

## Article

# The Effect of Organic Lake Sediments (Sapropel) on the Properties and Biological Resistance of Unfired Clay Bricks

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**Abstract:** Clay materials were prepared with clay and sapropel (SP) or clay and modified (frozen) sapropel (FSP) as the main raw materials. Clay-based materials were formed by mixing clay with a different dosage of SP or FSP (5–30 wt.%). The effect of SP or FSP on the properties and biological resistance of clay-based materials was studied. The results show that the bulk density of clay-based materials decreased, and the compressive strength and initial rate of water absorption increased with the increase in the SP or FSP amount in the clay mixture. Research has shown that SP or FSP can be added as a natural additive containing microfibers to improve the mechanical properties of clay materials. When clay bricks had less than 15% sapropel, dry or frozen, we tested the resistance impact of the fungi *Rhodotorula mucilaginosa*, *Stachybotrys chartarum*, *Cladosporium cladosporioides*, and *Aureobasidium pullulans* under normal conditions.

**Keywords:** clay; sapropel; frozen sapropel; water absorption; durability; biological resistance



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## 1. Introduction

Due to current global concerns about sustainable development, interest in natural building materials such as unfired clay materials has developed. Unfired clay materials have a record of accomplishment as being sustainable as they are a natural material with less embodied energy with minimal emission of CO<sub>2</sub> [1–7]. Using unfired clay materials has several sustainability advantages: (1) unfired clay materials are made from abundant and locally available raw materials, reducing the need for transportation and minimizing the environmental impact associated with extracting and transporting building materials; (2) the production of unfired clay materials generally requires less energy compared to other building materials [1,8]; (3) such materials have good thermal/hygroscopic properties, helping to regulate indoor humidity and temperatures, and this can contribute to energy efficiency [9–13]; and (4) unfired clay materials are biodegradable, meaning that at the end of their life cycle, they can return to the environment without causing long-term harm [14–16]. To meet increasingly rigorous requirements, the demand for natural building materials is growing rapidly, and the building materials industry must adapt to the use of materials of lower environmental impact.

Clay raw materials play an important role in the development of environmentally/eco-friendly building materials. In many regions of Europe, there are significant reserves of clay and sapropel (SP). SP is an organic material with a colloidal structure formed over thousands of years at the bottom of lakes from the remains of aquatic animals and plants. There are about 10 billion m<sup>3</sup> of sapropel in the lakes and swamps of Lithuania. According to data from the Lithuanian Geological Service, the forecasted resources of sapropel amount to 152,886 thousand m<sup>3</sup>. New technologies allow for the acquisition of SP in various forms:

dry, frozen, or granulated. From this point of view, SP is a promising material for use in the building and construction industries.

Latvian researchers investigated the properties and sound absorption characteristics of composite materials made from sphagnum moss, flax fiber, vermiculite, and SP as a binder [17]. They demonstrated that the compressive strength of such composite materials was 0.1–0.29 MPa, whereas their bending resistance ranged between 0.2 and 0.42 MPa. According to their data, composite materials created with an SP binder had good sound absorption results.

Also, it was demonstrated that composite materials that were made using hemp shives and SP had exceptional thermal and acoustic properties [18–20]. The compressive strength of such composites was 0.61–0.28 MPa, whereas their density was 210–410 kg/m<sup>3</sup>. The lower-density composites best absorb the waves of 300–600 Hz frequency because sound absorption exceeds 0.5 for this frequency range [18]. Vėjelis et al. [21] developed a thermal insulation biocomposite from sapropel and wood processing waste with lower thermal conductivity (0.0612 to 0.0659 W/(mK), and its compressive stress values varied from 0.414 to 1.051 MPa. The bulk density of such a biocomposite was 300 kg/m<sup>3</sup>.

SP can be used in the production of cement–concrete mixtures for road construction. The results showed that the compressive strength of mixtures containing 5% SP was 28% higher. The increased compressive strength can be explained by the accelerated hydration of the three-calcium silicate of the cement when SP is added [22]. Also, modified SP (SP + zeolite) accelerates the hydration of Portland cement [23]. The effect of SP on the thermal properties of clay soil was examined by Navickas et al. [24]. The authors found that adding about 1–2% (*w/w*) SP decreases the thermal conductivity of clay soil samples by 18–30%. The effect of SP on expanded clay properties was examined by Vaickelionis et al. [25]. The bloating coefficient of expanded clay was improved when the SP proportions were limited (not more than 5%). Expanded clay samples with 5% (*w/w*) SP had water absorption of no more than 20%.

Sapropels are rich multicomponent biogenic systems of organic elements that are made by microorganisms during the eutrophication process in lakes. Such processes play an important role in organic decomposition, the nutrient cycle, and intestinal food networks and generally affect several processes of the overall water system [26,27]. Therefore, it can be expected that the wet sapropel, which may contain living microorganisms, could influence the tested materials. Because the samples were made of two components—sapropel and clay—it is important to emphasize that the pH of clay is usually between 8 and 10 [28]. This pH range does not support microorganism growth [29,30]. Therefore, in this work, we produced clay bricks with two types of sapropels, wet and frozen ones.

There are few studies that use SP in the production of building materials. We believe that it is worth paying attention to this natural material and its use in industry. Therefore, this study assesses the potential of sapropel (SP) and its modified form—frozen sapropel (FSP)—as a clay material component. We also tested the structure, physical properties, and biological resistance of such materials. SP and FSP are easy to incorporate into mixtures to achieve the desired properties. The incorporation of a higher amount of SP or FSP in manufacturing lightweight clay bricks yielded higher compressive strength compared with clay samples without the addition of SP and FSP.

## 2. Materials and Methods

### 2.1. Materials

Clay was collected from a brick manufacturer located in Lithuania (Figure 1). The clay was dried at 65 °C and 105 °C for 12 h and passed through a 1.25 mm sieve. The chemical and granulometric compositions and Atterberg limits of the clay are shown in Table 1. The bulk density of the clay is 1.14 g/cm<sup>3</sup>.

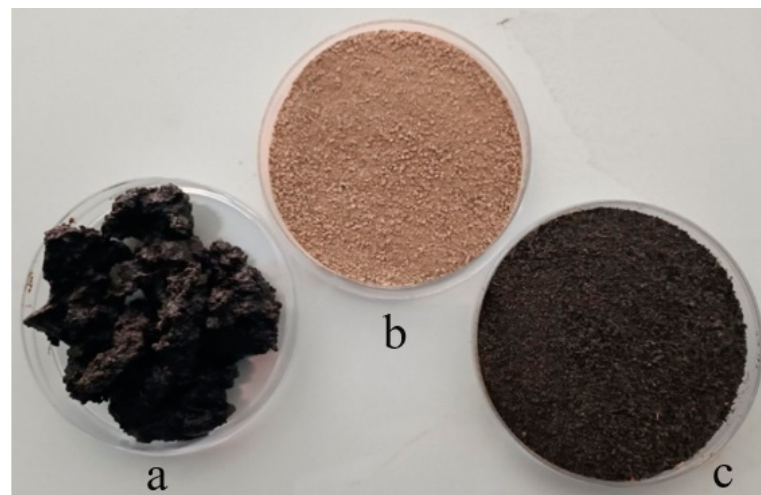


**Figure 1.** Images of the materials: (a) SP, (b) clay, and (c) FSP.

**Table 1.** Chemical and granulometric compositions and Atterberg limits of the clay.

| Chemical Composition, %        |       | Granulometric Composition, % |       | Atterberg Limits |          |
|--------------------------------|-------|------------------------------|-------|------------------|----------|
| SiO <sub>2</sub>               | 48.76 | >50 µm                       | 3.27  | Liquid limit, %  | 34 ± 0.2 |
| Al <sub>2</sub> O <sub>3</sub> | 16.26 | 50–10 µm                     | 13.50 | Plastic limit, % | 16 ± 0.1 |
| TiO <sub>2</sub>               | 1.17  | 10–5 µm                      | 16.18 | Plasticity index | 18 ± 0.1 |
| Fe <sub>2</sub> O <sub>3</sub> | 5.53  | 5–1 µm                       | 24.44 |                  |          |
| CaO                            | 9.87  | <1 µm                        | 42.51 |                  |          |
| MgO                            | 4.57  |                              |       |                  |          |
| K <sub>2</sub> O               | 2.24  |                              |       |                  |          |
| Na <sub>2</sub> O              | 0.42  |                              |       |                  |          |
| Loss on ignition               | 11.18 |                              |       |                  |          |

The organic lake sediment used, sapropel (SP), was obtained from Gervinio Lake in the Druskininkai region, Lithuania (Figure 1). The color of SP is black–brown, and it has a very weak odor (of wet soil). The characteristics of SP are presented in Table 2. SP contains more than 80% organic matter and less than 20% ash [31,32]. The bulk density of SP is 0.68 g/cm<sup>3</sup>, whereas that of the skeleton is 0.47 g/cm<sup>3</sup>. The electrical conductivity of SP is estimated to be 6.18 mS/m.

Modified (frozen) sapropel (FSP) was also used in this study. The method used comprises the filtering of SP, freezing the filtered SP droplets, assembling the frozen SP droplet mass, defrosting them, removing the formed water, and drying the SP. The biocolloidal internal links of water and other material complexes are destroyed via the formation of sapropel droplets into snowflake crystals. After melting said crystals, the biocolloidal links do not recover [33]. The dynamics of the freezing of SP allows one to recognize the following stages of physicochemical and texture-forming processes: free water crystallization laws govern texture formation; the forming of an ice skeleton causes the directed growth of ice crystals; thicker ice crystals force units of the organo-mineral skeleton apart, thus deforming and compressing it; the compression of the SP skeleton is accompanied by dehydration; the desiccation of the SP skeleton activates the aggregation and coagulation of the organo-mineral component; and the high content of the organic component showing high adhesive characteristics in SP causes mineral particle binding in organo-mineral aggregates [34].

**Table 2.** Characteristics of SP.

| Characteristics                        | Results |
|----------------------------------------|---------|
| pH                                     | 6.6     |
| Moisture content (drying at 105 °C), % | 95.41   |
| Dry matter, %                          | 4.6     |
| In dry matter:                         |         |
| Total nitrogen, %                      | 4.5–6.7 |
| Organic matter (fired at 500 °C), %    | 85.7    |
| Content of ash, %                      | 14.1    |
| Content of humic acids, %              | 1.83    |
| Content of fluvic acids, %             | 0.44    |
| CaO, %                                 | 1.59    |
| Fe <sub>2</sub> O <sub>3</sub> , %     | 0.6     |
| SiO <sub>2</sub> , %                   | 7.43    |
| K <sub>2</sub> O, %                    | 0.38    |
| P <sub>2</sub> O <sub>5</sub> , %      | 0.1     |
| Al <sub>2</sub> O <sub>3</sub> , %     | 0.71    |
| SO <sub>3</sub> , %                    | 1.34    |
| CO <sub>2</sub> , %                    | 0.76    |
| C (organic), %                         | 42–48   |
| SiO <sub>2</sub> /CaO, %               | 4.13    |
| Na, mg/kg                              | 42      |
| F, mg/kg                               | 3.59    |
| Zn, mg/kg                              | 38.76   |
| Cu, mg/kg                              | 5.88    |
| Mn, mg/kg                              | 4.1     |
| Se, mg/kg                              | <0.1    |
| Mg, mg/kg                              | 54      |

The dry matter content in the FSP is 22.27%, and the pH is 8.8. The FSP was passed through a 1.25 mm sieve. The bulk density of the FSP obtained was 0.25 g/cm<sup>3</sup>, whereas the skeleton density of the FSP was 0.42 g/cm<sup>3</sup>.

The clay, SP, and FSP surface morphology are shown in Figure 1. Clay has been found to have a diverse composition of particle sizes. The mica grains flanked particles of the fine clay fraction. The 0.5–1.5 µm mica particles exhibit irregular edges and pointed extremities. The shape of the other particles is round or elongated. The size of the particles is from 1 µm to 5 µm. Also, the SEM picture (Figure 2a) reveals voids with a width down to about 3 µm.

SP consists of different particles; the structure is heterogeneous. Some SP particles are discrete, about 20 µm round, dense particles. There are also some in the form of 2–5 µm thick strips and 100–150 µm in length (Figure 2b,c). The FSP particles are discrete, about 20–30 µm round, with some being dense and some being rough. Also, some are in the form of stringy, filamentous particles, with them being 0.3–0.5 µm thick and about 10–20 µm long. Such a stringy feature is observed between coarse particles (Figure 2e). Also, there are 20–100 µm long strips (Figure 2d).

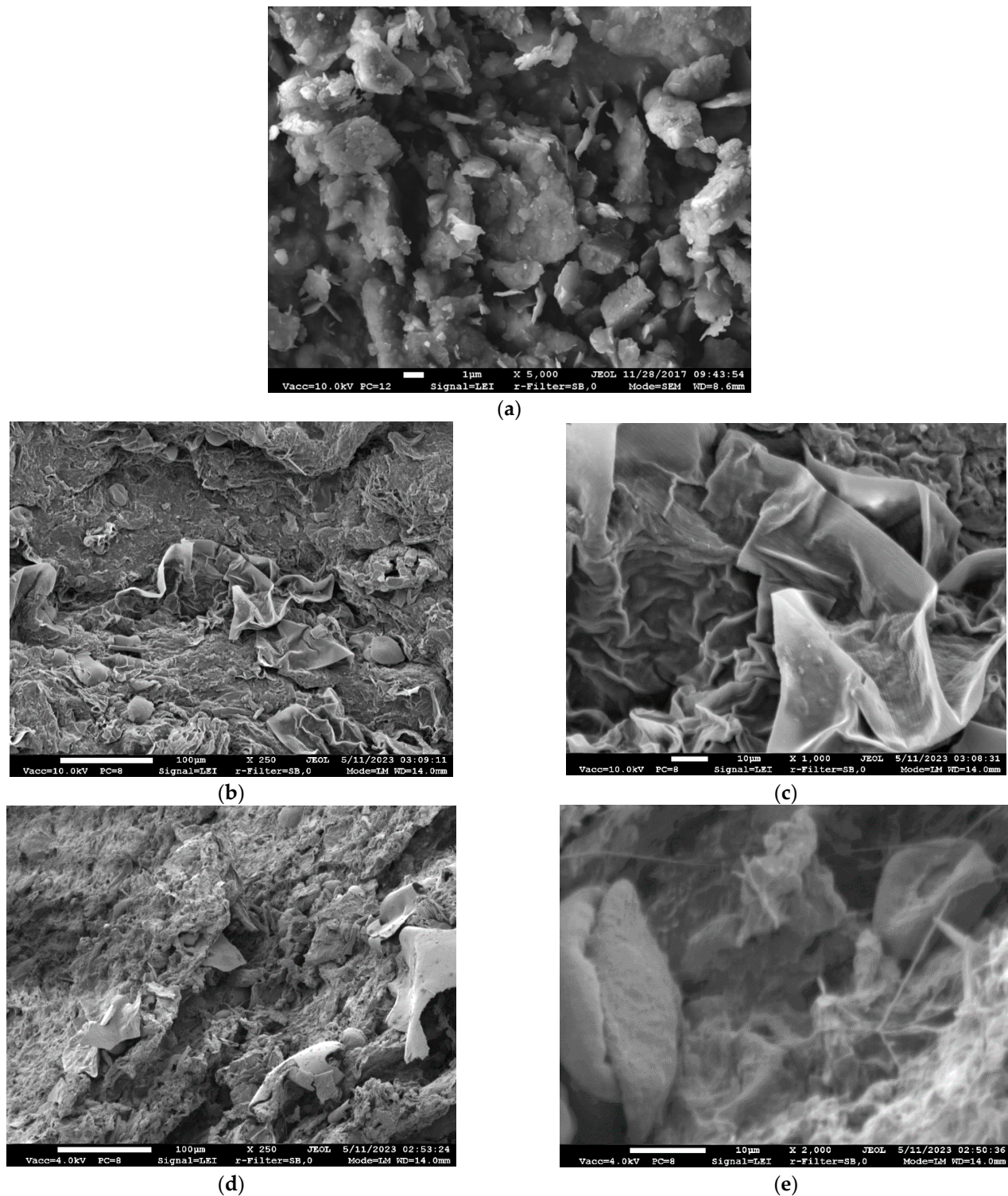


**Figure 2.** The structure of clay (a), SP (b) and (c), and FSP (d) and (e).

## 2.2. Methods

Firstly, a dry mixture was prepared after mixing clay and sapropel (clay and SP) and clay and frozen-thawed sapropel (clay and FSP) in different dosages. Five different mixtures (clay + SP and clay + FSP) were generated by adding increasing dosages of SP or FSP (0%, 5%, 10%, 15%, 20%, and 30% of SP or FSP by weight) (Table 3). Later, water (22.0–6.0%) was added, and the mixture was left for 12 h. Additional water was not added to the clay mixtures with 20% SP (mixture code SP20) and 30% SP (mixture code SP30)

because the moisture content of the SP was 95% (please see Table 2). Afterward,  $60 \times 30 \times 18$  mm clay samples were prepared. The samples were formed under a pressure of 5 MPa. The clay samples were dried in the laboratory (20–22 °C; humidity 50–65%) for 14 days.

**Table 3.** The mixtures and plasticity of the clay samples.

| Mixture Code | Clay Content, % | Sapropel Content, % | Water Content, % | Mixture Plasticity, % |
|--------------|-----------------|---------------------|------------------|-----------------------|
| SP0          | 100             | 0                   | 22               | 16–18                 |
| SP5          | 95              | 5                   | 16               |                       |
| SP10         | 90              | 10                  | 11               |                       |
| SP15         | 85              | 15                  | 6                |                       |
| SP20         | 80              | 20                  | -                |                       |
| SP30         | 70              | 30                  | -                |                       |
| FSP5         | 95              | 5                   | 22               |                       |
| FSP10        | 90              | 10                  | 22               |                       |
| FSP15        | 85              | 15                  | 22               |                       |
| FSP20        | 80              | 20                  | 22               |                       |
| FSP30        | 70              | 30                  | 23               |                       |

Plasticity is a fundamental property in the processing of clay-based materials since it defines the technical parameters to convert a clay mixture into a given shape by the application of different pressures. A plasticity of 16–18 is desirable for the production of clay products [35–37].

The evaluation phase of the clay samples entailed the testing of physical–mechanical properties including shrinkage, bulk density, compressive strength, and the initial rate of water absorption. Also, the evaluation phase entailed testing of the structure and biological resistance.

The raw materials and specimens that were used were analyzed by means of scanning electron microscopy (SEM). We used a JSM-7600F device (JEOL, Tokyo, Japan), with 10 kV and 20 kV voltage; at a 7–10 mm distance from the sample surface, the surface of the specimens under testing was covered with gold. The chemical compositions of the materials were determined using X-ray fluorescence (XRF-WD). A ZSX Primus IV spectrometer (Rigaku Corp., Tokyo, Japan) equipped with an Rh tube with an anode voltage of 4 kV was employed. Tablet-shaped samples with a diameter of 37 mm were prepared and compressed at 200 kN for analysis. The water content and organic matter of the SP and FSP were determined according to EN 12570 [38] and EN 13820 [39], respectively. The shrinkage, bulk density, and compressive strength of the specimens were determined according to the ASTM C326-09 (2014) [40], LST EN 772-13:2000 [41], and LST EN 826:2013 [42] standards, respectively. The Atterberg limits of the mixtures were determined according to the ASTM D4318 standard [43]. The initial rate of water absorption was determined according to EN 772-11:2011 (E) [44].

Biological resistance was determined according to LST EN 15457:2022 [45]. The fungi *Rhodotorula mucilaginosa* DSM 70825, *Stachybotrys chartarum* DSM 2144, *Cladosporium cladosporioides* DSM 19653, and *Aureobasidium pullulans* DSM 3042 were incubated on the PDA (VWR BDH Chemicals, Darmstadt, Germany) media for 10–21 days for sporulation; then, these spores were collected in 20 mL of 0.9% NaCl and diluted to 106 units/mL. The suspensions of microorganisms were mixed in equal parts, and then, 1 mL of this mix was poured onto two of the samples: SP0–SP30, and FSP5–FSP30. These samples with the microorganisms were incubated for 3 weeks in a Memmert thermostat at 22 °C and 65% humidity. Images were taken every week.

### 3. Results and Discussion

A clear decrease in bulk density was observed with increasing SP or FSP content (Figure 3). The decrease in bulk density with increasing SP or FSP content is a result of the lower density of the SP or FSP compared to the clay density. The additives

of organic matter make it possible to obtain clay samples with a lighter, more porous structure [3,46–53]. It should be mentioned that the modification of bulk density during stabilization with natural additives can have a high impact on the material's mechanical and thermal properties [48,49,53–56]. Authors [53] reported that corn plant and fescue additives can improve the flexural strength of adobe bricks by 89% and 26%, respectively. Ghavami et al. [57] studied the effect of sisal and coconut fibers on the behavior of soil. The inclusion of 4% sisal or coconut fibers increased the compressive strength from 1.5 MPa to 2.0 MPa. Yetgin et al. [58] addressed the incorporation of straw fibers into adobe bricks. The results showed that as the fiber content increased from 18.8% to 51.5%, the bulk density decreased from 1.83 to 1.43 g/cm<sup>3</sup>, and the compressive strength decreased in some cases from 3.5 MPa to 1.0 MPa. Millogo et al. [46] investigated the effect of vegetable fiber—Hibiscus cannabinus—on adobe bricks. The results showed that the incorporation of 0.2–0.6 wt.% of 30 mm long Hibiscus cannabinus fibers reduced the thermal conductivity from 1.67 W/(m·K) to 1.30 W/(m·K) of adobe bricks and increased the flexural strength from 0.5 MPa to 1.1 MPa.

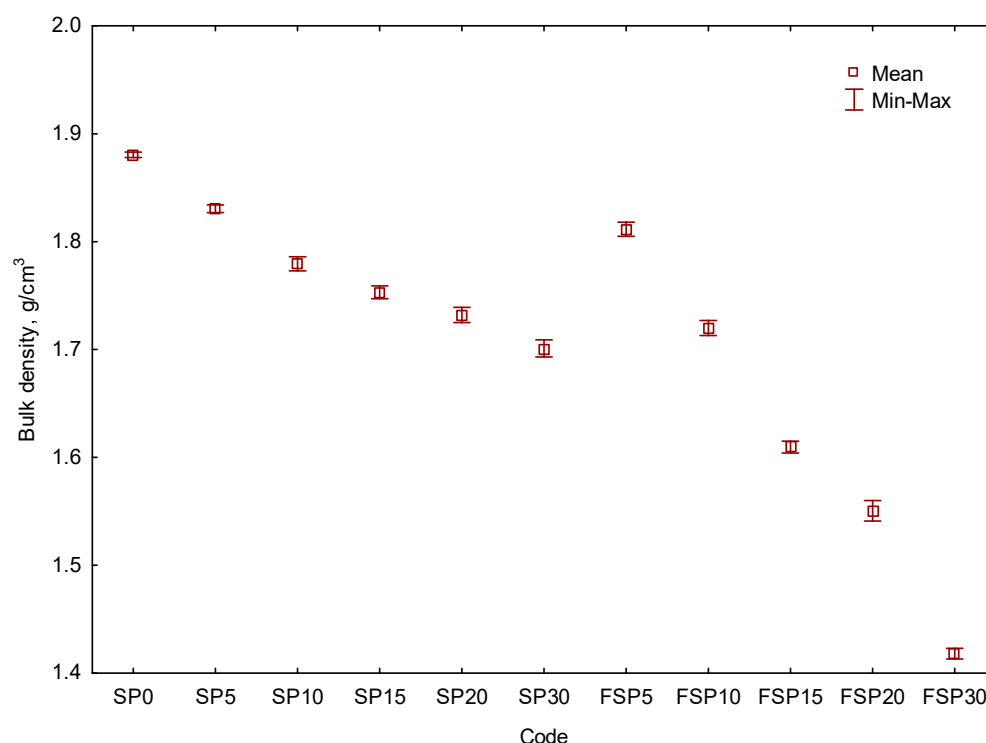


**Figure 3.** Bulk density of the clay samples.

The bulk density value of the SP5–SP30 samples varied from 1.7 g/cm<sup>3</sup> to 1.83 g/cm<sup>3</sup> and that of the FSP5–FSP15 samples varied from 1.42 g/cm<sup>3</sup> to 1.81 g/cm<sup>3</sup>. The results showed that adding 5–30% SP (SP5–SP30 samples) decreased the density by 2.7–9.5% compared to the control sample (SP0 sample); also, adding 5–30% FSP (FSP5 and FSP15 samples) decreased the density by 3.7–24.5% compared to the control sample (SP0 sample).

The compressive strength increased when the 5–30% SP or 5–30% FSP content increased (Figure 4). The results showed that adding 5–20% SP (SP5–SP30 samples) increased the compressive strength by 8.8–19.9% compared to the control sample (SP0 sample); also, adding 5–15% FSP (FSP5 and FSP15 samples) increased the compressive strength by 8.7–22.1%. As the SP or FSP content is further increased, the compressive strength decreases somewhat.

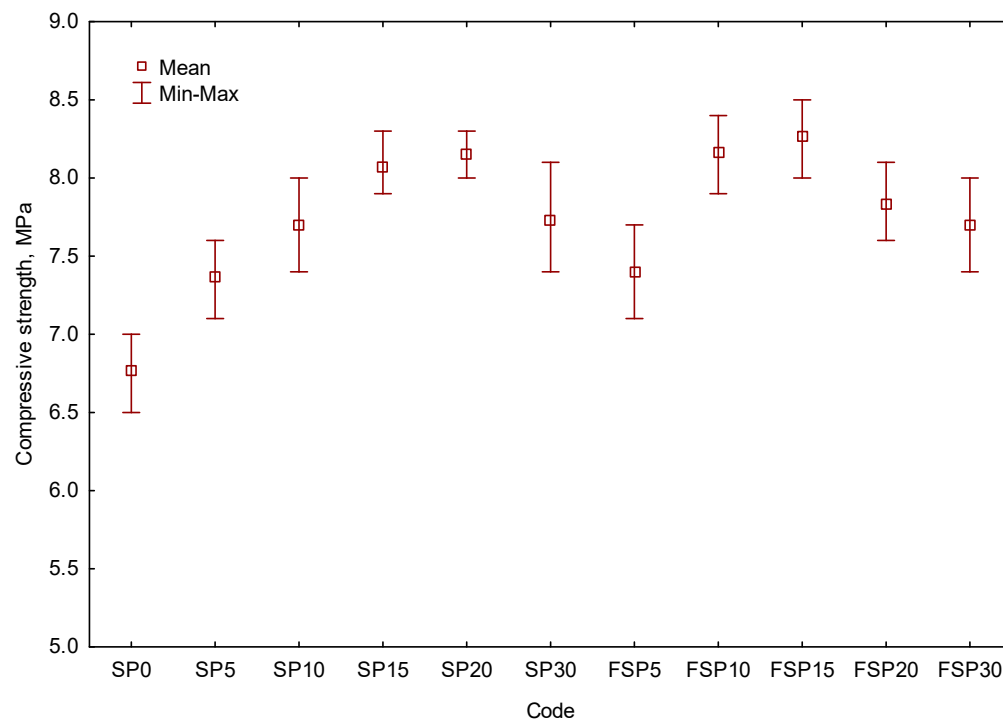


**Figure 4.** Compressive strength of the clay samples.

Different research studies have shown that the compressive strength of Earth materials can be improved by using natural additives [59–61]. Natural additives generally include hemp, sugarcane bagasse, rice husk, straw, wool, coconut fibers, etc. [2,62–71]. The authors attributed the reason for the increase/decrease in the compressive strength of the clay materials modified with different proportions of natural additives to the better/worse adhesion of the soil matrix with natural additives [55,65].

Our research shows that SP or FSP can also be added as a natural additive containing microfibers (long strips with filamentous particles of SP, Figure 2b,c, and long stringy, filamentous particles of FSP) to improve the mechanical properties of clay materials. The reason may be the redistribution of internal forces from the clay matrix to the “reinforcing natural microfibers”. It should be mentioned that according to the DIN 18945 (2013–08) standard [66], all clay samples with SP and FSP additives belong to the highest Earth bricks class 5 (EB5) because their compressive strength is more than 6.3 MPa.

Figure 5 shows the shrinkage for different samples. The shrinkage value varies from 7.8% to 11.5% for the SP5–SP30 samples and from 6.8% to 9.0% for the FSP5–FSP30 samples. The shrinkage of the control sample is 6.3%. The shrinkage increases with the increase in SP or FSP content in clay mixtures, and it is at its maximum at 30% SP (the shrinkage of the SP30 sample is 11.5%) and its minimum at 5% FSP (shrinkage of the FSP5 sample is 6.8%). Samples FSP5–FSP10 (90–95% clay + 5–10% FSP) and the control sample had no significant difference in their shrinkage results. However, samples SP5–SP30 and FSP20–FSP30 had significant differences because the shrinkage of the SP5 and FSP samples was about 6.5% and the shrinkage of the SP30 and FSP samples was 11.5% and 9.0%, respectively. However, sufficiently high shrinkage did not cause the specimens to crack. The authors [67] reported that the shrinkage should not be above 12% for samples in order to obtain dried bricks without cracking.

The highest water content in the SP20 and FSP30 mixtures (Table 3) causes the highest shrinkage. Organic, porous materials absorb water quickly and release water more easily during the drying process [68,69]. Thus, samples with SP or FSP show higher shrinkage than control clay samples after drying.

The initial rate of water absorption tests demonstrated that as the SP or FSP percentage in the samples increased, the capillary water absorption was higher compared to the control clay

sample (Figure 6). This is because the SP and FSP are organic porous matter and have higher absorption of water than clay. The results showed that adding 5–30% SP increases the initial rate of water absorption by 5.3–40.4% compared to the control sample. Also, adding 5–30% FSP increases the initial rate of water absorption by 8.7–49.1% compared to the control sample.

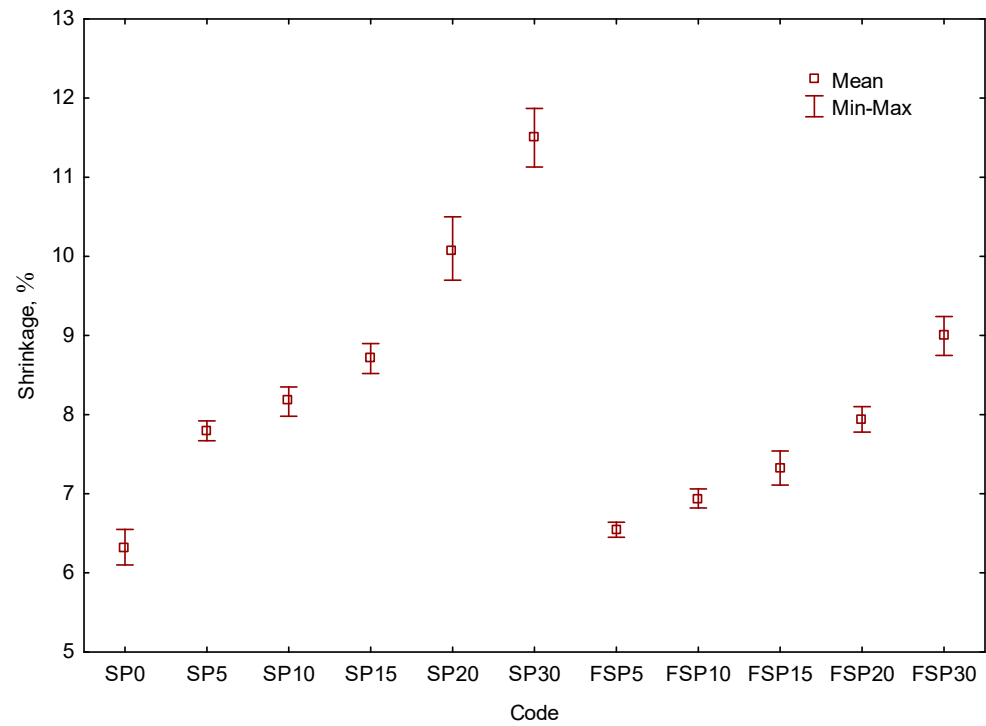


**Figure 5.** Shrinkage of the clay samples.

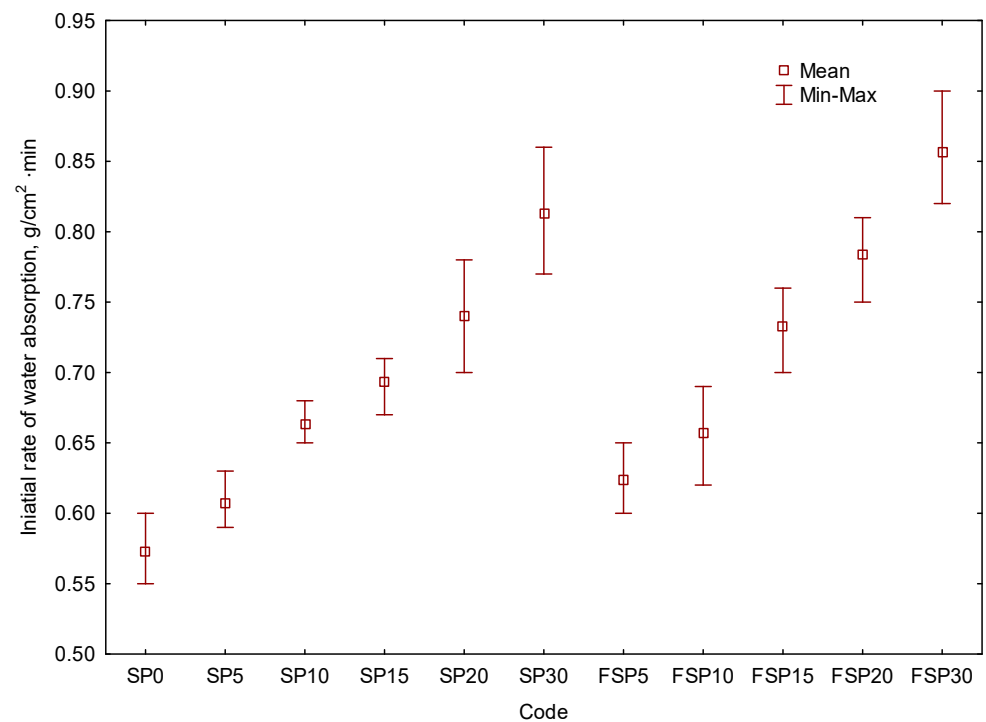
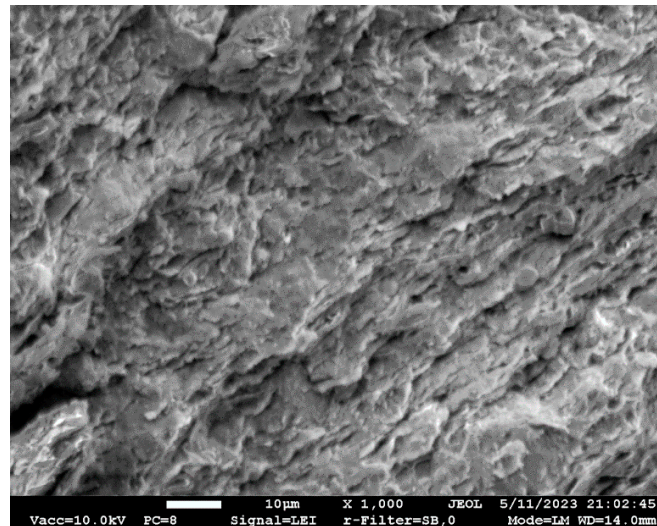


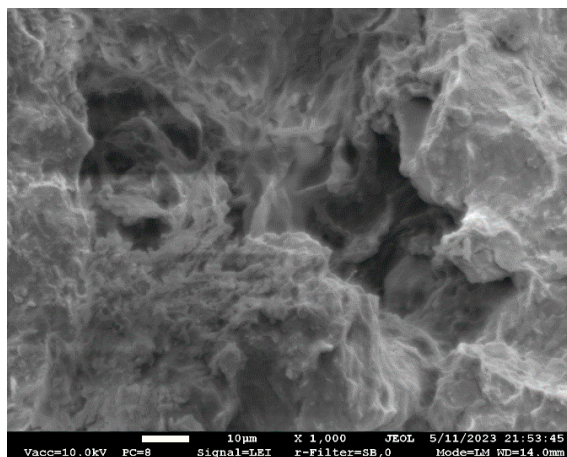
**Figure 6.** Initial rate of water absorption by the clay samples.

In addition, the incorporation of SP or FSP additives prompted changes in the matrix structure, resulting in the creation of interlayer spacing and porous structures in the samples'

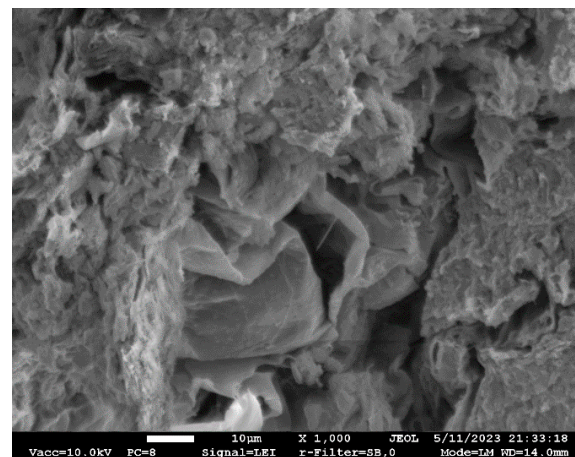
matrix. These porous structures inside the clay matrix serve as larger capillary spaces (Figure 7b). In summary, higher SP or FSP content promotes capillary water absorption, due to more pores and void creation. These pores and voids facilitate fluid transfer inside the clay samples' matrix and increase water absorption rates as a result. Authors [70–73] highlighted the same relationship between the addition of organic porous materials and the water absorption of clay/Earth materials.



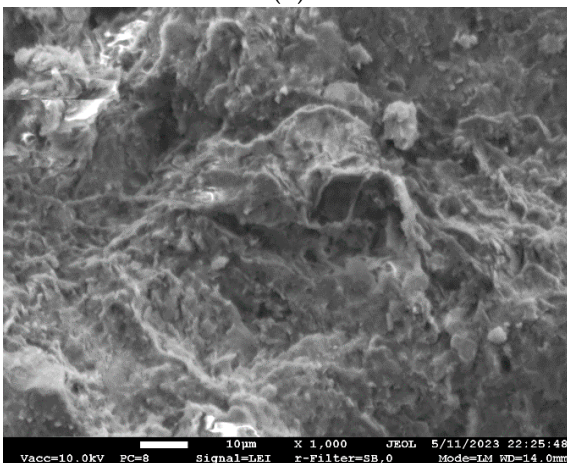
(a)



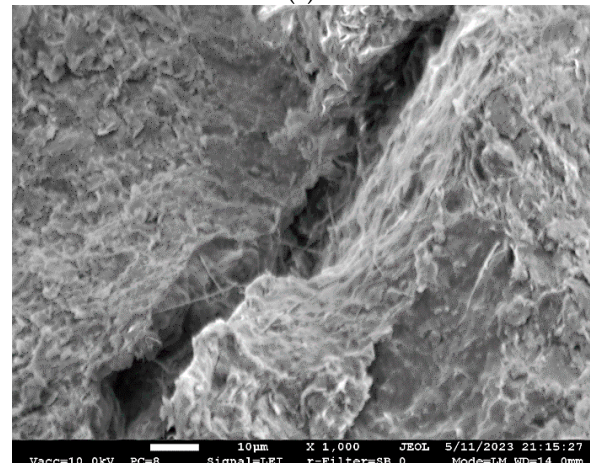
(b)



(c)



(d)



(e)

**Figure 7.** The structure of the samples: (a) SP0, (b) SP5, (c) SP30, (d) FSP5, and (e) FSP30.

Figure 7 shows the SEM images taken from the brick samples. As shown in Figure 7, increasing the SP or FSP content partially caused an increase in voids in the clay sample structure, thus decreasing the densification (Figure 3) and increasing the initial rate of water absorption (Figure 6) of the clay samples. There is also a noticeable more homogenous matrix between the clay and FSP compared to clay and SP (Figure 7). The structure of the SP30 sample (Figure 2b) reveals voids with a width down to about 20–30  $\mu\text{m}$ . The FSP30 sample structure has pores of 5–10  $\mu\text{m}$  (Figure 2d). Also, increasing the SP or FSP content caused visible microfibers in the clay sample structure. These microfibers seem to reinforce the structure, which increases the compressive strength (Figure 4) of the clay samples.

To evaluate the impact of microorganisms on new bricks, the suspensions of fungi mix of four species were inoculated in the clay bricks with wet and frozen–thawed sapropel. The suspension was prepared including the following types of fungi: interior environment *Rhodotorula mucilaginosa* and *Stachybotrys chartarum* and exterior environment *Cladosporium cladosporioides* and *Aureobasidium pullulans* by LST EN 15457. To identify how the microorganisms in the environment can impact clay bricks, they were incubated under normal conditions at 22 °C with 65% humidity for 3 weeks. The microorganisms did not grow on the bricks with the wet and frozen–thawed sapropel at 0, 5, 10, and 15%, but they grew on the bricks with the 20 and 30% sapropel, which were saturated with the organic matter of 89.5%, total nitrogen of 4.2–6.7%, and carbon of 45–48% (Table 2). The primary constraint on microbial growth in indoor environments is moisture, with fungi displaying greater tolerance for low-moisture conditions compared to bacteria. Moreover, the deliberate or accidental introduction of liquid water and the presence of adsorbed water at certain levels may also facilitate growth [74].

The defects as macro- and micro-cracks, formed on the surface in the first week of the brick samples, were examined. Supposedly, these cracks were formed from excess moisture from the fungi suspensions. Damage that occurs affects the biological resistance of the samples because moisture penetrates into the deeper layers of the samples more easily and the accumulated moisture creates more favorable conditions for the reproduction of microorganisms.

Three weeks after incubation, the defects that appeared on the surface of the samples did not spread to the surface layers of the area, but the microorganisms grew intensively during the second and third weeks of incubation. However, on the bricks with 5, 10, and 15% sapropel, there were visible microorganisms' spores from the suspension, but the hypha of the fungus was not observed. This indicated that the microorganisms did not grow, but white aerial mycelia of fungi, most likely *Aureobasidium pullulans*, were growing on clay bricks with 20% and 30% sapropel. After 6 months, the samples were examined repeatedly with light microscopy (Figure 8); these white hyphae colonies indicated that *Aureobasidium pullulans* could grow when the clay bricks remained in the standard conditions of the room.

White mycelium hyphae indicated that fungi were growing in the cracks of the bricks where there was more humidity. It is possible that the cracks in the bricks were made by excess moisture from the microorganism suspension (the solution of NaCl 0.9%) or that it accumulated from the environment. The microorganisms that grew on the brick with less than 20% of the sapropel, can to inhibited because of lack nutrient or the pH of the samples was greater than approximately 8, as described [29]. No mycelia were observed on the clay bricks with 5%, 10%, and 15% wet or frozen sapropel, which indicated better resistance to biological degradation compared to sapropel concentrations exceeding 20%.

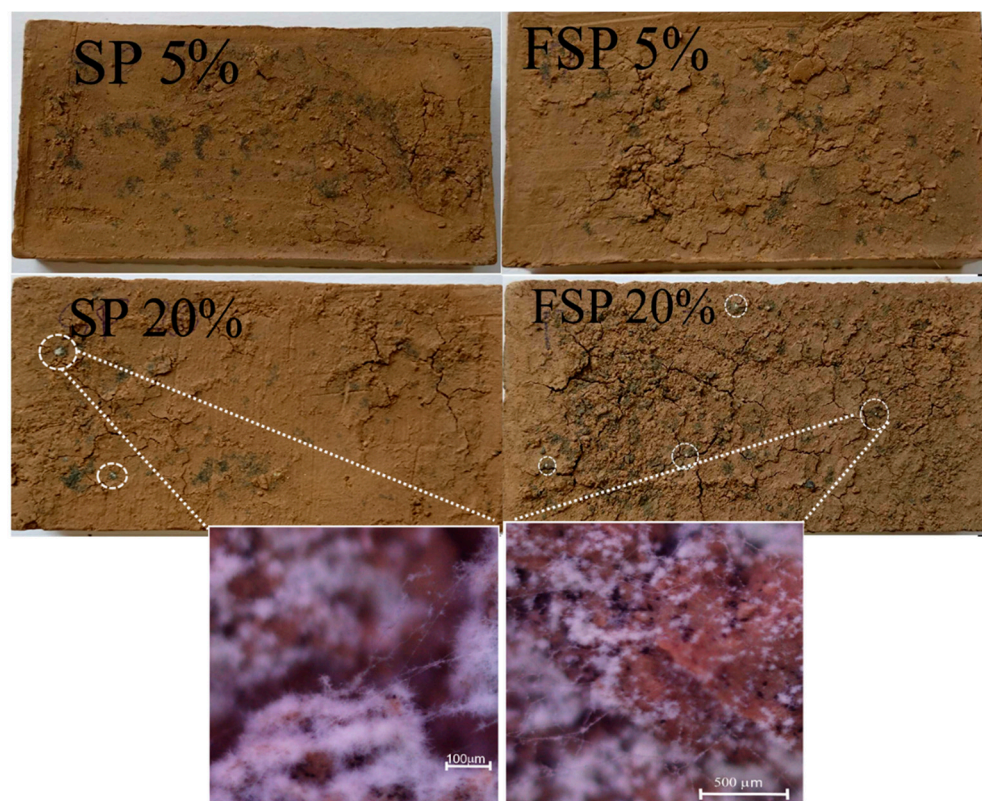


**Figure 8.** Clay bricks with the 5% and 20% sapropel after the third week of incubation at 22 °C and 65% humidity. The white circle defines a hypha of fungi. After 6 months, these microorganisms were examined with light microscopy magnification at 40×.

#### 4. Conclusions

Sustainability plays an ever-increasing role in building material manufacturing. Therefore, there is growing interest in unfired clay materials as an eco-material due to their local character and low energy consumption.

To produce eco-materials, an ecological raw material must be used. One such material that is natural and not harmful to environmental and human health is sapropel. In the present study, the properties, structure, and biological resistance of clay materials with SP (sapropel) or FSP (modified (frozen) sapropel) were investigated. The SP or FSP content varied from 5 to 30 wt.%.

Different microfibers are found in SP and FSP structures, which help reinforce the structure and increase the compressive strength of the clay materials. When the SP or FSP content is 5–30 wt.%, clay materials show good compressive strength, with this being 8.7–19.9% and 8.7–22.1% higher than the control clay samples, respectively.

The higher FSP content (20–30 wt.%) of the clay mixtures leads to lighter clay materials (the bulk density is 1.42–1.55 g/cm<sup>3</sup>), with 15.3–22.4% less bulk density than the control clay samples; however, their compressive strength is still high enough (about 7.7 MPa).

The use of SP or FSP in the production of clay materials increases the compressive strength of these clay materials, which is particularly important for unfired clay/soil/Earth materials.

The biodegradation processes due to microorganisms' impact play an important role in organic material decomposition, and it is known that sapropel is rich in these organic compounds and could impact the degradation of bricks with sapropel. However, we determined that the biological durability of the clay bricks which have less than 15% sapropel and without excess moisture is good enough, and the wet or frozen sapropel could be used for brick production.

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