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Hydric, Physical and Mechanical Behavior of Adobes Stabilized with Sugar Cane Molasses

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Abstract: The use of raw earth as an eco-construction material is a solution to reducing energy and greenhouse gases caused by the manufacturing of conventional construction materials such as cement. Thus, the main objective of this work is to study the hydric, physical and mechanical behavior of adobes stabilized with sugar cane molasses (MCS) for the construction of sustainable habitats. To do this, a raw clayey from Burkina Faso composed of kaolinite (49 wt%), quartz (37 wt%) and goethite (10 wt%) with a plasticity index of 21% was amended with sugar cane molasses at levels of up to 10 wt%. Then, the hydric properties (capillary water absorption and total immersion test), physical (apparent density, closed porosity and volumetric shrinkage) and mechanical (compressive and flexural strength) of the different adobes elaborated were determined. The various results obtained showed that the water absorption coefficient of adobes decreases when the MCS content increases, providing the materials with good water resistance. Furthermore, the presence of MCS in adobe increases its density then reduces its volumetric shrinkage due to the good adhesion of MCS with the particles of the clayey raw material. The addition of sugar cane molasses improves the mechanical performance of adobe with a maximum value of 7.46 MPa in compressive with adobe containing 6 wt% MCS. The improvement of the different technological properties of adobes gives them a use in the construction of sustainable habitats.

1. Introduction

For several decades people have been building cities, raw earth has been and remains, through historical and popular traditions, one of the main construction materials used on our planet. Increasingly, this type of construction is being abandoned in favor of cement block construction in view of its mechanical performance. However, this construction method is more expensive and energy-consuming (Sory *et al.*, 2021). It therefore appears that ecological construction for a low-income population in a developing country can rely on the use of hand-molded raw earth bricks (Sanou *et al.*, 2024b). The disadvantage is that this method of construction does not always withstand bad weather and many raw earth buildings suffer damage due to their poor quality (Ramakrishnan *et al.*, 2021), (Millogo *et al*., 2014). This is how research work aimed at improving the technological properties of these bricks through the use of various stabilizers including plant fibers, cement and lime was carried out (Babé *et al*., 2020), (Serebe *et al*., 2024), (Millogo *et al*., 2012), (Dao *et al*., 2018), (Millogo *et al*., 2008). The work carried out by Millogo et al on the stabilization of adobes with cement showed an improvement in the mechanical properties of these adobes (Millogo *et al*., 2012). According to them, the addition of cement to raw clayey, containing a significant quantity of quartz used for the manufacture of adobes, induced the formation of calcite and tobermorite of the CSH type, ettringite and iron oxy-hydroxide. Calcite ensures the reaction between portlandite and carbon dioxide in the atmosphere. The CSH resulting from the pozzolanic reaction involving kaolinite and fine quartz from raw clayey would be responsible for improving the physical and mechanical characteristics of adobes. According to Serebe et al, the incorporation of kenaf fibers into the clay matrix reduces the drying shrinkage of adobes and lightens the material by increasing porosity (Serebe *et al*., 2024). Also, the presence of kenaf fibers in adobes helps to reduce their conductivity, diffusivity and thermal effusivity. Also, Ouedraogo et al showed that the addition of sugar cane bagasse (Ouedraogo *et al*., 2023a) and rice husk (Ouedraogo *et al*., 2022) to raw clayey leads to a reduction in the thermal conductivity of the adobes produced. This drop in conductivity was due to the insulating nature of the cellulose contained in the sugar cane bagasse and the rice husk and to the presence of closed porosity in the adobes. Danso et al recommend the use of a content of 0.5% of fibers from agricultural waste to improve the physical, mechanical and durability properties of soil blocks (Danso *et al*., 2015). Although the use of stabilizers has made it possible to improve the mechanical (case of cement) and thermal performances of adobes (case of plant fibers), few studies have been devoted to the use of sugar cane molasses in the adobes manufacturing to our knowledge (Malanda *et al*., 2022). However, given its binding properties, sugar cane molasses could constitute a good stabilizer and contribute to improving the durability of adobes (Ouedraogo *et al*., 2023b).

The aim of this study is to study the influence of sugar cane molasses on the hydric, physical and mechanical behavior of adobes. To do this, the geotechnical, chemical and mineralogical characteristics of the raw clayey material will first be determined. Then the adobes will be elaborated by gradually adding up to 10 wt% sugar cane molasses to the raw clayey. Finally, the hydric properties (capillary water absorption and total immersion test), physical (apparent density, closed porosity and volume shrinkage) and mechanical (compressive and flexural strengths) properties of the adobes will be determined.

2. Materials and methods

2.1 Materials

The raw clayey used for making adobes was taken from Matourkou, a village located 15 km from the city of Bobo-Dioulasso (Burkina Faso). The Matourkou clayey site has geographical coordinates (11° 4' North and 4° 22' West). It is a red-brown earth (**Figure 1a**) characteristic of lateritic clayey. It is a potential site operated by the company ZI-MATERIAUX for the manufacture of compressed earth blocks. For the rest of the work, this raw material will be referenced MAT. Sugar cane molasses (**Figure 1b**) used as a stabilizer has already been the subject of previous scientific work for the stabilization of a clay from Burkina Faso for use in road construction (Ouedraogo *et al*., 2023b). Molasses is a fluid obtained after the crystallization of sweet sugar cane juice. It is a very viscous acid solution (average density of 1.4). It is produced at a rate of 30 kg/ton of sugar cane, or 3% of the raw material. It contains sucrose, as well as glucose, fructose, water and minerals (Malanda *et al*., 2022). Sugar cane molasses contains water in the range of 12-17%. The quantity of molasses obtained depends on the nature of the sugar cane (local growing conditions and the effects of weather) and its composition depends on the processing processes at the sugar factory, such as the efficiency of juice clarification, the method of crystallization during boiling and separating the sugar crystals. It will be referenced MCS for the rest of the work.

Figure 1 (a) : Raw clayey; **(b) :** Sugar cane molasses

The bands corresponding to the vibrations of the bonds of the compounds contained in the sugar cane molasses studied were identified by Fourier transform infrared spectrometry (FTIR) given in **Figure 2**. Thus, the band around 3305 cm^{-1} corresponds to the stretching vibrations of O-H bonds of polysaccharides (sucrose and fructose) (Shanshan *et al*., 2013). This same band is attributable to the stretching vibrations of the O-H bonds of water present in sugar cane molasses. The bands observed at 2939, 1409, 1269 and 927 cm^{-1} are associated with the vibrations of the C-H bonds of the aromatic ring structures of polysaccharides (Ouedraogo *et al*., 2023b). The band at 1636 cm^{-1} corresponds to the C=O elongation vibrations of the aromatic ring structures of polysaccharides (Le Troedec *et al*., 2008), (Shanshan *et al*., 2013). The band at 1590 cm^{-1} is attributable to C=C-C elongation vibrations of the aromatic ring structures of polysaccharides (Sanou *et al*., 2024b). Furthermore, the band around 1049 cm^{-1} corresponds to the C-O-C deformation vibrations of the acetyl groups (xylans) of the polysaccharides and that at 993 cm-1 is due to the antisymmetric C-O and Si-O elongation vibrations of the polysaccharides (Ouedraogo *et al*., 2023a).

2.2 Experimental methods

2.2.1 Methods for characterizing raw clayey material

The characterization of the raw clayey consisted of determining its geotechnical, chemical and mineralogical properties through a set of experimental techniques in order to judge its use for the production of adobes. The geotechnical properties concern the determination of the Atterberg limits, the methylene blue value and the particle size of the particles constituting the raw material. The Atterberg limits and the methylene blue value were determined respectively through the standards NF P 94-051 and NF P 94-068. The particle size distribution was determined by sieving on fractions of raw clayey for particle diameters greater than 80 µm according to standard NF P 94–056 and by sedimentometry for particles with a diameter less than 80 µm from of standard NF P 94-057.

Inductively coupled plasma atomic emission spectrometry (ICP-AES) was used to determine the chemical composition. The procedure consisted of dissolving 25 mg of sample previously dried in an oven at 100 °C for 24 hours then introduced into a teflon tube. To this was added 4 ml of hydrofluoric acid (HF) and 1 ml of nitric acid (HNO_3); everything is placed in the microwave oven which is brought to 180 °C at 30 bars for 20 minutes. X-ray diffraction (XRD), Fourier transform infrared spectrometry (FTIR) and differential scanning calorimetry coupled with thermogravimetry analysis (DSC-TGA) were used to identify the phases present in the raw clayey. The powder diffractograms were obtained using a Bragg-Brentano assembly in a Brüker D5000 diffractometer with rear graphite monochromator, operating at a voltage of 40 kV and an intensity of 50 mA with the Kα1 line of copper, driven by a computer equipped with Diffracplus D version 2.2 software. The device used for infrared spectrometry is a Perkin Elmer Spectrum One Fourier Transform Spectrograph (FTIR). The thermograms were obtained from a Netzsch SATA 449 F3 Jupiter type device.

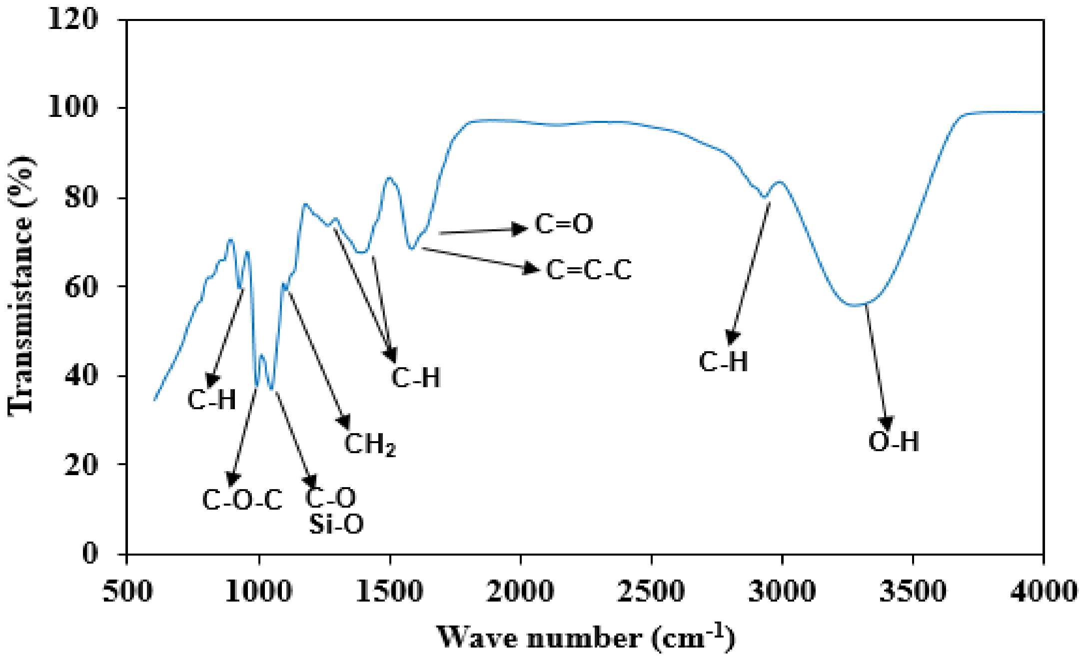

Figure 2. Infrared spectrum of sugar cane molasses

2.2.2 Adobes manufacturing process

The adobes were made from a mixture of raw clayey (passing through a 5 mm sieve) and sugar cane molasses at contents ranging from 2 to 10 wt% at increments of 2 wt%. First, a mass of raw clayey is taken, then a percentage of MCS is added to the raw clayey mass and then mixed until a homogeneous mixture is obtained. Then, a quantity of water is added to the mixture. This water content is obtained from the value of the Atterberg limits using **Relation 1** for the mixture not containing MCS (Bamogo *et al.*, 2020). For mixes containing molasses, the water content decreases as the MCS content increases in the mix until a consistent paste is obtained. The mixture is then kneaded until a homogeneous paste is obtained. The dough obtained is placed in a standardized mold (4 cm x 4 cm x 16 cm) in two layers with manual compaction of 30 strokes for each layer then smoothed. The mold is kept in the shade for 24 hours then unmolded. The adobe specimens obtained are kept for a minimum period of 28 days. **Table 1** gives the composition of the elaborated specimens.

$$\mathbf{W}(\%) = \frac{(\mathbf{W_L}+\mathbf{W_P})}{\mathbf{2}} \quad \textbf{Relation 1}$$

With: W: the water content used; W_L: liquidity limit (%) and W_P: plasticity limit (%)

Table 1. Proportions of mixtures per 1400 g of raw clayey used in the adobes manufacturing

Code	M0	M2	M4	M6	M8	M10
MCS content (wt%)	0	2	4	6	8	10
Mass of MCS (g)	0	28	56	84	112	140
Mass of water (g)	413	311	262	218	209	192

2.2.2 Adobes characterization methods

After adobes manufacturing, the hydric, physical and mechanical characteristics of the adobes were determined. The exterior of buildings is exposed to water or humidity, which causes capillary rise of water through the external pores. This phenomenon can be demonstrated through the test of water absorption by capillary action. This involves determining the increase in mass experienced by an adobe sample whose lower face is in contact with a quantity of water during time intervals fixed at 1, 4, 9, 16, 25, 36, 49 and 64 minutes. The water absorption coefficient noted (A) is determined from **Relation 2** (Ouedraogo *et al*., 2022).

$$A = \frac{m_1 - m_0}{S.\sqrt{t}} \qquad \textbf{Relation 2}$$

With: m_1: mass of the specimen soaked in water for a time t (kg); m_0: mass of the dried specimen (kg); t: absorption time in seconds and S: base area of specimen (m^2).

The water resistance of the adobes was demonstrated by the total immersion test in water. The test consists of completely immersing the adobe specimens in water and evaluating the time during which each specimen completely disintegrates. The density was determined by the hydrostatic weighing method used by several authors (Dao *et al*., 2018), (Kerroum *et al*., 2018), (Sanou *et al*., 2024b). As for porosity, it should be noted that it is of two types. Closed porosity is observed when the pores of the material do not communicate with the outside. As for open porosity, it is observed when the pores of the material communicate with the outside. The water absorption coefficient determines the open porosity of the material. Open porosity is the most important, because it is the cause of problems such as permeability and reductions in the mechanical strengths of adobes. The two porosities constitute the total porosity. Thus, the closed porosity was deduced from the apparent density using **Relation 3**:

$$\eta\ (\%) = (1 - \frac{d_a}{d_s}) \times 100 \qquad \textbf{Relation 3}$$

With: η (%): closed porosity, d_a: apparent density and d_s: absolute density.

The percentages R (%) of volume shrinkage are obtained by the difference in the volumes of the adobe specimen before drying (V_i) and that after drying for a minimum period of 28 days (V_f) according to **Relation 4**:

$$R(\%) = \frac{V_i - V_f}{V_i} \times 100 \qquad \textbf{Relation 4}$$

The mechanical characteristics of the adobes determined are essentially the flexural and compressive strengths. The flexural test was carried out on prismatic specimens of type 4 cm x 4 cm x 16 cm. The specimen used for the flexural test gives two halves usable for the compressive test. Each half is subjected to a monotonously increasing load until rupture. Flexural and compressive tests are carried out in accordance with standard NF P 15-471.

3. Results and Discussion

3.1 Characterization of the raw clayey

3.1.1 Geotechnical characterization

Atterberg limits, particle size, and methylene blue value are the geotechnical characteristics studied. The various results are recorded in **Table 2**. The grain size curve in **Figure 3** shows that the MAT sample has a fairly spread grain size composed of 40 wt% sandy fraction (15 wt % coarse sand and 25 wt% fine sand), 20 wt% fine particles and 7 wt % clay fraction. Thus, the sandy fraction will represent the skeleton, the fine particles will play the role of filler and the clay fraction will serve as a binder between the larger grains in the adobe (Sanou *et al*., 2019). The methylene blue value (1g/100g) indicates that MAT clay can be classified in the group of sandy clay soils. The Atterberg limits (W_L and W_P) made it possible to access the value of the plasticity index ($I_P = W_L - W_P$) showing that MAT belongs to the category of poorly plastic clays. Furthermore, the value pair (W_L, I_P) made it possible to position the raw clayey in the zone of the plasticity indices of the soils usable for the manufacturing of bricks (**Figure 4**) defined by "le Centre International de la Construction en Terre, CRATerre-EAG" (Dao *et al*., 2018). Considering its geotechnical characteristics, MAT can be used as a basic raw material for the adobes manufacturing.

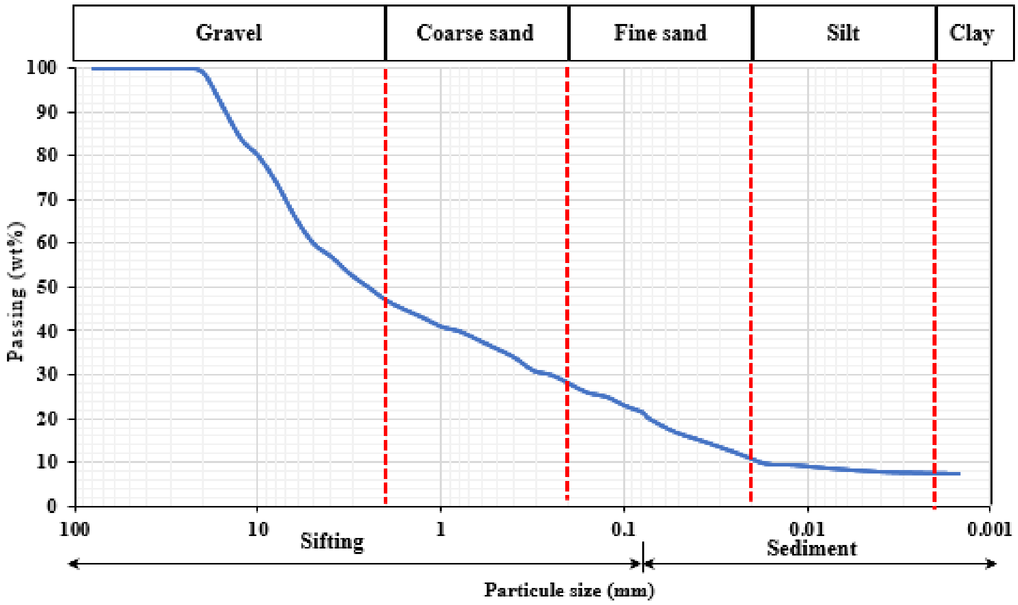

Figure 3. Particles size curve of the raw clayey

Table 2. Geotechnical characteristics of the raw clayey

Particle size distribution (wt%)				Atterberg's limits (%)			Methylene blue value (g/100g)
Coarse sand (0.2-2 mm)	Fine sand (20–200 µm)	Fine particles < 80 µm	Clay (< 2 µm)	W_L	W_P	I_p	
15	25	20	7	40	19	21	1.00

3.1.2 Chemical and mineralogical characterization

Table 3 presents the results of the elemental chemical analysis of the raw clayey. Analysis of this table shows that raw clayey contains a high silica content (SiO_2), an acceptable alumina content (Al_2O_3) and a significant iron oxide content (Fe_2O_3). In view of these results, it appears that silica and alumina are the major oxides in the sample, reflecting the membership of MAT in the aluminosilicates group.

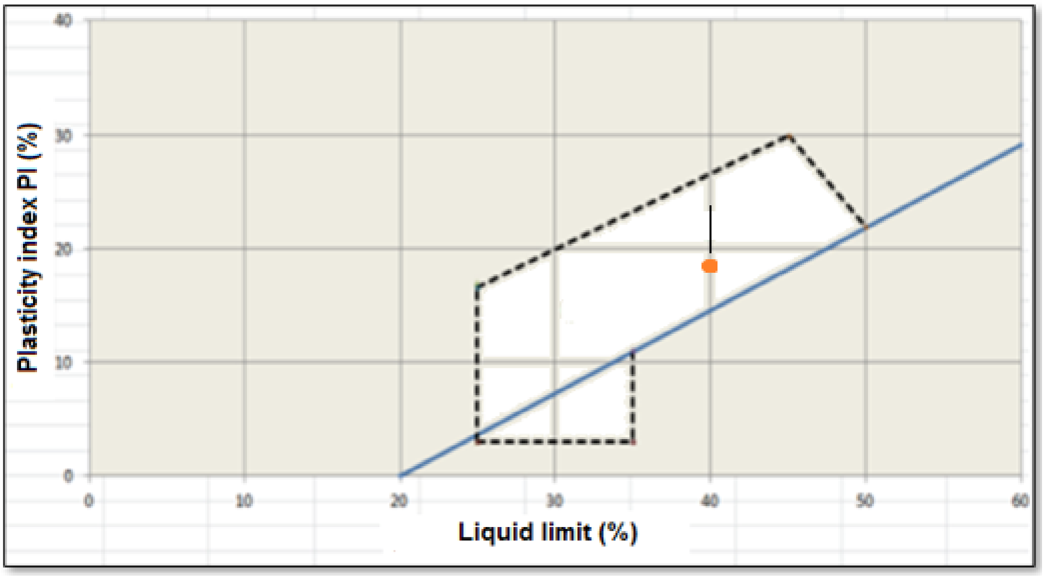

Figure 4. Position of raw clayey in CRATerre-EAG diagram

Table 3. Chemical composition of raw clayey

Oxides	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	K_2O	TiO_2	PF	Total
(wt%)	60.01	19.42	9.01	0.14	0.21	0.23	0.81	9.56	99.39

Analysis of the diffractogram of the raw clayey (**Figure 5**) shows that it is composed of kaolinite ($Al_2Si_2O_5(OH)_4$), quartz (SiO_2) and goethite (FeO(OH)) as crystalline phases. Analysis of the infrared spectrum in **Figure 6** made it possible to identify the characteristic bands attributable to the different minerals contained in raw clayey. Thus, the bands at 3696, 3628 and 3622 cm^{-1} correspond to the vibrations of the hydroxyl (O-H) of kaolinite (Seynou *et al*., 2016). The bands at 1113 and 1000 cm^{-1} are characteristic of the vibrations of the Si-O bonds of kaolinite. The band at 1627 cm^{-1} is attributable to hygroscopic (absorbed) water and that at 1027 cm^{-1} corresponds to the Si-O-Si vibration of kaolinite (Poggetto *et al*., 2022). The two bands observed around 912 and 749 cm^{-1} are associated respectively with the deformation vibrations of the Al-OH (Poggetto *et al*., 2022) and Si-O-Al bonds of kaolinite. The two Si-O-Si deformation bands around 790 and 676 cm^{-1} are attributable to quartz (Golnaz *et al*., 2022). The vibration band at 676 cm^{-1} would correspond to the vibrations of the Fe-OH bonds of goethite.

The analysis of the DSC-TGA curves in **Figure 7** makes it possible to identify the characteristic phenomena of the phases identified by X-ray diffraction and infrared spectrometry. The endothermic peak around 100°C corresponds to the departure of the adsorbed water. This phenomenon is associated with a mass loss of 0.9%. The endothermic peak around 272 °C with a mass loss of 1.67% is attributable to the dehydroxylation of goethite to hematite (Seynou *et al*., 2009; Sanou et al., 2024). The third endothermic peak at 473 °C corresponds to the dehydroxylation of kaolinite to metakaolinite. This dehydroxylation corresponds to a mass loss of 4.62% (Bamogo *et al*., 2020). The overall dehydroxylation reaction is given by **equation 1**:

$$\text{kaolinite } (Al_2O_3.2SiO_2.2H_2O) \xrightarrow{450\text{–}700°C} \text{métakaolinite } (Al_2O_3.2SiO_2) + H_2O \quad \textbf{equation 1}$$

The 571 °C peak corresponds to the allotropic transformation of α quartz into β quartz. Finally, the only exothermic peak around 950 °C corresponds to the structural reorganization of metakaolinite

(Gnoumou *et al.*, 2023). This involves the reorganization of mekaolinite into more stable structures (spinel, mullite) in addition to amorphous silica following **equation 2**.

$$\text{métakaolinite} \xrightarrow{950°C-1000°C} \text{Al-Si spinelle } (Si_3Al_4O_{12}) + SiO_2 \text{ (amorphe)} \qquad \textbf{equation 2}$$

The semi-quantitative composition of the crystalline phases of raw clayey was obtained by coupling the results of chemical analysis and those of X-ray diffraction through the relationship of Yvon et al cited by Sanou et al (Sanou *et al.*, 2024b). The results obtained are recorded in **Table 4**. Analysis of the table shows that raw clayey is rich in kaolinite and quartz with a significant content of goethite. The balance (4 wt%) could be attributed to amorphous compounds and/or organic matter contained in this raw material. Thus, the absence of swelling minerals such as montmorillonite in raw clayey shows that it is suitable for the production of raw earth bricks. Indeed, swelling minerals increase the plasticity of materials and therefore have harmful effects on the durability of raw earth bricks.

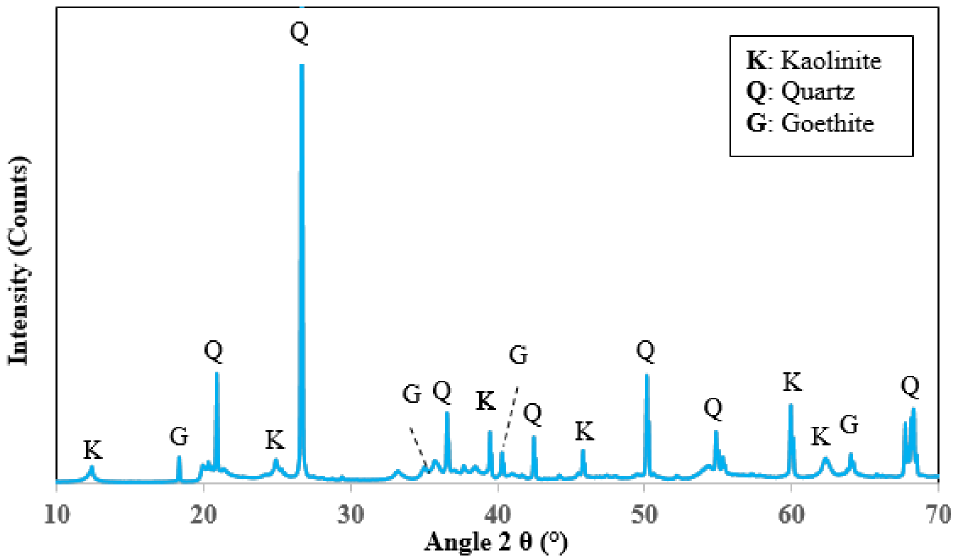

Figure 5. X-ray diffraction pattern of the raw clayed

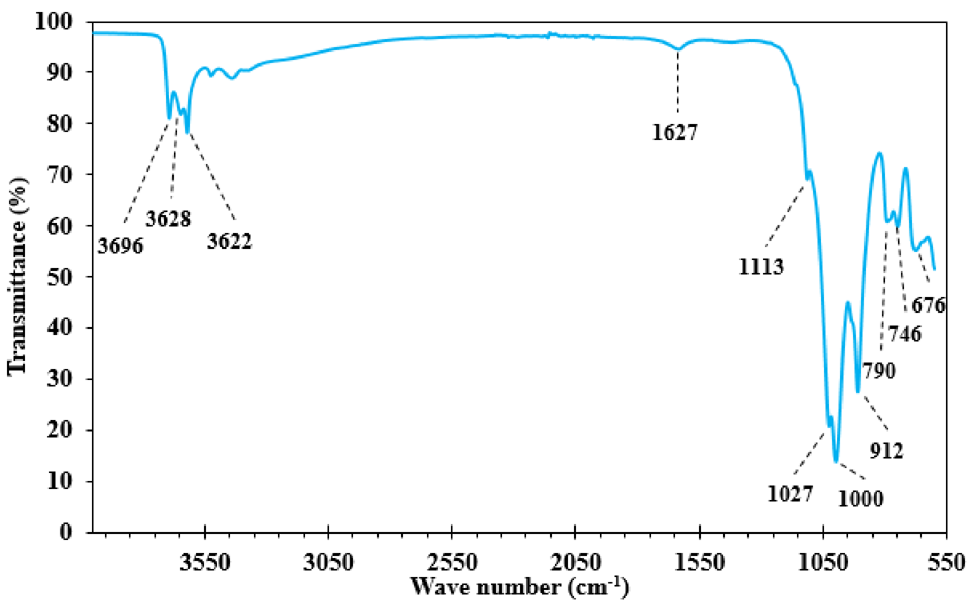

Figure 6. FTIR spectra of the raw clayed

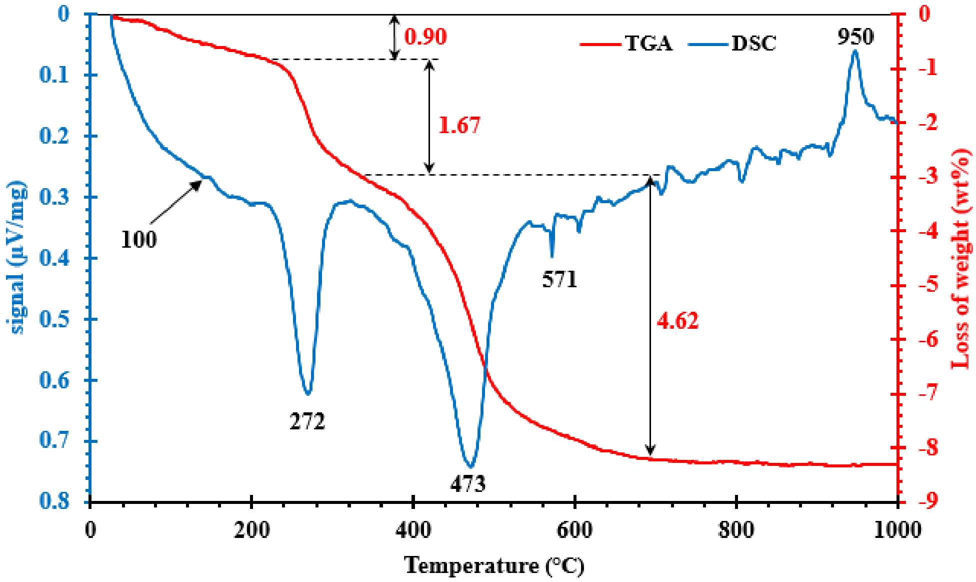

Figure 7. DSC-TGA curves of the raw clayed

Table 4. Mineralogical composition of the raw clayed

Mineral	Kaolinite	Quartz	Goethite	Balance	Total
Wt%	49	37	10	4	100

3.2 Hydric, physical and mechanical characteristics of adobes

3.2.1 Hydric behavior of adobes

Figure 8 presents the capillary water absorption coefficients of adobes as a function of their molasses content. Analysis of the figure shows that the water absorption coefficient by capillary action decreases as the molasses content in the adobe increases. This change in the water absorption coefficient reflects a low penetration of water into the adobe in the presence of molasses. This behavior of adobes results from the reduction in pores accessible to water due to the presence of molasses. Indeed, the sticky property of sugar cane molasses makes it a good binder for the particles of the raw clayey material, making the composite compact and therefore difficult to access by water. Sanou et al observed a similar behavior for adobes stabilized with cement and metakaolin (Sanou *et al*., 2024a). According to them, the presence of metakaolin slows down the phenomenon of capillary absorption of water in adobe. Metakaolin, due to its micro-filling effect due to its fine size, can be inserted between the grains of the clay matrix. Which promotes shrinking of pore size. As a result, adobe has difficulty absorbing water, leading to a reduction in the absorption coefficient. Furthermore, the values of the water absorption coefficients of adobes amended with molasses are low compared to those obtained by these authors. This indicates the effectiveness of sugar cane molasses in making composites waterproof compared to metakaolin-cement composites.

Most often, adobe constructions exposed to rainwater suffer more or less pronounced damage, thereby reducing the lifespan of these buildings. Thus, the behavior of adobes exposed to water is highlighted through the test of total immersion in water. This test makes it possible to monitor the duration of total degradation of adobes completely immersed in water as a function of time. **Figure 9** shows the degradation time of adobes as a function of molasses content. Analysis of this figure shows that the extent of adobe degradation depends on their sugar cane molasses content. The higher the molasses content in adobe, the longer its degradation time. The image in **Figure 10** shows that adobe containing no molasses degrades quickly in water. This behavior of adobes exposed to water is in agreement with the evolution of their water absorption coefficient showing that the permeability of adobe increases its sensitivity to water, thus promoting its rapid degradation. Ouedraogo et al also showed that adobe amended with sugar cane bagasse suffered less degradation in water than raw adobe (Ouedraogo *et al*., 2023a). For them, this resistance to water is mainly explained by the good cohesion between the clay matrix and the sugar cane bagasse resulting from the formation of a large number of hydrogen bonds between the free doublets of oxygen and hydrogen from clay mineral (kaolinite) and sugar cane bagasse (cellulose, lignin, hemicelluloses). Additionally, the presence of solubilized sucrose in the clay matrix contributed to the increase in water resistance of adobes due to the binding of isolated soil particles by solubilized sucrose.

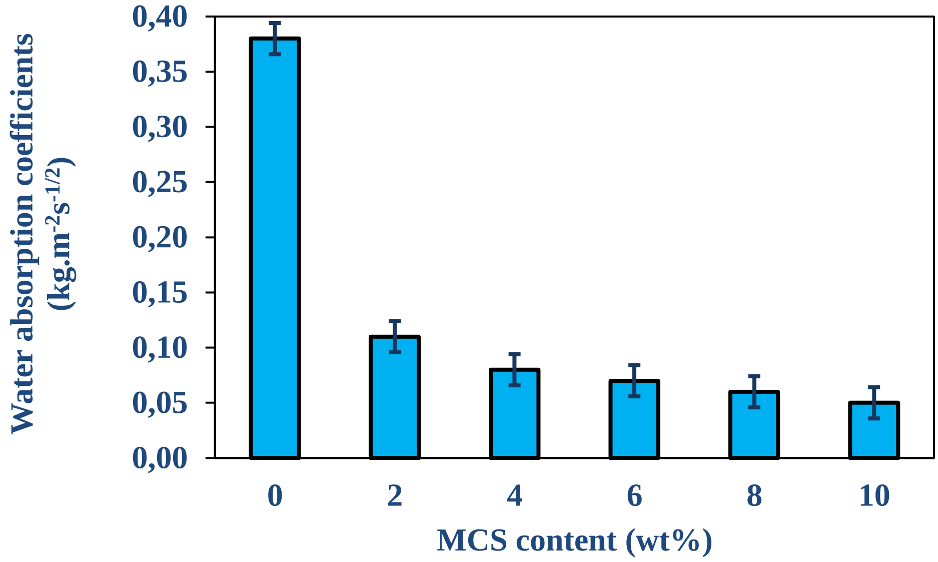

Figure 8. Water absorption coefficients of adobes

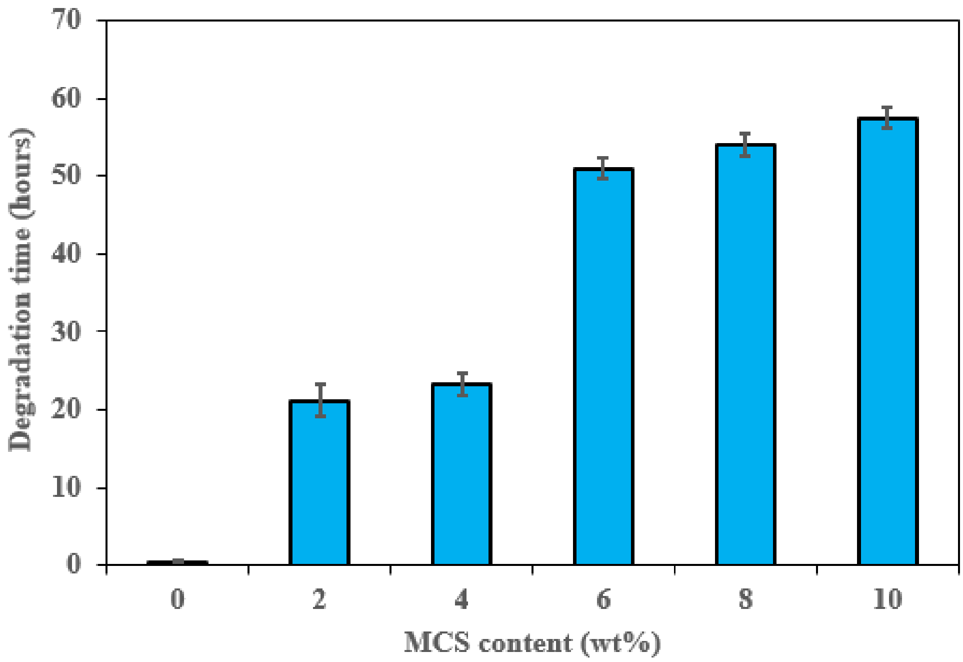

Figure 9. Adobes total water immersion test results

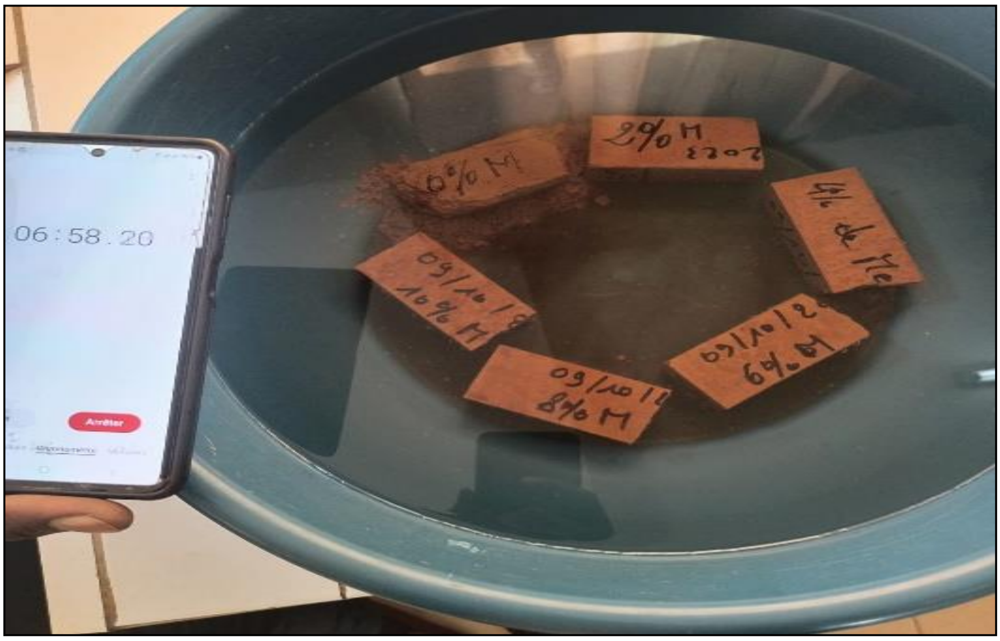

Figure 10. Image of adobes completely submerged in water

3.2.2 Physical properties of adobes

Adobes show changes in size either by shrinkage or by swelling after drying. These transformations on a certain scale can impact the use of these adobes in buildings. The influence of the molasses content on the volume shrinkage of the adobes is presented in **Figure 11**. Thus, the adobes not containing molasses have the greatest shrinkage. This could be explained by the presence of fine particles likely to lodge in the cavities left by the departure of water after drying. Indeed, drying causes the water to leave the adobe, leaving cavities that can be occupied by fine particles of the clay raw material, causing the material to shrink. Also, for a given raw clayed material, the greater the percentage of water contained in the dough to be shaped, the greater the shrinkage.

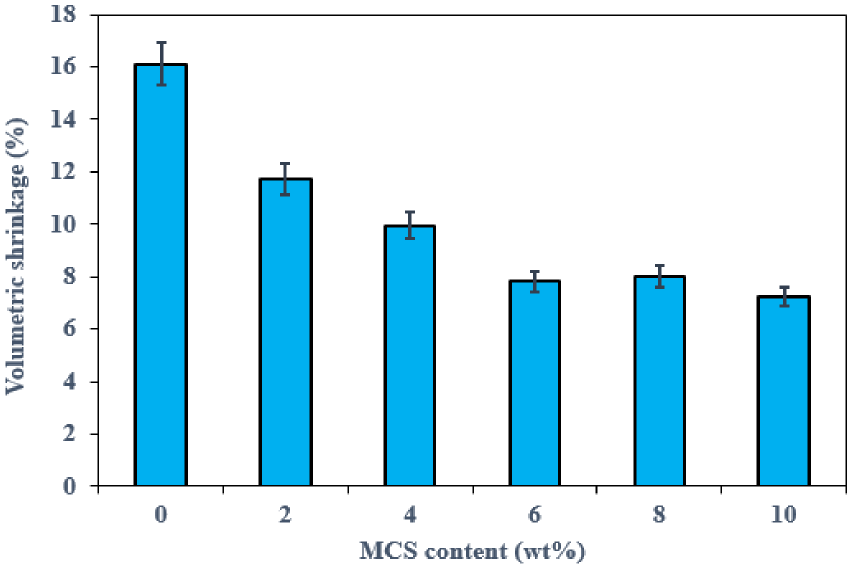

Figure 11. Volumetric shrinkage of adobes

Adobes containing molasses show low volume shrinkage. This is justified by the fact that adobes containing molasses need a small quantity of water (**Table 1**) to reach their normal consistency. Also, the ability of molasses to consolidate the clay particles results in a low loss of water during drying, thus limiting the shrinkage phenomenon. The reduction in the shrinkage of adobes constitutes an advantage for buildings because it is the shrinkage which is the basis of the cracks observed in buildings.

The evolution of the apparent density and the closed porosity of the adobes as a function of the sugar cane molasses content is illustrated in **Figure 12**. The analysis of this figure shows that the apparent density and the closed porosity evolve in the direction reverse. So, when the density of adobe increases, its porosity decreases. Also, the apparent density increases with the content of molasses in the adobe. The density of the adobes increases up to a substitution rate of 6 wt% of molasses in the adobe before decreasing slightly. This behavior would be due to good cohesion between the clay raw material and the sugar cane molasses which allows the clay particles to insert easily by eliminating the pores. Furthermore, a high content of molasses (beyond 6 wt%) in the adobe prevents the good cohesion of the clay particles and the molasses, thus causing a reduction in density. Despite this decrease, adobes amended with molasses present the best density values compared to raw adobe. Also, the maximum value of the apparent density obtained (1.88 g/cm^3) is better than that obtained by other authors who used other stabilizers (Sanou *et al*., 2019), (Dao *et al*., 2018).

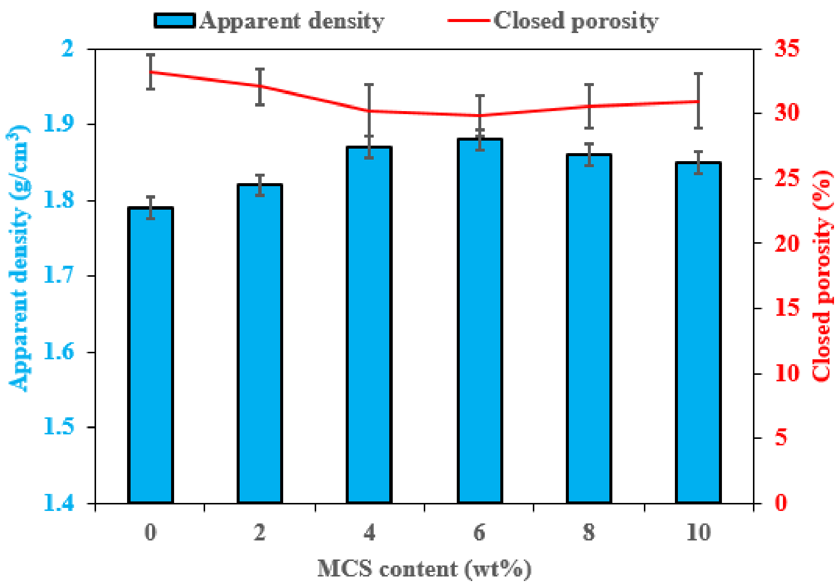

Figure 12. Apparent density and Closed porosity of adobes

3.2.3 Mechanical behavior of adobes

The mechanical behavior of adobes in flexural and compressive is illustrated in **Figure 13**. Analysis of the figure shows that the mechanical strengths in both flexural and compressive increase with the content of molasses in the adobe up to 6 wt%. For molasses contents exceeding 6 wt%, mechanical strength decreases. The evolution of the mechanical strength of adobes is of the same order as that of their apparent density. Thus, the densification of adobe improves its mechanical strength. Ouedraogo et al also attributed the improvement in the mechanical behavior of clay-sugarcane molasses composites to the densification of the composite (Ouedraogo *et al*., 2023b). For them, the densification of the composite would be due to the formation of strong bonds between the polysaccharides of the molasses and the fine particles of the clay material. In fact, the denser the adobe, the less porous it is. However, the presence of pores in a composite makes it fragile, thus reducing its mechanical performance. Several authors have also linked the drop in the mechanical strength of raw earth bricks to the presence of pores in the material. Bobet et al reported a decrease in the mechanical strength of adobes amended with peanut shell (Bobet *et al.*, 2020). According to them, for high shell contents, the microstructure of the adobes becomes heterogeneous, which leads to significant porosity in the brick, resulting in a loss of mechanical strength. For Malanda et al, the presence of sugar cane molasses in a soil induces the evolution of the soil structure towards a more dense and compact structure, which leads to an improvement in the mechanical properties of the soil (Malanda *et al.*, 2022). The evolution of the behavior at breakup of adobes given in **Figure 14** are in agreement with the values of the mechanical strengths obtained. Indeed, the analysis of these curves shows that the greater the force necessary to obtain rupture, the better the strength value. Furthermore, the maximum compressive strength value obtained with 6 wt% molasses in adobe is 7.46 MPa. This value is higher than the maximum strength values obtained by several authors for adobes amended with other types of stabilizers (Sanou *et al.*, 2024b), (Dao *et al.*, 2018), (Millogo *et al.*, 2008). In addition, all the compressive strength values of the adobes obtained are greater than the minimum value of 2 MPa required by the standard in force in the field of construction for raw earth (XP P 13-901, 2001).

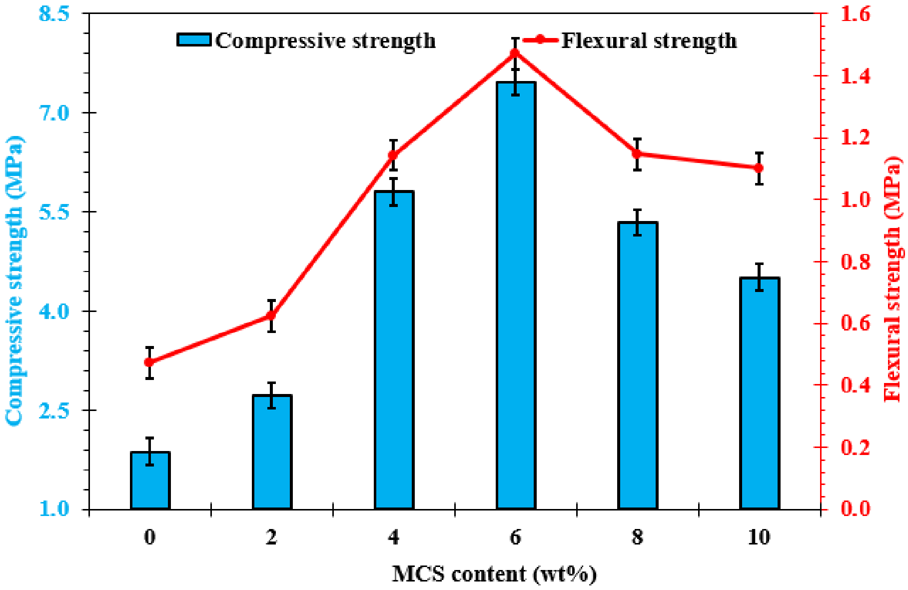

Figure 13. Compressive and Flexural strengths of adobes

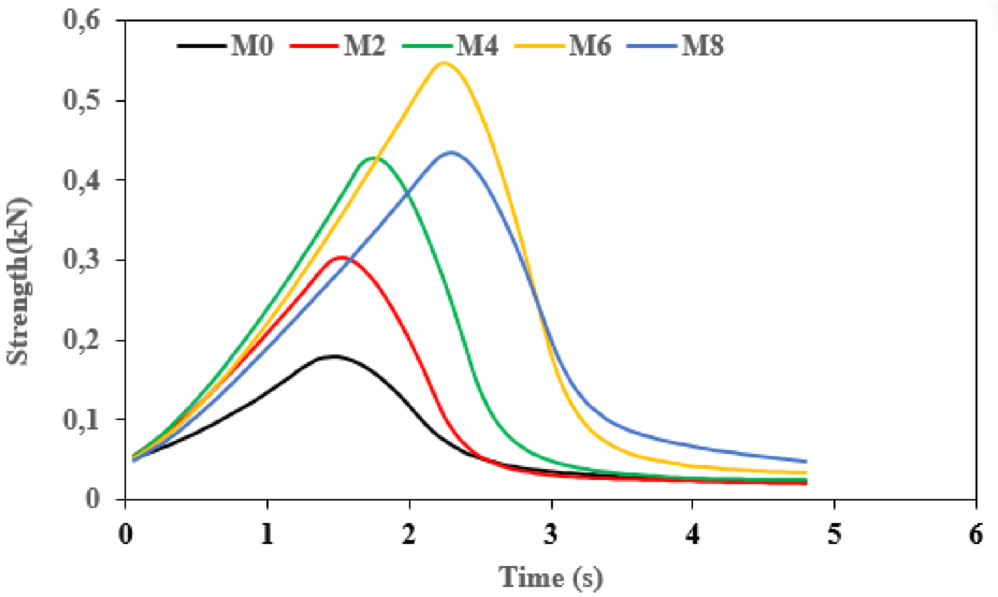

Figure 14. Behavior at breakup of adobes

Conclusions

The main objective of this work was to study the hydric, physical and mechanical behavior of adobes stabilized with sugar cane molasses for the construction of sustainable habitats. The following remarkable conclusions emerge from the various results obtained:

(1) the raw clayed material used is composed of kaolinite (49 wt%), quartz (37 wt%) and goethite (10 wt%) with a methylene blue value of 1 g/100 g and a plasticity index of 21%, this raw material is therefore suitable for the adobes manufacturing.

(2) the presence of sugar cane molasses within the raw clayed material strongly influenced the water, physical and mechanical behavior of the adobes produced with:

(a) a reduction in the water absorption coefficient by capillarity reflecting low water penetration into the adobe and therefore resistance to water due to the good adhesion of the raw clayed material with the sugar cane molasses.

(b) densification of the clay-molasses composite, thus limiting the shrinkage phenomenon. (c) an improvement in the mechanical behavior due to the densification of the material and the formation of strong bonds between the polysaccharides of the molasses and the fine particles of the clayey soil. Given their good water resistance and mechanical performance, adobes amended with sugar cane molasses can be used for the construction of sustainable habitats. Despite the good hydric, physical and mechanical properties of the elaborated adobes, certain tests prove necessary and will therefore be the subject of future work. This involves the study of the aging of adobes in order to know their fate over time, the study of their hygrothermal properties in order to understand their thermal behavior in the humid state.

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