weak. The addition of bentonite improves the compressive strength of Bensmim clay. The reason behind this may be related to the mineral and chemical composition of this additive. In fact, Bentonite clay used in this study is mainly composed of montmorillonite that enhances Bensmim clay's plasticity and contains an important amount of calcium carbonate. This explains the improvement in compressive strength observed with the addition of bentonite.

Table 5. Evolution of compressive strength with Bentonite addition.

	Compressive strength σ_{comp} (MPa)				*Measurement error * (%)*		
specimen	Test 1	Test 2	Test 3	Mean value	Test 1	Test 2	Test 3
0% bentonite	5.3	5	5.6	5.3	8	1.4	8.4
3% bentonite	6.4	5.99	6.2	6.1	3.7	1.8	1.8
6% bentonite	7.9	8.1	7.6	7.8	5.2	3.4	5.2
10% bentonite	7.8	8.5	8.3	8.2	0.7	2.5	1.8
Ref (EB)	8.5	9	8.9	8.8	0.5	0.1	0.1

Conclusion

In this study, Authors identified the physical properties of an unexploited clay from Bensmim region (known for its weak mechanical performance) in order to study its suitability in clay brick production, and suggested the addition of bentonite clay to ameliorate its mechanical performances. Since rheological behavior of clay material is critical for quality control of clay bricks in the fresh state, the study of bentonite addition effect on Bensmim clay was performed by studying the rheological performance of clay mixtures.
The following conclusions can be drawn from the findings of this study:

- The clayey fraction of Bensmim is mainly composed of illite and kaolinite. Extrabrick, on the other hand, is composed of kaolinite and an important amount of smectite
- Grain size analysis and Atterbergs limits showed that Extrabrick clay is characterized by high plasticity. However, Bensmim has low plasticity.
- Based on the conducted tests, Bensmim clay was found to be unsuitable as a potential raw material for clay brick manufacturing if used in its raw form. The reason is related to its weak plasticity resulting from its low clay fraction, lack of swelling clay, and significant sand content.
- The rheological and mechanical tests showed that increasing the percentage of bentonite has a beneficial effect on the properties of Bensmim clay bricks. In fact, the addition of 10% showed an increase in the yield stress, viscosity, and the mixture exhibited a rheological behavior similar to the reference sample.
- The founded experimental data were fitted to the Herschel-Bulkley classical model. Results showed that the addition of bentonite decreases the flow index value and increases the consistency index of Bensmim clay.
- The obtained viscosity at different stress levels showed the sensitivity of the studied samples to stress variations: For relatively small stresses (less than the yield value), the viscosity of the material increases with time until it eventually stops flowing. However, above a certain critical value of applied stress, the apparent viscosity, which was initially quite high, gradually decreases to a constant value, indicating that an equilibrium state has been reached. On the hand, the viscosity of Bensmim clay increases as the percentage of bentonite increases and becomes closer to reference sample viscosity.
- The compressive strength showed a value of 5.3 MPa, and 8.2 MPa for the brick without additive, and the brick with 10% of bentonite, respectively. However, the reference sample showed a value of 8.8 MP.

In a nutshell, the addition of bentonite up to 10% ameliorates the rheological properties of Bensmim clay, and improves its mechanical performance. As a result of this modification, Bensmim clay is now suitable for use as a raw material in manufacturing clay bricks.
The obtained results allow us to envisage new research works following the same methodology in order to make any clay soil suitable for the production of construction materials. Furthermore, the exploitation of the local clay resources in the production of construction materials enables to produce Clay-based materials locally with similar properties and lower costs than the imported ones. Thus, the cost and carbon footprint of material transportation is minimized.