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ORIGINAL ARTICLE

The potential of sludge from wastewater treatment plants to improve the mechanical properties of bricks

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Abstract

This paper aims to study the effect of adding sludge from wastewater treatment plants (WWTPs) in Eastern Algiers on swelling clay brick as a natural substitute for a degreaser to valorize it and minimise the risks related to its storage. First, physico-chemical analyses for clay and dried sludge were carried out using X-ray fluorescence (XRF), Scanning Electron Microscopy (SEM) analysis, Atterberg limits, and laser granulometry. Cylindrical brick specimens were prepared by compaction at 10 MPa, incorporating 0%, 5%, 10%, and 15% of dried sludge depending on the weight of the clay, then fired at 600 °C, 800 °C, and 1000 °C. Brick density, mass absorption, porosity, and compressive strength were evaluated at different temperatures for each sludge dosage. The results show that adding dried sludge to swelling clay improves compressive strength and reduces shrinkage. In contradiction to what has been published in the literature. The addition of 5% sludge to the weight of the clay in the brick composition fired at 800 °C resulted in the highest compressive strength of 32.26 MPa, twice the control bricks' compressive strength. Therefore, using sewage sludge from WWTPs in brick production is an essential sustainable development choice that benefits both the environment and the economy.

Keywords WWTPs · Sewage sludge · Brick · Compressive strength · Shrinkage

Introduction

The production of sludge from WWTPs is a major environmental problem around the world, with increasing amounts being reported each year [1]. In Algeria, for example, WWTPs produce between 100 and 130 tonnes of sludge daily, a figure that reflects the country's rapid population growth. These quantities of sludge are deposited in landfills occupying large storage areas; unfortunately, this situation has long-term consequences, especially with regard to the contamination of groundwater and the food chain [2], because sludge often contains pollutants, biodegradable organic matter, toxic materials, and pathogens [3, 4]. The management of this waste represents a real challenge for the protection of the environment and public health [5].

To reduce the impact on the environment, several countries privilege agricultural use when there is no health risk. In France, 70% of the sludge produced is used in agriculture, either directly or by composting [6]. Research has been carried out in various fields, such as chemistry, such as biofuel production [7] and phosphoric acid production [8], and in the field of building materials manufacturing, such as light aggregates [9], brick and ceramic production[10–19], and cement production [20–24].

The physicochemical characterization of the sludge had shown that it could be added to building materials, such as brick clay [25–27]. Since 1982, sludge has been incorporated to replace part of the clay [28]. The firing temperature, the origin of the sludge used, and the percentage of sludge incorporation in the brick clay were among the key factors determining the quality of the brick in terms of compressive strength, firing shrinkage, porosity, and mass absorption [11, 29, 30]. Previous studies agree on the fact that the addition of sludge to the brick clay leads to an increase in porosity as well as mass absorption [5, 10, 16, 31–33]. However, this

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addition leads to incoherent compressive strengths and firing shrinkage [10, 16, 19, 31].

The decrease in compressive strength with the addition of sewage sludge in clay bricks is mainly due to the increase in porosity and mass absorption [10, 11, 34]. However, increasing the firing temperature of the bricks to 1000 °C or more improves this resistance [16, 31, 33]. The firing of bricks amended with sludge from sewage treatment plants at 930° with moisture adjustment indicates that the addition of sludge up to 15% by weight of clay does not affect the average compressive strength for any quantity of sludge added [19]. According to the results of Weng et al. [30], The addition of 15% dried sludge to the clay with a firing at 960 °C results in first-degree bricks, while second-degree bricks result from the addition of 30% fired at 1000 °C. It is evident that the increase in firing temperature leads to an increase in shrinkage. Nevertheless, the addition of 0–40% sludge to the clay bricks fired at 980 °C led to a decrease in shrinkage of the order of 1–2.5% [10]. This was not observed when adding up to 35% sludge to the brick clay firing at 1050 °C, 1100 °C, 1120 °C, and 1150 °C. The shrinkage of the bricks increases with the addition of sludge [19, 30, 31, 35], reaches a maximum of 15%, then decreases with additions from 20 to 35% [31]. The firing of sludge-amended bricks at 700 °C and 900 °C indicates a constant firing shrinkage for any amount of sludge added; however, firing at 1100 °C leads to a decrease in shrinkage after adding 10% sludge [33]. At present, there is little published research on clay bricks amended with sludge fired at temperatures below 900 °C. This lack of research is particularly true for clays of a swelling nature with high shrinkage after firing. Although some studies have been conducted on this topic, they have not reached coherent conclusions regarding the impact of the sludge addition on the mechanical behaviour and shrinkage of amended bricks. Therefore, it is difficult to draw consistent conclusions about the effectiveness of the sewage sludge addition in brick manufacturing.

In Algeria, the brick sector is confronted with a problem of great shrinkage of the bricks after firing, which is worrying. To solve this problem, brick manufacturers add natural degreasing agents such as sand or tuff in percentages ranging from 5 to 25%. However, with the rapid expansion of the construction sector in Algeria, the demand for sand has increased considerably, with negative environmental consequences. Indeed, the preservation of sand reserves is rapidly decreasing.

Therefore, the use of clay bricks fined by sludge from sewage treatment plants can be an economic and environmental alternative. In fact, the use of sludge from sewage plants in the manufacture of bricks will reduce the environmental impact of the production of clay bricks by reducing the quantities of sand extracted for this purpose. The objective of this study is to fill this gap and provide guidelines for the use of sludge from wastewater treatment plants in the brick industry to promote sustainable development in Algeria. In this paper, the sludge from the Barraki sewage treatment plant and the swelling clay used were previously dried and then submitted to physicochemical analysis and granulometric analysis, and rates of 0%, 5%, 10%, and 15% of sludge were incorporated in the design of 72 cylindrical test specimens, a series fired at 600 °C, another at 800 °C, and one at 1000 °C. Compressive strength, firing shrinkage, mass absorption, porosity, density, mineralogy, and morphology were studied to determine the quality of the final product.

Materials and methods

Sludge preparation

The sludge studied in this article comes from the Barraki WWTP, located in the municipality of Hussein Dey to the east of Algiers, Algeria, about 2 kms northwest of Bordj el Kiffan beach, which collects wastewater from different industrial zones and the national company NAFTAL. The water treatment process in the plant is based on the activated sludge method; the dry matter content varies from 28 to 30%.

The sludge was collected in June, in plastic bags, and then transferred to a metal drum. As shown in Fig. 1a, b, the collected sludge has increased in volume; this fermentation phenomenon is due to the high temperature.

The sludge was dried at 105 °C according to the NF EN 12880 standard [36]. The grinding was carried out using a "VEB BHK Albert Funk Freiberg/Sa Rationalisierungsbetrieb" type disc mill and then sieved using a 1 mm sieve (refer to Fig. 2a, b).

Preparation of the brick specimens

This study examined four different types of bricks. Each type was made for a one kilogramme quantity of clay, and different percentages of DS were added to each type of brick: 0% (control), 5%, 10%, and 15%. 18 cylindrical test specimens of 2.35 cm diameter and 4.70 cm height were prepared for each composition. The clay used was supplied by Baba Ali-El Mouchir Brick and Tile Complex, located in the municipality of Baba Ali, about 20 kms east of downtown Algiers. The clay is extracted from the deposit, which is located in the locality of Chéraga, which is located in the north–west of Algiers, approximately 18 km west of Algiers. 14% by weight of distilled water was added to ensure high-density blocks. The specimen dimensions respect the diameter/height ratio recommended for the compression tests.

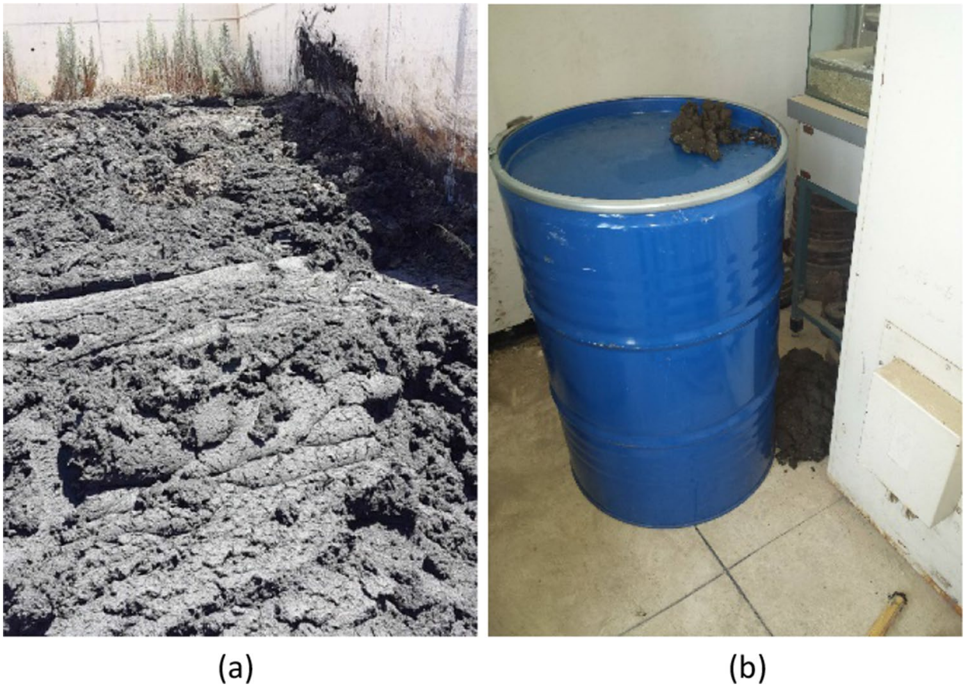


Fig. 1 Sludge in the wastewater treatment plant (**a**) and fermentation phenomenon (**b**)

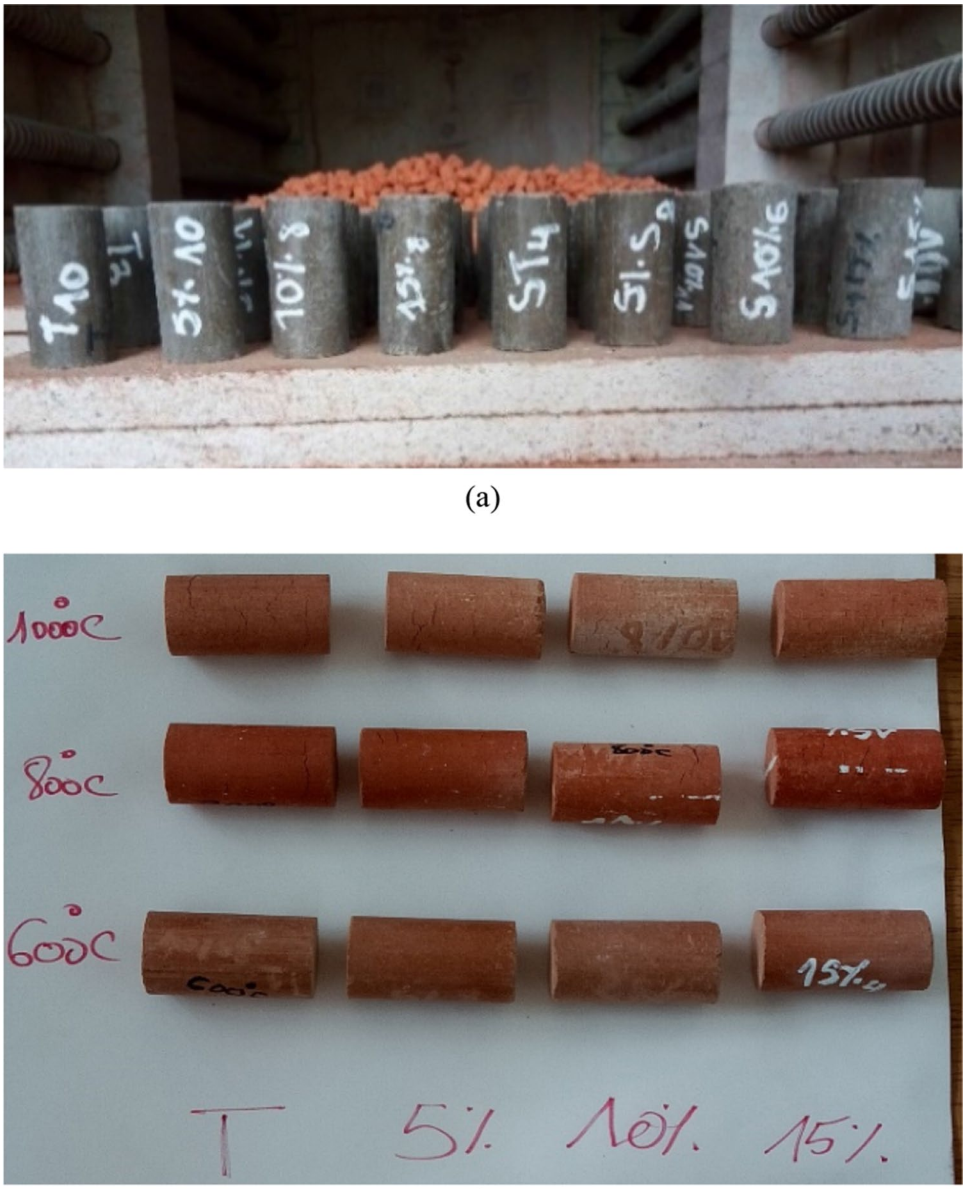
Fig. 2 Sludge grinding (**a**), preparation of mixtures (**b**), mixing (**c**) and moulding (**d**)

As illustrated in Fig. 2c, the mixtures were first homogenised for 15 min in a mixer before being compressed with a simple compression strength machine (RCS Wykeham-Fairance) at a pressure of 10 MPa and a speed of 4 mm/min (refer to Fig. 2d). The brick samples were then air-dried, dried in a 50 °C oven for 24 h, and fired at 600, 800, and 1000 °C using a muffle furnace that was kept at the necessary temperature for 6 h (refer to Fig. 3a, b).

Physico-chemical characterization of raw materials

The chemical elements content determination was carried out for both the clay and DS at the CRAPC's Laboratory. The level of heavy metals was also evaluated using the Rigaku ZSX Primus II apparatus by the XRF method on pellets prepared by compression and composed of 5 g of sample. A scanning electronic microscope (SEM) of type THERMO SCIENTIFIC Prisma E is used to determine the morphology of the DS and the clay at the CRAPC's Laboratory.

A 5 g sample supplemented with 100 g of distilled water was tested for pH at the CNERIB's laboratory, using a DELUXE pH METRE 101 pH meter after being shaken for 15 min. The determination of the $CaCO_3$ content and the measurement of the soil blue value (VBS) were carried out at the LNHC Laboratory. The $CaCO_3$



(a)

(b)

Fig. 3 Brick test piece before firing (**a**), Brick test piece after firing (**b**)

content is determined by measuring the carbon dioxide (CO_2) released when a certain quantity of dry matter is attacked by hydrochloric acid. The soil blue value (VBS) is measured according to NF P94-068 [37] by expressing the quantity of methylene blue adsorbed per 100 g of soil in grams.

The evaluation of the apparent density and the actual density of the materials were determined according to NF ISO 11272 [38] and NF ISO 11508 [39], respectively. The distribution, grain size of the samples and the mineralogical analysis were also carried out using the MASTERSIZER 2000 apparatus and an X-ray diffract meter, respectively.

Characterization of brick specimens

The determination of the compressive strength of all the specimens is carried out using a CONTROLS brand flexural and compressive strength testing machine.

The porosity and density of the brick specimens were determined according to NF P 18-459 [40] standard. The masses of the specimens are measured in their dry state (after firing), then in water at a temperature of 20 °C for 24 h. After wiping the surface, the second measures are taken in water by a hydrostatic weighing.

The porosity and density are calculated according to the following formulas:

The apparent density ρ_d is given by the following equation:

$$\rho_d = \frac{W_d}{W_a - W_w} * \rho_{\text{eau}}. \tag{1}$$

The water accessible porosity ε is expressed as a percentage by volume and is given by the following equation:

$$\varepsilon = \frac{W_a - W_d}{W_a - W_w} * 100 \tag{2}$$

Which W_d, Weight of the brick sample dried at 50 °C; W_a, Weight of saturated brick specimen weighed in air; W_w, Weight of the saturated brick sample measured in water.

Linear shrinkage was determined according to Eq. (3) by measuring the length of the samples before and after curing using an electronic calliper with an accuracy of ± 0.01 mm

$$\text{shrinkage} = ((l_0 - l_{\text{fired}})/(l_0)) * 100 \tag{3}$$

With l_0, Length of the brick specimen before drying (mm); l_{fired}, Length of the fired test piece.

The morphology of brick specimens is obtained using a scanning electronic microscope (SEM) type THERMO SCIENTIFIC Prisma E. The tests were carried out at CRAPC's Laboratory.

The mineralogical analysis of bricks powder is done by an X-ray diffractometer in the laboratory of the Faculty of Mechanics at the USTHB.

Results and discussion

Results of the physico-chemical characterization of raw materials

The pH and the level of calcium carbonate $CaCO_3$ and VBS

Table 1 shows the results obtained for the measurement of pH and $CaCO_3$ as well as the soil blue value of the different clays and dried sludge.

The results show that the pH of the clay is basic, while that of the sludge is acidic, which was expected, since the sludge is rich in organic matter and the percentage of $CaCO_3$ in the clay is higher than in the dry sludge. Nevertheless, both samples are classified as non-calcareous materials, since the calcium carbonate content does not exceed 10% as found by El Fagaier [41].

Table 1 PH value and calcium carbonate content $CaCO_3$ and VBS

Materials	pH	% $CaCO_3$	VBS
Clay	7.81	9.66	4.48
DS 105 °C	6.34	7.73	1.24

The pH of the clays influences the mechanical resistance properties and the colour of the bricks, the best results of the pH of the acid clays and the neutral or basic clays are between 6 and 8.5 and between 7.3 and 10.5, respectively [42].

The clay studied is classified as salty clay soil according to NF P 94–068 [37] standard is between 2.5 and 6, while the dry sludge is found in low plastic salty soils between 0.2 and 2.5.

The real and apparent density

The results obtained for the measurement of the real and apparent density of clay and dry sludge are represented in Table 2.

It can be observed from Table 2 that the real and apparent densities of the dried sludge are lower than the considered clay.

Chemical composition

The main chemical components of clay and dried sludge are illustrated in Table 3.

Table 2 Real and apparent density of the constituents of the clay and the dried sludge

Materials	ρ_a (g/cm^3)	ρ_r (g/cm^3)
DS 105 °C	0.65	1.95
Clay	0.90	2.80

Table 3 Chemical composition of the materials used

Oxides	Clay (%)	DS 105 °C (%)
SiO_2	42.6935	21.7825
Al_2O_3	14.0583	9.1251
Fe_2O_3	4.677	3.566
CaO	13.5329	9.9761
MgO	2.4193	0.9895
SO_3	0.8299	2.1646
K_2O	1.8639	0.9811
Na_2O	0.4336	0.3604
TiO_2	0.6255	0.3657
MnO	0.0288	0.0339
Cl	0.0465	0.0751

Table 4 Oxides in clay and dried sludge

Oxides	Composition (%)	
	Clay	DS 105 °C
SiO_2/Al_2O_3	3.03%	2.38%
$Fe_2O_3 + TiO_2$	5.30%	3.93%
MgO + CaO	15.95%	10.96%
$K_2O + Na_2O$	2.29%	1.34%

Table 5 Loss on ignition (LOI) (%)

	Clay	DS 105 °C
LOI	17.54	40.34

The X-ray fluorescence analysis illustrated in Table 3 reveals that SiO_2 is the main component of the clay and dry sludge followed by Al_2O_3 and CaO and then Fe_2O_3. It is also observed that the percentage of Fe_2O_3 in the two samples is close which means that the colour of the finished product will not change after firing as it is responsible for the red colour of the bricks [15].

The CaO values match the $CaCO_3$ values. However, the excessive presence and the presence of MgO can have a negative effect on the bricks by creating porosity [43, 44].

According to Wetshondo Osomba [44], the alumina content of the clay is between 10 and 30%, and the silica SiO_2 content is 85%, classifying it as a silico-clay refractory product. The clay used in this study is classified as a silico-clay refractory product. Other residues of oxides (Mn, Na, Ti, P, K) were detected in the chemical analysis of both samples.

The values of SiO_2/Al_2O_3 presented in Table 4 show that the free silica in the clay is close to that of the sludge. The values of colouring oxides such as Fe_2O_3 and TiO_2 are slightly discrepant, which do not change the colour of the bricks containing DS. It is also observed from Table 4 that the values of (MgO + CaO) are higher in the clay, which results in high porosity in the brick samples. The results obtained for the K_2O and Na_2O show that the clay contains a slightly higher amount than the DS, but tolerable levels [15, 35].

Loss on ignition

The loss of ignition for both clay and dry sludge is illustrated in Table 5. The results indicate a significant discrepancy between the clay and the DS values; the DS presents a loss of ignition twice as high as the clay. The loss of ignition is mainly caused by the decomposition of organic matter and the decomposition of calcium carbonates. The high organic content may cause micro-cracks in the brick and may reduce its mechanical properties [45].

Trace metals

The level of metallic trace elements in clay and dry sludge is given in Table 6.

As shown in Table 6, all the values of the metallic trace elements of the dry sludge are higher than those of the clay. In exception, chromium presents a higher value in the clay. All values are lower than those given by the Algerian standard NA17671 [6], which favours the incorporation of the dried sludge in the bricks without any impact on the health of human beings.

Morphology (MEB)

Figure 4a–d shows the SEM image of the morphology of the DS and the clay, respectively. It can be seen from Fig. 4a, b that the DS presents a variable and irregular grain structure with a rough outer surface, while the clay grain structure is roughly regular with an outer surface between smooth and rough.

X-ray diffractograms

Figure 5 shows the XRD measurements of the clay and sludge dried at 105 °C.

From Fig. 5, the results show the presence of quartz (33%), halloysite (26%), illite (37%), and montmorillonite (24%) as the main clay minerals; quartz (22%), halloysite (24%), anorthite (38%) and magnesium hydroxide sulphate hydrate (36%) as the crystalline component of the DS, these

Table 6 Level of metallic trace elements in clay and dry sludge

	Clay (%)	DS 105 °C (%)	Metals	Clay (mg/kg)	DS 105 °C (mg/kg)	NA 17671-2010
V_2O_5	0,0266	–	–	–	–	–
Cr_2O_3	0,0174	0,0162	Cr	1507,71	140,377	1750
NiO	0,0044	0,004	Ni	34,5708	31,428	400
CuO	0,0015	0,0179	Cu	11,9882	142,98	1750
ZnO	0,0096	0,0433	Zn	77,11	347,8289	4000
BaO	–	0,0353	Ba	–	316,1468	–
PbO	–	0,0093	Pb	–	86.3319	1200

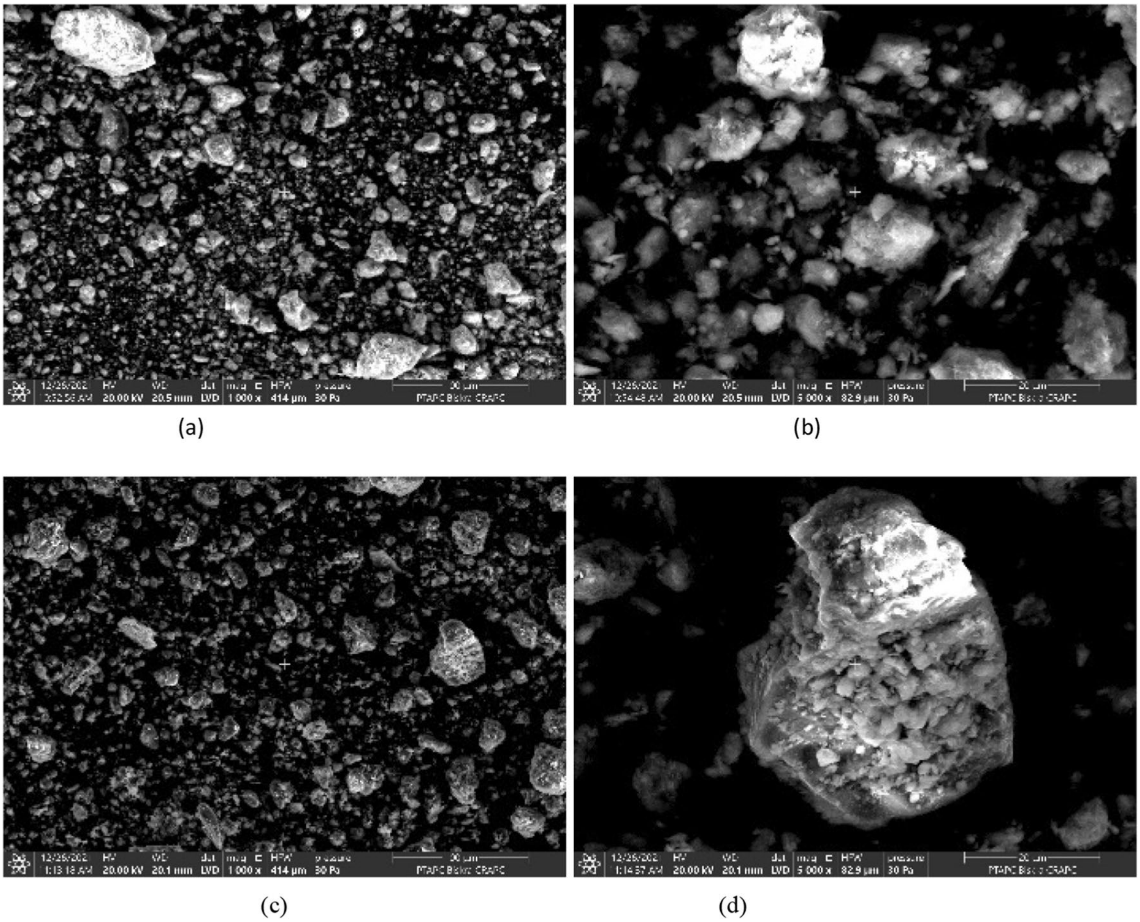


Fig. 4 Dried sludge × 1000 (**a**), dried sludge × 5000 (**b**) Clay × 1000 (**c**), Clay × 5000 (**d**)

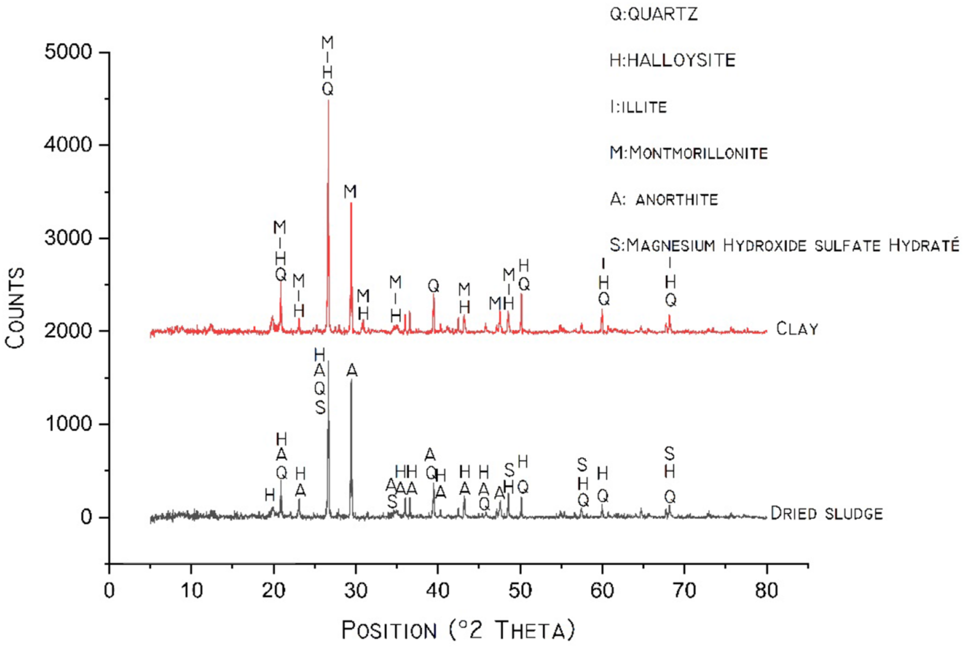


Fig. 5 XRD of the dried sludge and clay

Table 7 Laser granulometry of the DS 105 °C and clay

	D10 (µm)	D50 (µm)	D90 (µm)
DS 105 °C	14.31	209.476	800.274
Clay	1.725	14.767	93.152

Table 8 Atterberg limits of prepared mixtures

	0% DS	5% DS	10% DS	15% DS
WL	57.87	56.3	58.36	60.72
WP	22.61	32.76	30.05	35.57
IP	35.25	23.53	28.3	25.14

results are in agreement with the chemical composition presented in Table 3.

The presence of Montmorillonites (belonging to the smectites group) causes soil destruction as they swell and create large cracks upon dehydration [46]. This may be due to the large specific surface area of smectites of up to 800 m^2/g [42], which causes shrinkage due to the fineness of these particles.

It can be seen from Fig. 5, the mineralogical composition of the sludge sample contains hydrated magnesium hydroxide sulphate. Its presence can cause efflorescence; the sulphates dehydrate and then rehydrate after cooling, and they migrate to the surface of the bricks. During the drying process, they form a layer on the surface of the bricks [47].

Laser granulometry

The particle size distribution of dried sludge and clay is presented in Table 7.

The particle size results presented in Table 7 show that the sludge has a coarse particle size compared to the clay.

Atterberg limits

The results of the Atterberg limits are illustrated in Table 8. The results indicate that the clay used in this investigation is classified as high-plasticity clay and the addition of sludge gives it the texture of a highly plastic organic soil.

Results of the tests carried out on the brick specimens

Mass loss of bricks (%)

The results of the mass loss of control bricks and bricks with the addition of 5%, 10% and 15% dried sludge by weight of clay and fired at 600, 800 and 1000 °C are shown in Fig. 6.

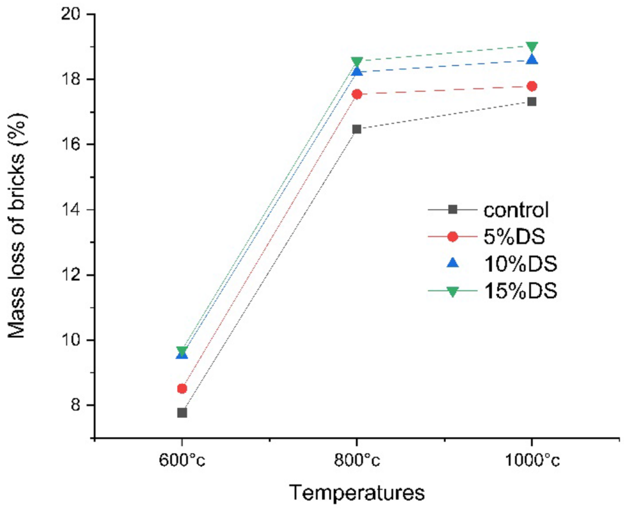


Fig. 6 Mass loss of bricks fired at 600, 800 and 1000 °C

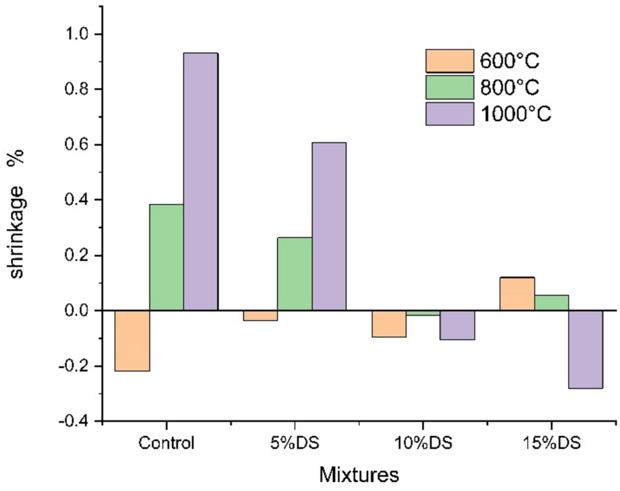


Fig. 7 Shrinkage of bricks fired at 600, 800 and 1000 °C

It can be seen from Fig. 6 that the mass loss of all bricks increases as the firing temperature and the percentage added of dry sludge increase. In fact, at 600 °C, the mass loss of the bricks varies from 7.77 to 9.70%. The mass loss becomes more important at 800 °C (varies from 16.48 to 18.56%). For all the percentages added of dry sludge, while there is no significant loss between 800 and 1000 °C, The significant mass loss increase is caused by the decarbonisation of calcite from 800 °C up, [17, 23], where the release of carbon dioxide causes a very noticeable loss of weight [44].

Brick shrinkage (%)

Figures 7 and 8 show the results of the shrinkage tests and a comparison of the cracking patterns obtained for the different bricks fired at 600 °C, 800 °C, and 1000 °C, respectively.

Fig. 8 Visible cracks on control bricks (T10) and (5% 10) fired at 1000 °C and white film on the surface of 5%, 10% and 15% bricks

The results presented in Fig. 7 indicate that when fired at 600 °C, the brick sample with 15% dry sludge experienced minimal shrinkage, whereas neither the control bricks nor the bricks with 5% or 10% dry sludge demonstrated any signs of shrinkage.

When the brick samples are exposed to a temperature of 800 °C, the control sample shrinks by 0.38%. By adding 5% dry sludge, shrinkage is reduced by 31% compared to the control bricks. However, the addition of 10% sludge shows no sign of shrinkage, while the sample containing 15% dry sludge experiences an 81% decrease in shrinkage compared to the control bricks, as shown in Fig. 7.

When the samples are exposed to a temperature of 1000 °C, the control sample shrinks by 0.93%. However, the addition of 5% dry sludge reduces the shrinkage by 35%, while bricks containing 10% and 15% dry sludge show no signs of shrinkage. These results are in agreement with those obtained by Liew et al. [10], who used up to 40% clay sludge by weight for the manufacture of bricks fired at 985 °C, as well as with research conducted by Hua [28], who used up to 50% dry clay sludge by weight.

The decrease in brick shrinkage after the addition of sludge can be explained in different ways. First, according to Liew et al. [10], the non-plasticity of dry sludge has a greater effect on the bricks after firing. In addition, the coarse grain size of dry sludge, compared to clay, can act as a degreaser in the brick, as shown in Table 7. Another explanation is provided in Fig. 8, showing that the addition of dry sludge reduces the propagation of cracks that are often present on control bricks. These cracks are mainly caused by the swelling nature of the clay, which contains montmorillonite, as shown in Fig. 5 through X-ray diffraction. Montmorionite is a member of the smectite group and has a very high specific surface area, which leads to a high shrinkage after firing.

Furthermore, it was observed that the presence of high amounts of sludge leads to an increase in the presence of white skin on the surface of the bricks. This observation is attributed to the presence of sulphates in the sludge, which causes the fluorescence phenomenon, as shown in Fig. 5.

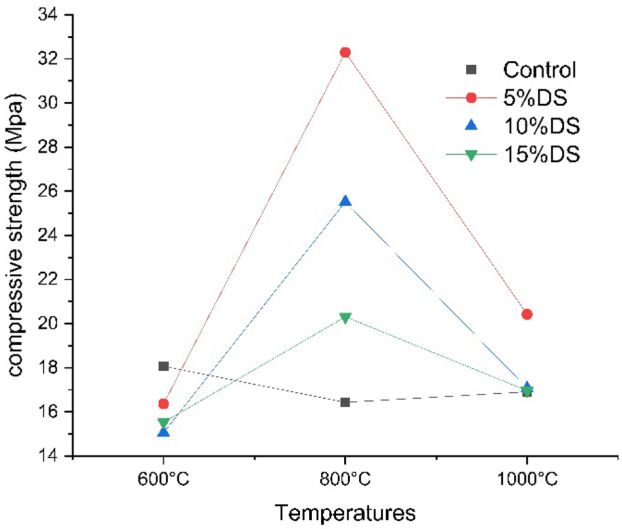


Fig. 9 Compressive strength of bricks fired at 600 °C, 800 °C and 1000 °C

Compressive strength

Compressive strength is regarded as the most crucial factor to examine in this study, since it allows us to evaluate the quality of the bricks. The strength of the construction increases as brick strength increases. The compressive strength test results of the brick samples are shown in Fig. 9. According to our research, adding dry sludge reduces the compressive strength of bricks burned at 600 °C. The control bricks have a compressive strength of 18.06 MPa, but when 5%, 10%, and 15% dry sludge are added, there is a corresponding decrease in strength of 9.41%, 16%, and 14%. The rise in organic matter, which leads to the creation of microcracks, can be used to explain this decline [48].

Figure 9 shows that the bricks' compressive strength was greatly increased by the addition of dry sludge before they were fired at 800 °C. The compressive strengths of the samples containing 5%, 10%, and 15% dry sludge rose by 96%, 55%, and 23%, respectively, in comparison with the reference sample, which had a compressive strength of 16.44 MPa.

The compressive strength of bricks burned at 1000 °C was lower than that of bricks fired at 800 °C; hence, this promise for increased compressive strength was not realised. The reference bricks had a compressive strength of

16.90 MPa, while bricks containing 5%, 10%, and 15% dry sludge had compressive strengths that were 20%, 0.64%, and 0.35% higher than the reference sample.

In summary, the results indicate that the addition of dry sludge can increase the compressive strength of bricks; this improvement depends on the firing temperature of the bricks and the amount of sludge added. Consequently, this increases the potential for sludge valorization in the production of clay bricks. The results obtained are in disagreement with what has been reported in the literature. In effect, all previous studies had shown that there could not be an increase in compressive strength following the addition of sludge from sewage treatment plants. According to Esmeray and Atıs [16]. the addition of 5–15% sludge resulted in a reduction in compressive strength compared to control bricks from 37.7 to 86% when bricks were fired at 900 °C and from 28.55 to 77% for bricks fired at 1050 °C. Liew et al. [10] also found a reduction of 44–70% compared to control bricks when the addition of slurry was 10–40%, respectively, when firing bricks at 985 °C. According to Areias et al. [12], the incorporation of 2.5% mud by mass of clay does not affect the compressive strength, but the incorporation of 10–15% decreases the compressive strength by 23% and 53%, respectively, when fired at 950 °C. However, the study of Zat et al. [19] showed that the incorporation of 2–15% of sewage sludge in the clay mixture does not significantly influence the compressive strength, and the average compressive strength of ceramic bricks fired at 930 °C was 15 2 MPa, regardless of the sludge content. This difference in compressive strength results is attributable not only to the different organic matter contents but also to the physicochemical properties of the sludge considered by Ukwatta et al. [34]. However, according to the results we have obtained, the difference can also be attributed to the nature of the clay used and the interaction of the components of the sludge and the clay used. This is confirmed when the control bricks fired at 800 °C and 1000 °C showed cracks due to the presence of montmorillonite clay, which has a high specific surface area (see Fig. 8 for cracks and Fig. 5 for the presence of montmorillonite), which explains their low compressive strength compared to the bricks incorporated in the sludge of the wastewater treatment plants. The addition of 10% or 15% sludge also results in a reduction in compressive strength, which is still higher than the control. This decrease in strength may be due to the addition of an increased amount of organic matter present in the sludge, which affects the quality of the brick. In addition, the results of the study showed an increase in the compressive strength of bricks fired at 600 °C to 800 °C, but this strength decreases at 1000 °C, whereas it would be expected to increase as temperature increases [16]. This decrease in compressive strength at 1000 °C is mainly due to the increase in porosity.

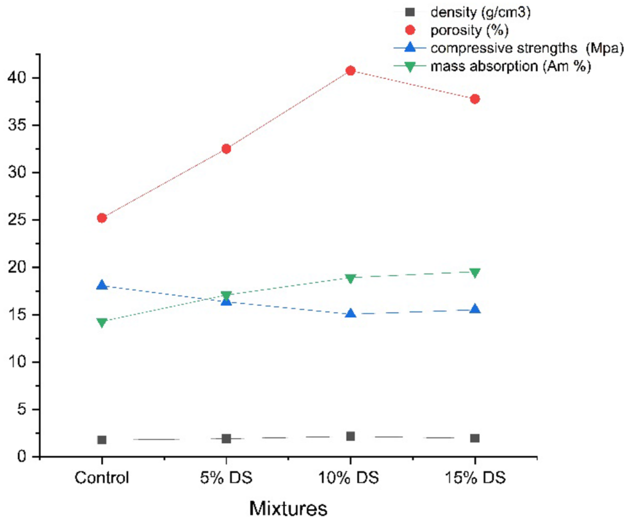


Fig. 10 Brick density "ρ" (g/cm^3), porosity, mass absorption Am (%) and strength (MPa) of bricks fired at 600 °C

Brick density, mass absorption and porosity

The results of measuring the densities (ρ), porosities (ε), mass absorptions (Am%), and compressive strengths of the control bricks and those with 5%, 10% and 15% addition by weight of the clay and fired at 600 °C are shown in Fig. 10.

It is evident from Fig. 10 that the addition of sludge impacted the density (ρ), porosity (ε) and mass absorption (Am %) of the bricks. Porosity increased proportionally with the addition of dried sludge, with an increase of 28%, 61%, and 15%, respectively, for the 5%, 10%, and 15% compositions compared to the control bricks ($\varepsilon = 25\%$). Similarly, mass absorption increased by 19%, 32%, and 36% for the 5%, 10%, and 15% compositions, respectively, compared to the control bricks, which have a mass adsorption of 14.3%. The increase in porosity and mass absorption can be explained by the thermal decomposition of the organic matter. As for the densities of the bricks fired at 600 °C with the addition of 5%, 10% and 15% of dried sludge, they slightly increased by 8%, 22% and 9%, respectively, compared to the control bricks (1.76 g/cm^3). This increase is due to the elimination of a part of the pores following the frittage. No research was found on bricks amended with sludge from sewage treatment plants and fired at 600 °C, however, the work of Lin et al. [49]showed that increasing the firing temperature of bricks with 100% sludge from 600 to 900 °C increased their density, which corroborates with our results. For our bricks with added sludge, the porosity increased compared to the control, inducing a higher mass absorption, which slightly negatively influenced the compressive strengths. However, it should be noted that the results obtained for mass absorption and compressive strength confirm the negative correlation condition (-0.96) between these parameters.

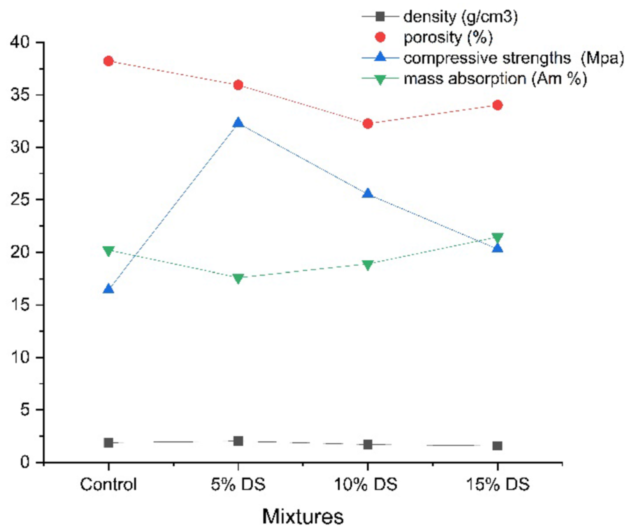


Fig. 11 Brick density "ρ" (g/cm^3), porosity, mass absorption Am (%) and strength (MPa) of bricks fired at 800 °C

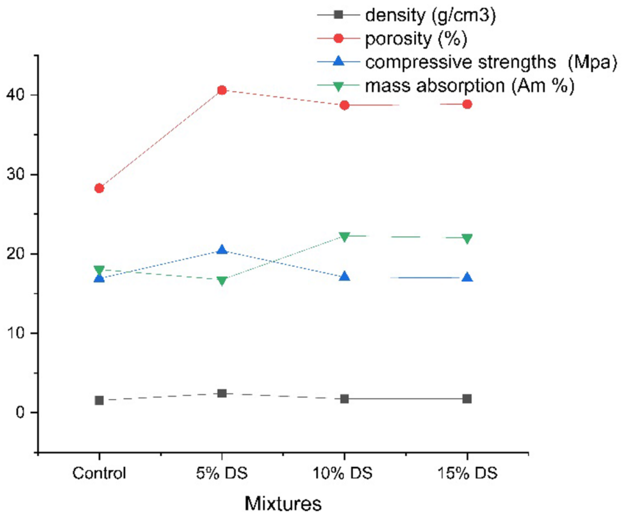
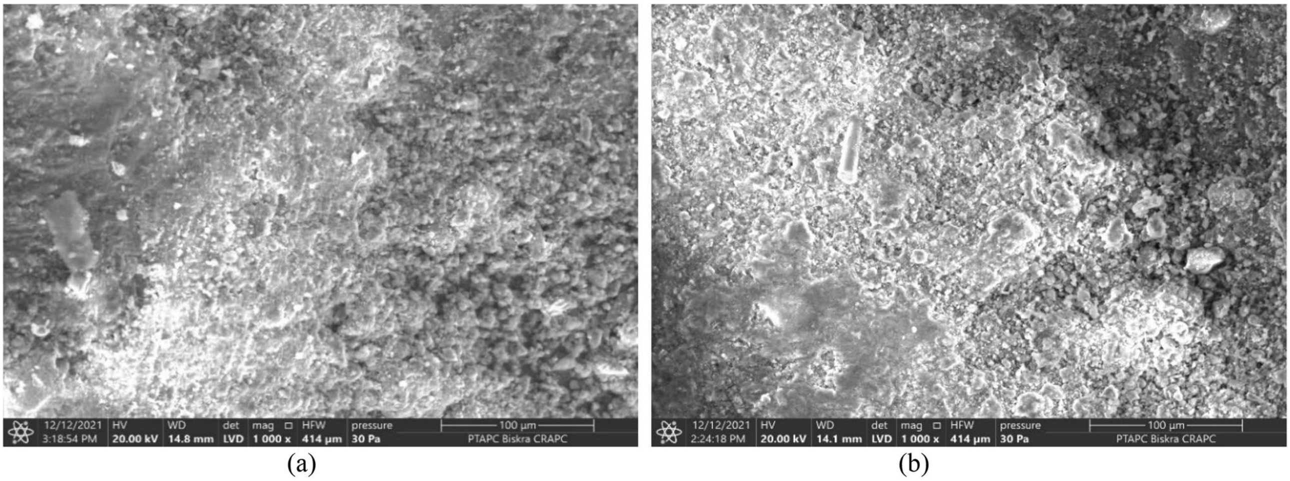


Fig. 12 Brick density "ρ" (g/cm^3), porosity, mass absorption Am (%) and strength (MPa) of bricks fired at 1000 °C

The results observed in Fig. 11 clearly indicate that the incorporation of sludge had a significant impact on the density (ρ), porosity (ε) and mass absorption (Am%) of the bricks fired at 800 °C. In fact, the addition of 5% dry sludge resulted in a 7% increase in the density of the bricks compared to the control bricks, while the addition of 10% and 15% dry sludge by weight of clay resulted in a decrease in the density of the bricks by 10.05% and 16.4%, respectively. The bricks containing 5%, 10%, and 15% dry sludge by weight of clay showed a decrease in porosity compared to the control specimens, with decrease rates of 5.95%, 15%, and 11%, respectively. For mass absorption, it decreased by 12.82% and 6.53% for the 5% and 10% sludge addition compositions, respectively, and then increased by 6.18% for the 15% composition compared to the control bricks. The results obtained for compressive strength confirm the trends observed for density, mass absorption, and porosity. In effect, we notice that the addition of dry sludge positively influenced the compressive strength, which is consistent with the decrease in porosity and mass absorption as well as the increase in density observed for the bricks with the addition of sludge compared to the control bricks. The observed result is closely related to the sintering process, which led to the suppression of some of the pores and resulted in a high density (2.04 g/cm^3) for bricks containing 5% sludge. The decrease in density of the bricks with the addition of 10% and 15% sludge can be explained by the amount of organic matter contained in the sludge, which can potentially be incinerated. The higher the amount of organic matter in the bricks, the greater the porosity and the less noticeable the sintering effect, which leads to a lower density. The high porosity of the control samples may be related to the high amount of CaO and MgO in these bricks compared to bricks containing dry sludge [43]. The results of this study are in opposition to the findings of Weng et al. [30], the only previous research found in the literature on bricks amended with sewage sludge and fired at a similar temperature of 800 °C (880 °C). In this previous study, it was found that the addition of increasing amounts of sludge during firing resulted in a decrease in the density of bricks, an increase in their water absorption capacity, and a reduction in their compressive strength.

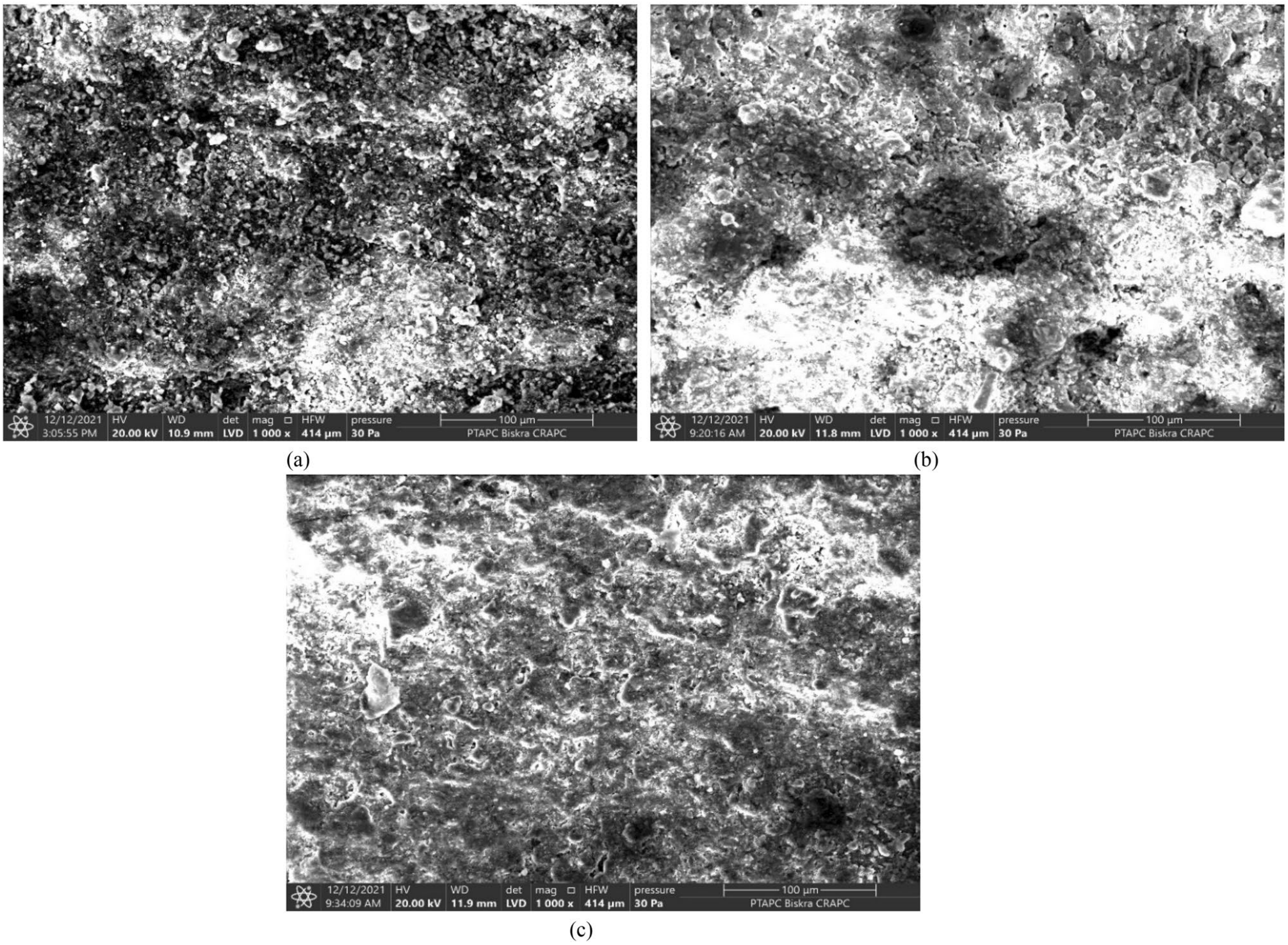
Figure 12 shows the results of measuring densities (ρ), porosities (ε), mass absorptions (Am%), and compressive strengths (MPa) of control bricks with 5%, 10%, and 15% addition to the weight of the clay and fired at 1000 °C.

The addition of 5% dry sludge resulted in a 54% increase in the densities of the bricks fired at 1000 °C compared to the control bricks (1.57 g/cm^3). On the other hand, the addition of 10% and 15% dry sludge only resulted in a density increase of 11% and 12.5%, respectively. Porosity measurements showed an increase of 43%, 33%, and 37% for the additions of 5%, 10%, and 15% dry sludge by weight of clay, which naturally increased the mass absorption by 23.5% and 22% for the 10% and 15% additions, respectively, while the addition of 5% sludge resulted in a slight decrease of 7%. The addition of sludge resulted in a slight increase in the compressive strength of the bricks compared to the control bricks. This trend follows the evolution of density and is negatively correlated with mass absorption. Although porosity increased, it did not impact the mechanical properties of the bricks modified by the addition of sludge. Increases in brick porosity and mass absorption result principally from the decomposition of organic matter and the destruction of



(a) (b)

Fig. 13 Control brick fired at 600 °C × 1000 (**a**), Brick with 5% dry sludge fired at 600 °C × 1000 (**b**)



(a) (b) (c)

Fig. 14 Control brick fired at 800 °C × 1000 (**a**), Brick with 5% dry sludge fired at 800 °C × 1000 (**b**), Brick with 15% dry sludge fired at 800 °C × 1000 (**c**)

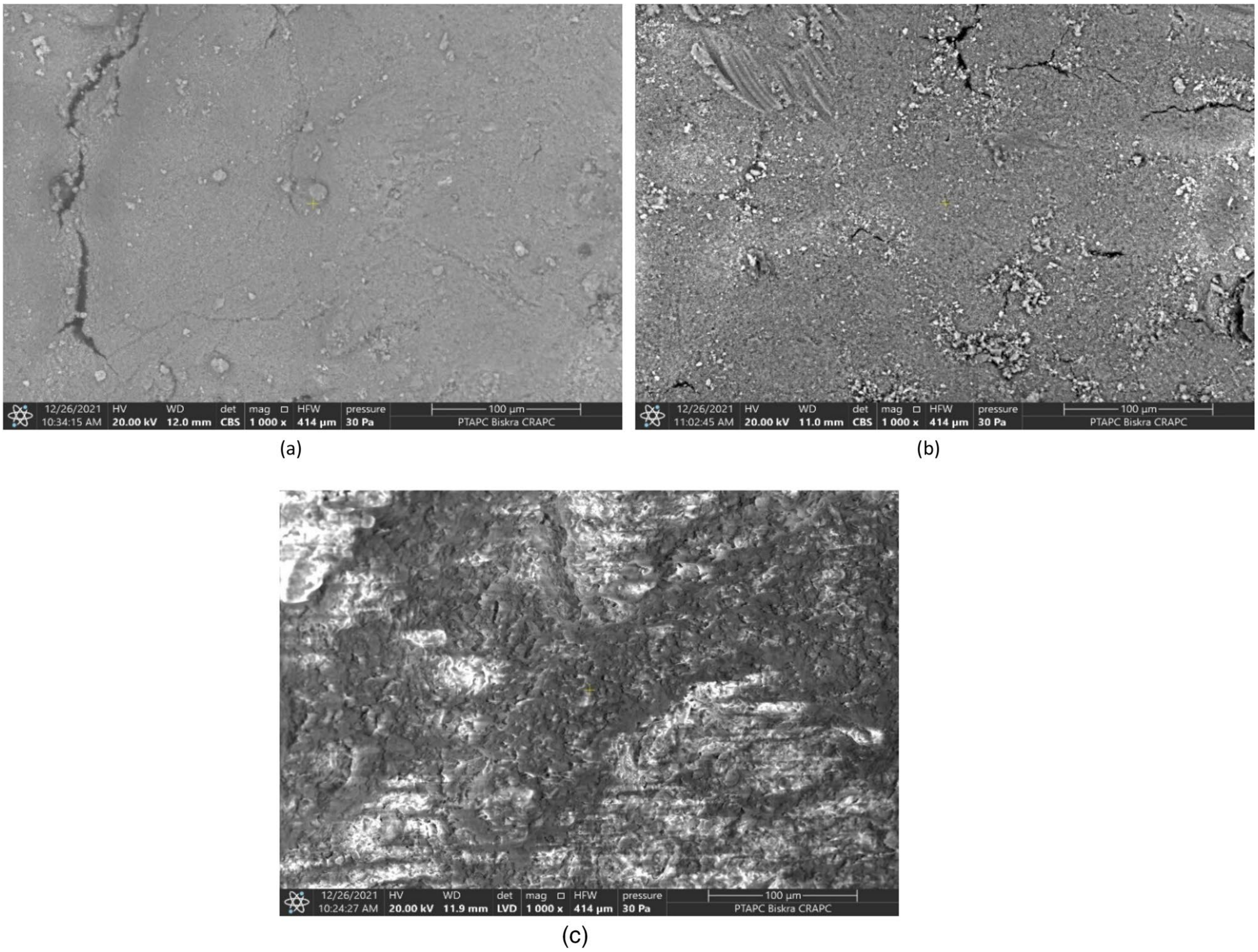


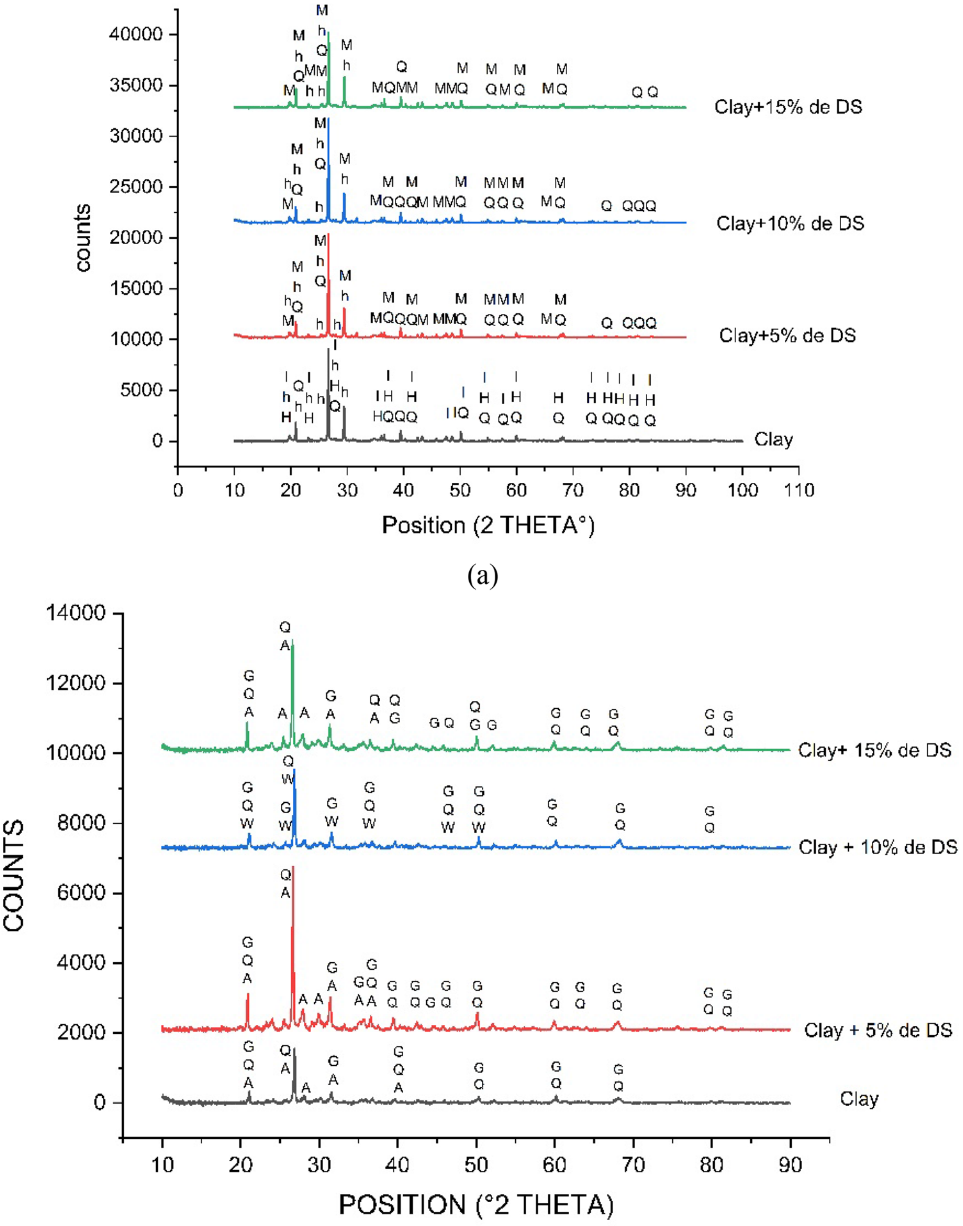
Fig. 15 Control brick fired at 1000 °C × 1000 (**a**), Brick with 5% dry sludge fired at 1000 °C × 1000 (**b**), Brick with 15% dry sludge fired at 1000 °C × 1000 (**c**)

calcite. This result is in accord with the results obtained by Zat et al. [19], who showed an increase in the density of bricks fired at 930 °C by 4% over control bricks when 2% sludge by weight of clay was added, followed by a decrease of 3%, 15%, and 14.9% with the addition of 5%, 10%, and 15% dry sludge, respectively. Although the addition of dry sludge resulted in a significant increase in mass absorption ranging from 1 to 70% compared to the control samples for additions of 2–15% sludge by weight of clay, it should be noted that the modified bricks showed a slight improvement in compressive strength. Moreover, the works of [10, 11, 16, 31, 34] have all shown that the addition of sludge to brick clay leads to an increase in porosity and mass absorption but negatively affects compressive strength. However, these studies were conducted at firing temperatures ranging from 900 to 1150 °C.

It should also be noted that during the firing of bricks at a temperature of 1000 °C and in the presence of added dry sludge, the formation of a white film on the surface of the bricks increases proportionally to the amount of sludge added. This negative phenomenon is attributable to the presence of sulphates detected by XRD (see Fig. 5) in the sludge, which migrate to the surface of the bricks during drying [47].

Morphology of bricks design with sludge

The SEM images of the control brick specimen and the brick specimen containing 5% of dry sludge fired at 600 °C are shown in Fig. 13a, b, respectively. The results show that compared to the bricks containing 5% dry sludge (Fig. 13b), the grains in the control specimen are denser (Fig. 13a), and



(a)

(b)

Fig. 16 XRD of bricks fired at 600 °C (**a**) (Q: Quartz; M: Montmorillonite; H: Halloysite; h: Hatrurit; I: Illite), XRD of bricks fired at 800 °C (**b**) (A: Anorthite; G: Gehlénite; Q:Quartz; W:Wolastonite)

the porosity is more visible, which can justify the compressive strength results.

The structural evolution of the bricks fired at 800 °C shows that the vitreous part persists according to the addition of sludge. Figure 14a shows that the clay grains in the control specimens are dispersed compared to those of the bricks containing 5% (Fig. 14b) and 15% (Fig. 14c) of dry sludge, which are more welded following the appearance of the liquid phase. This could justify the results of density and the high compressive strength with the addition of sludge as well as the decrease in porosity.

The SEM images of the bricks fired at 1000 °C show that the control bricks have a denser structure with a rather smooth appearance with large open cracks (Fig. 15a) compared to the bricks containing 5% dry sludge which have a rough appearance with much fewer open cracks (Fig. 15b). This can be justified by the fact that the addition of 5% dry sludge increases porosity. The Bricks containing 15% dry sludge have a crystalline appearance and the liquid phase is visible without cracks (Fig. 15c).

The SEM images of the bricks fired at 800 °C and 1000 °C showed that the sludge had a degreasing effect

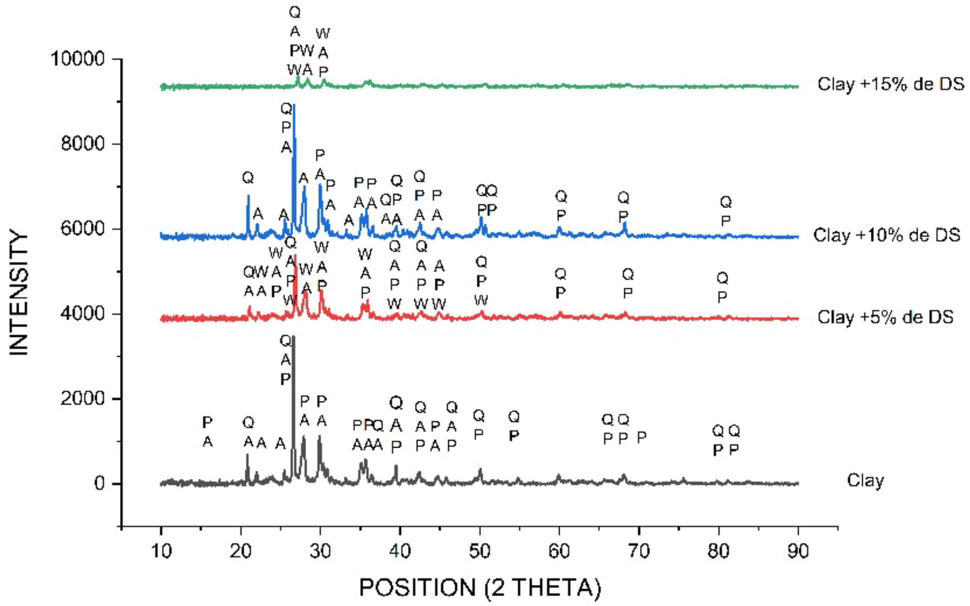


Fig. 17 XRD of bricks fired at 1000 °C

due to the appearance of the liquid phase, which reduces shrinkage. This was confirmed by the coarse grain size of the sludge compared to the clay. The results of this study are in opposition to the findings of Esmeray and Atıs [16], In this previous study, it was found that the addition of increasing amounts of sludge during firing disrupts clay brick, the glassy structure cannot occur, the sintering decreases.

X-ray diffractograms of control bricks and bricks with sludge

The X-ray diffractogram analysis of the control bricks and the bricks containing 5%, 10% and 15% dry sludge by weight of clay fired at 600 °C are shown in Fig. 16a. The results show that the majority of the phases contained in these bricks are those initially contained in the clay and sludge. There was no formation of new crystalline phases; which is probably due to the insufficient firing temperature. This has influenced the compressive strength results after the addition of the sludge.

The XRD analysis of the control bricks and the bricks containing 5% and 15% of dry sludge by weight of the clay fired at 800 °C (Fig. 16b) shows the presence of residual quartz phases and the appearance of new phases. The Gehlinite and Anorthite as a result of the reactions of decomposed CaO, and Illite from the clay decomposed during the firing process [50]**,** whereas the bricks with the addition of 10% dry sludge by weight of the clay, show the appearance of Wollastonite with the disappearance of Anorthite.

Compared to the control bricks, it appears on the X-ray diffractograms (XRD) that the bricks with 5% dry sludge addition, fired at 800 °C (Fig. 16b) show more lines and intensity of quartz, gehlenite and anorthite. For bricks with 10% and 15% addition, these lines and intensity decreased, this can justify the increase in compressive strength when adding 5% of dry sludge.

For bricks fired at 1000 °C, their XRD patterns showed the disappearance of Gehlinite and the formation of pyroxenes (Fig. 17). Large quantities of wollastonite were detected in the bricks containing 5% dry sludge by weight of the clay, while small quantities were detected in those containing 15% dry sludge. It is also observed that the amounts of quartz for all bricks decreased to form Anorthite, which becomes the majority [50, 51].

According to [51],the formation of wollastonite leads to a heterogeneous structure at the points of contact between the quartz and the lime. It has been observed that a large quantity of wollastonite is formed (84%) in the bricks containing 10% of dry sludge fired at 800 °C. This can justify the decrease in the compressive strength of these bricks compared to those containing 5% of dried sludge that has not had the formation of wollastonite.

Wollastonite also appeared in bricks containing 5% of dried sludge and firing at 1000 °C (50%) which in principle leads to a decrease in compressive strength compared to control bricks; however, the compressive strength has increased compared to the control this is justified by the degreasing effect played by the addition of sludge as shown in Fig. 15 which has reduced the large cracks that appeared in the brick control hence the increase in compressive strength compared to the control brick.

Conclusion

The following conclusions can be drawn from this study:

- The chemical and mineralogical compositions, as well as the firing temperature, are the parameters that determine the final product characteristics.
- At 600 °C, the compressive strength decreased with the increase of the amount of dry sludge, this is due to the non-development of the crystalline structure for the reason of the low firing temperature as proved by the XRD result; whereas, at 800 °C, an increase in density and compressive strength is noticed, while the shrinkage decreased especially for brick specimens containing 5% of dry sludge.
- At 1000 °C, the compressive strengths dropped due to the appearance of large shrinkage cracks, but the addition of sludge had shown a beneficial effect on the brick confirmed by SEM images, which significantly reduced shrinkage and improved compressive strength, particularly for bricks containing 5% sludge to weight ratio of clay.
- The results of this research show that the sludge from the Barraki WWTP can be reused in the manufacture of swelling clay bricks with a percentage of 5% of dry sludge, which is the perfect amount for improving compressive strength, saving in firing energy (800 °C) and having a less cracked external appearance due to its role as a degreaser instead of sand.
- This alternative to landfill will have an undeniable impact on the environment in addition to the economic impact. Indeed, the cost of landfilling is reduced.

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Declarations

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

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