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Exploring the Effect of Lime and Cement Ratios on the Mechanical Properties of Clay Bricks Made from Different Types of Soils

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Abstract: The clay brick industry is facing significant challenges related to improving its physico-mechanical properties and durability performance of sustainable products. The current study aimed to investigate the effect of stabilizers (lime and cement) on the clay brick properties of three soils. The investigated soils were taken from different regions of Algeria. A series of laboratory experiments were carried out to examine the effect of lime and cement addition with different ratios of 2%, 4%, 6%, 8%, and 10%, on the mechanical properties. The assessment was based on compressive strength, flexural strength, total and capillary water absorption tests. The test results showed that the lime addition to soils A and B led to a significant increase in compressive strength (CS) by 47% and 101%, respectively. The highest values obtained were for the 8% ratio. The obtained gain in compressive strength soil C reached its maximum CS at 6% ratio, and the obtained gain was 44%. However, for cement addition, the highest CS values were obtained at the 10% ratio for all studied soils. The observed gains in compressive strength for soils A, B, and C were 24%, 15%, and 33%, respectively. Flexural strength (FS) followed a similar trend, with lime addition improving (FS) by up to 400% for soil A at an 8% ratio. Cement addition also enhanced (FS), with the highest improvement of 103%, which was observed for soil A at a 10% ratio. It was also observed that lime addition significantly decreased the total absorption by up to 36% at an 8% ratio for soils A and B, and at 6% for soil C. In contrast, the total absorption decreased uniformly with the cement addition up to the 10% ratio. The lowest absorption observed at a 10% ratio was 11.95%. Lime addition also decreased the capillary absorption of clay bricks, and the lowest value was observed at an 8% ratio for both soils (A and B) and 6% for soil C. The CA values decreased by approximately 24% for soils A and B and 14% for soil C. In the case of cement addition, it was noted that the capillary absorption had the same pattern as the total absorption. The percentage decreases in CA were 41%, 40%, and 38% for soils A, B, and C, respectively. These results indicate that the enhancement of clay brick was observed for lime addition ranging from 2% to 8%. Therefore, good mechanical strengths were obtained at a 10% cement ratio.

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1. Introduction

In light of recent environmental changes, it is crucial to reevaluate the production methods of building materials and their ecological implications. Cement, one of the most commonly used materials in construction, is notably associated with substantial greenhouse gas emissions, particularly carbon dioxide (CO_2) [1]. Research indicates that the cement industry accounts for approximately 5% to 8% of global CO_2 emissions. Furthermore, projections suggest that CO_2 emissions from cement production could increase by 4% by the year 2050, underscoring the need for sustainable alternatives and improvements in production practices [2,3]. Furthermore, cement manufacturing produces dust and fine particles that are harmful to all living organisms [4]. This requires finding more sustainable and efficient alternatives in the construction industry. The clay brick industry is emerging as one of the most promising alternative options, owing to the material's abundance and ease of fabrication [5]. Several research studies have confirmed that earthen blocks present economic and environmental advantages. They are made from natural components that are abundantly available everywhere, such as soil and water, which reduces dependence on non-renewable resources. Additionally, their production is more cost-effective compared to cement, offers better thermal insulation, and contribute to reducing carbon dioxide emissions (CO_2) [6,7]. Furthermore, earthen blocks are fully recyclable, enhancing their environmental sustainability. From an energy perspective, clay bricks are highly efficient, as their production requires less energy than cement [5]. This is because the manufacture of clay bricks primarily relies on natural drying or sometimes on low-temperature drying, unlike cement, which requires high temperatures of up to 1450 °C. This difference in energy consumption significantly contributes to reducing the emission of pollutants during the construction process with earthen blocks [8]. The old buildings constructed with clay bricks have proven their durability and resilience. For example, Khanguet Sidi Nadji palace in Biskra province (South of Algeria), that was built using clay bricks centuries ago, has shown remarkable durability [9]. Another example is the historical buildings of Shibam and Zabid in Wadi Hadramaut (Yemen), which stand as a testament to the endurance of clay bricks in harsh and dry climatic conditions [10]. Moisture significantly affects clay bricks, leading to the deterioration of their mechanical and structural properties over time. Unstabilized earthen blocks show considerable weakness against water, as they absorb water easily and quickly, causing them to disintegrate and collapse over time, especially in humid environments [11]. Several research studies mentioned that compressive and shear strengths were inversely proportional to the saturation water degree [12], and different methods were used to improve the clay bricks' behavior. In Egypt, straw was used as a stabilizing material for clay to improve its strength and reduce cracking [13,14]. Millogo et al. [15] revealed that the use of cow dung in clay bricks prevented crack propagation and strengthened them, owing to its fiber content. La Noce et al. [16] observed that adding a percentage ranging from 0.4% to 2% of basalt fibers reduced shrinkage and increased the compressive strength by 30%. Dawood et al. [17] concluded that the use of only clay bricks was unsuitable for construction, and they found that adding straw reduced the cracks and enhanced compressive strength.

Pozzolanic materials, including natural pozzolana and industrial byproducts such as fly ash and rice husk ash, have demonstrated substantial efficacy in improving the geotechnical properties of clayey soils. These materials function by reducing the soil's plasticity index, enhancing shear strength, and optimizing compaction parameters through pozzolanic reactions. The reaction mechanism involves the formation of calcium aluminosilicate hydrates, which interconnect soil particles, reduce void ratios, and mitigate dispersivity potential, particularly in soils with high susceptibility to erosion [18]. The synergistic addition of lime enhances these reactions, accelerating the development of cohesive forces and increasing the internal friction angle, resulting in durable and mechanically superior stabilized soils [19].

Fly ash, a byproduct of coal combustion, has been widely investigated as an economical stabilizer for expansive clay soils. Its inclusion decreases the soil's plasticity, improves workability, and enhances mechanical strength. Studies have established that optimal fly ash content reduces the optimum moisture content, increases maximum dry density, and maximizes critical strength parameters such as unconfined compressive strength (UCS) and California Bearing Ratio (CBR) values [20]. Additionally, fly ash significantly reduces swelling pressure and potential, making it an effective solution for expansive soil stabilization in various geotechnical applications [20,21].

Gypsum-based additives, including lime and volcanic ash, have shown further potential in stabilizing problematic soils. For instance, the incorporation of 6% lime into gypsum clay soil has been reported to substantially enhance UCS and modulus of elasticity, indicating improved load-bearing capacity [22]. Similarly, the combination of gypsum with calcium chloride has been found to optimize compaction characteristics and increase the bearing capacity of soils [23]. A mixture containing 2% gypsum and 9–10% volcanic ash resulted in a 99.28% improvement in UCS and a 104.27% increase in CBR, underscoring the synergistic effects of this blend for soil stabilization [24]. Moreover, industrial byproducts such as phosphogypsum and surkhi (brick kiln dust) have been identified as cost-effective and environmentally sustainable alternatives for enhancing the engineering properties of clayey soils [25]. These findings collectively highlight the versatility and effectiveness of pozzolanic and gypsum-based stabilizers in providing sustainable solutions for soil improvement in diverse geotechnical and civil engineering applications. The stabilization process using materials such as lime and cement is one of the successful methods to improve the mechanical properties of clay bricks. Research indicates that adding quantities of cement to the bricks increases their compressive and tensile strengths. Dao et al. [26] showed that adding cement to the clay mixture resulted in a significant increase in compressive and tensile strengths. Additionally, cement reduces the permeability of bricks to water, enhancing their resistance to moisture and increasing their durability. However, it is noted that small percentages of cement, such as 2%, can lead to a reduction in the compressive strength of earthen blocks before it starts to improve at higher percentages [27], requiring careful determination of appropriate values for use. On the other hand, lime is a chemical stabilizer that has been used to improve the behavior of clay bricks. Lime contributes to increasing the mechanical properties of bricks and to enhancing their resistance and stability against water. However, the optimal percentage should be identified, as exceeding it may negatively affect the behavior of the bricks due to internal chemical reactions that lead to the formation of large amounts of calcium hydroxide. This causes internal cracking in the brick structure. The optimal ratio changes from one soil to another, as it is related to the chemical and mineral components of each soil type [28]. In the study conducted by Khoudja et al. [29], the optimal percentage was 11%, while Layachi et al. [30], found it to be 10%, and Zaidi found it to be 12% [31]. To understand the behavior of both cement and lime in clay bricks, a comprehensive and in-depth study must be conducted, including the analysis of the mechanical and chemical properties of stabilized clay bricks using these materials.

Recent advancements in predictive modeling techniques, such as hybrid neural networks and support vector regressors, have shown significant potential in various fields, including geosciences and earthquake prediction [32]. These techniques could also be explored in the context of predicting the mechanical behavior of stabilized clay bricks under different environmental conditions, offering a new perspective on material durability and performance.

This study aimed to evaluate the effect of lime and cement as stabilizers in enhancing the mechanical properties of clay. Previous studies often lack a comprehensive evaluation of both mechanical properties and water absorption in a single investigation. Our study fills these gaps by providing a comparative analysis of lime and cement across three distinct soil types, sourced from different regions of Algeria. The results from using lime are compared with those obtained from cement, with varying stabilizer ratios ranging from 0% to 10%. Three different types of soil were used. The second part of this research paper is dedicated to analyzing the cement and lime effect on the mechanical properties of the bricks, including compressive strength, flexural strength, and water absorption. It can be predicted that the chemical nature of the soil in terms of composition has a significant impact on the choice of stabilizer type and its percentage to obtain positive results, thereby enhancing its role as a sustainable and eco-friendly alternative in the construction field.

2. Materials and Methods

2.1. Materials

In this study, cement, lime, and various soil types were used (Figure 1). The soils under investigation were collected from different regions of Algeria. Soil A was obtained from Oulad Adi in the M'Sila region, soil B from Oulad Ahlouf in Bordj Bou Arreridj, and soil C from Ain Oulmene (Sétif province). All samples were collected at a depth of 2 m from the ground surface. Tables 1 and 2 present the chemical and mineralogical composition of the studied soils using an X-ray fluorescence (XFR) analysis and X-ray diffraction (XRD) technique, respectively. Figure 2 shows the sieve analysis of the analyzed soils according to the standard NF EN ISO 17892-4 [33]. Figure 3 shows the XRD analysis, which indicated that soil A was rich in calcite with trace of sepiolite and kaolinite. Soil B was characterized by quartz and calcite, and soil C was also rich in quartz and calcite. The bulk densities were 2385 kg/m^3, 2482 kg/m^3, and 2423 kg/m^3 for soils A, B, and C, respectively. The Atterberg's limits of the soil samples were determined and are mentioned in Table 3.

Figure 1. Materials used in this study.

Table 1. Chemical composition of the studied soils.

Components	Soil A	Soil B	Soil C
SiO_2	37.35	37.55	47.33
Al_2O_3	3.8	6.2	4.23
Fe_2O_3	2.24	2.97	1.92
CaO	27.41	23.04	22.86
MgO	1.31	4.75	1.71
SO_3	0.61	1.44	0.14
K_2O	0.6	1.47	1.09
Na_2O	0.11	0.1	0.05
P_2O_5	0.08	0.24	0.07
TiO_2	0.25	0.34	0.27
Cr_2O_3	0.008	0.008	0.008
Mn_2O_3	0.02	0.004	0.05
ZnO	0.007	0.005	0.002
SrO	0.091	0.11	0.024
L.O.I	25.58	22	19.97

Table 2. Mineral composition of the studied soils.

Minerals	Soil A	Soil B	Soil C
Calcite	47.96	37.55	40.36
Dolomite	3.81	10.23	1.14
Siderite	-	-	0.04
Ankerite	-	-	0.28
Magnesite	-	-	0.81
Quartz	30.72	23.2	43.57
Pyrite	-	-	0.13
Illite	4.69	20.27	8.62
Kaolinite	4.61	2.06	1.89
Albite	0.32	0.39	0.61
K-Feldspar	-	-	2.55
Chlorite	-	0.35	-
Pyrophyllite	2.17	3.77	-
Microcline	4.19	1.4	-
Diaspore	0.28	0.04	-
Topaz	0.4	0.66	-
Flouri	0.84	0.07	-

Table 3. The results of the soil consistency test.

Atterberg Limits (%)	Soil A	Soil B	Soil C
Liquid limit (W_L)	36.09	25.64	30.28
Plastic limit (P_L)	14.5	17.48	14.61
Plastic index (P_I)	21.59	8.16	15.67

The lime used was commercially available from Saida Company (https://bmsdcompanies.com, accessed on 7 September 2024). Its chemical and physical properties are presented in Table 4. In this study, Portland cement (CEM II/B 42.5) was used. The physico-chemical properties of the used cement are mentioned in Table 5. This cement served as a chemical stabilizer for the soils under investigation, with incorporation ratios ranging from 2% to 10% of the total mass.

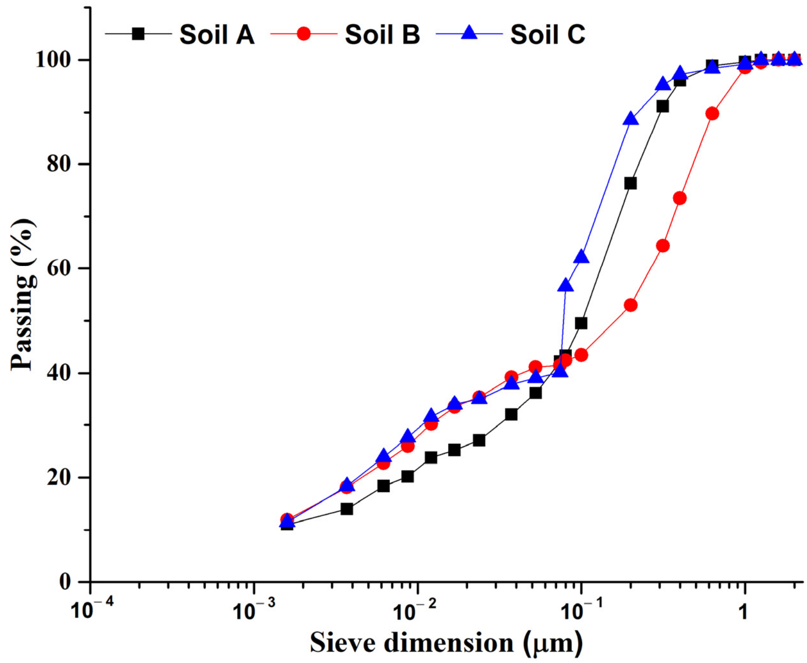

Figure 2. Grain size distribution of the used soils.

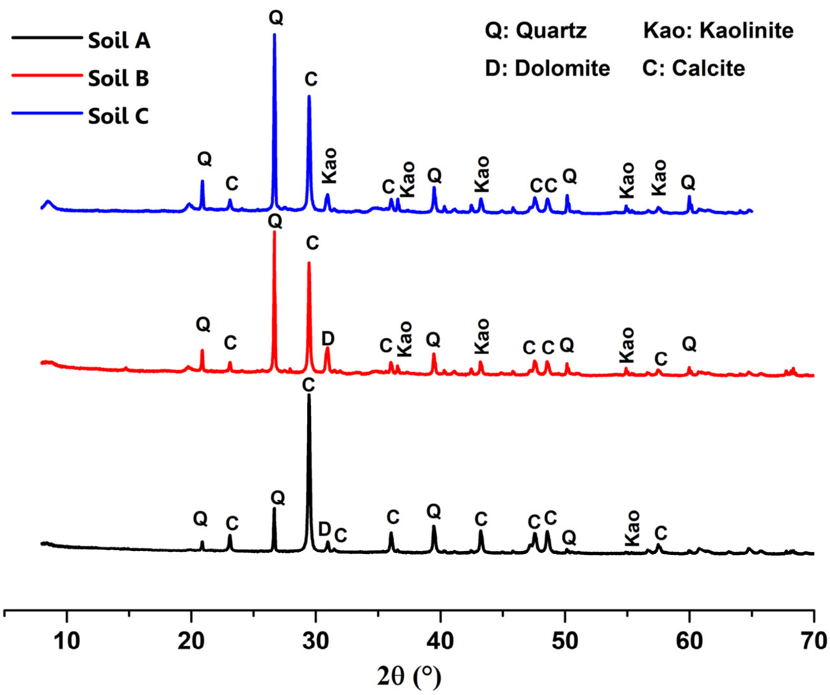

Figure 3. X-ray diffraction pattern of the investigated soils.

Table 4. Chemical and physical properties of the used lime.

Compounds	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	$CaCO_3$	Na_2O	CO_2
(%)	2.5	1.5	2	83.3	0.5	0.5	10	0.45	5
Physical appearance	Dry white powder								
Specific gravity	2.00								
Particles over 90 µm (%)	<10								
Particles over 630 µm (%)	0								
Insoluble material (%)	1								
Bulk density (g/L)	600–900								

Table 5. Physical and chemical properties of the cement.

Compounds	**SiO_2**	**Al_2O_3**	**CaO**	**Fe_2O_3**	**SO_3**	**MgO**	**$K_2O + Na_2O$**	**L.O.I.**
(%)	27.83	6.21	57.22	3.12	2.02	0.94	0.14	2.41
Setting time		Initial Final	2 h and 50 min 4 h and 06 min					
C3A = 11.19% C4AF = 9.5% C3S = 56.4% C2S = 23.2%		- Specific surface area = 3845 cm^2/g - Density = 3150 kg/m^3 - Expansion of cement = 1.22 mm						

2.2. Samples Preparation

For each soil type, two mixtures were prepared: one with clay treated with lime and the other with cement. The clay was stabilized using varying ratios of 2%, 4%, 6%, 8%, and 10%. The studied soils were sieved with a 2 mm sieve size and placed in an oven at 65 °C temperature for 24 h to remove moisture and ensure complete drying [15,29,30]. The different soil types were mixed with various cement proportions as mentioned above in one set of experiments, and with lime in the same proportions in another. These percentages were based on the total weight of the soil. The aim was to investigate the effects of both cement and lime on the soil, for determining which additive was more effective in achieving chemical and mechanical stability, both critical factors in the production of clay bricks [34]. For clay bricks' preparation, clean tap water was used [35]. The required water content (W) to achieve adequate mixture workability was calculated using Equation (1):

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

where W_L and W_P represent liquid limit and plastic limit, respectively. The obtained water content values were 25.30%, 21.56%, and 22.45% for soils A, B, and C, respectively. This method was adopted in several previous studies [15,29,30,36]. Firstly, dry soil lime and cement were mixed for approximately 2 min. Then, water was gradually added. For the mixtures containing lime, the amount of water added corresponded to the amount of lime used (i.e., for 1% of added lime, 1% of water was introduced). For the cemented mixtures, an additional amount of water equal to 45% of the cement ratio was added to the previously calculated water content. The mixing continued for 2 min until a homogeneous mixture was achieved. The prepared mixtures were placed into molds with inner dimensions of 4 × 4 × 16 cm^3 and 10 × 10 × 10 cm^3 and left to dry in an outdoor environment for 72 h [29,30]. Afterward, the samples were removed from the molds and sealed in airtight plastic film (Figure 4c). The samples containing lime, were cured in an oven at 65 °C for 7 days, according to the technique adopted in previous studies [30,37]. Moreover, the samples containing cement were dried for 28 days as adopted by Ho et al. [38]. The composition of the prepared mixtures is detailed in Table 6.

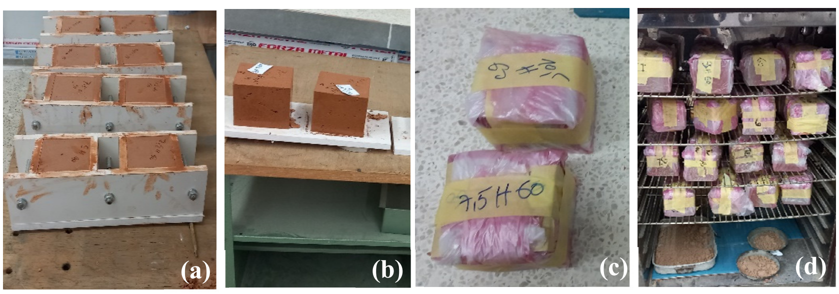

Figure 4. Samples' preparation setup: (**a**) molds filling, (**b**) demolding, (**c**) conservation of specimens in plastic film, and (**d**) samples in an oven at 65 °C.

Table 6. Composition of mixtures.

Type of Soil	Clay		Lime		Cement		Water	
	Ratio (%)	Quantity (Kg/m^3)	Ratio (%)	Quantity (Kg/m^3)	Ratio (%)	Quantity (Kg/m^3)	Ratio (%)	Quantity (Kg/m^3)
Soil A	100 *	1202	-	-	-	-	25.29	303.99
	98	1177.96	2	24.04	-	-	27.29	328.03
	96	1153.92	4	48.08	-	-	29.29	352.07
	94	1129.88	6	72.12	-	-	31.29	376.11
	92	1105.84	8	96.16	-	-	33.29	400.15
	90	1081.8	10	120.2	-	-	35.29	424.19
	98	1177.96	-	-	2	24.04	26.19	314.8
	96	1153.92	-	-	4	48.08	27.09	325.62
	94	1129.88	-	-	6	72.12	27.99	336.44
	92	1105.84	-	-	8	96.16	28.89	347.26
	90	1081.8	-	-	10	120.2	29.79	358.08
Soil B	100 *	1254	-	-	-	-	21.56	270.36
	98	1228.92	2	25.08	-	-	23.56	289.53
	96	1203.84	4	50.16	-	-	25.56	307.7
	94	1178.76	6	75.24	-	-	27.56	324.87
	92	1153.68	8	100.32	-	-	29.56	341.03
	90	1128.6	10	125.4	-	-	31.56	356.19
	98	1228.92	-	-	2	25.08	22.5	276.51
	96	1203.84	-	-	4	50.16	23.44	282.18
	94	1178.76	-	-	6	75.24	24.38	287.38
	92	1153.68	-	-	8	100.32	25.32	292.11
	90	1128.6	-	-	10	125.4	26.25	296.26
Soil C	100 *	1220	-	-	-	-	22.45	273.89
	98	1195.6	2	24.4	-	-	24.45	298.29
	96	1171.2	4	48.8	-	-	26.45	322.69
	94	1146.8	6	73.2	-	-	28.45	347.09
	92	1122.4	8	97.6	-	-	30.45	371.49
	90	1098	10	122	-	-	32.45	395.89
	98	1195.6	-	-	2	24.4	23.36	284.99
	96	1171.2	-	-	4	48.8	24.28	296.22
	94	1146.8	-	-	6	73.2	25.19	307.32
	92	1122.4	-	-	8	97.6	26.1	318.42
	90	1098	-	-	10	122	27.02	329.64

* Mix of reference.

2.3. Conducted Tests

2.3.1. Compressive Strength Test

The compressive strength (CS) tests were carried out on test specimens with dimensions of 10 × 10 × 10 cm^3 using an Incotecnic model PA/MPC-2 machine, with a 200 kN capacity, as illustrated in Figure 5, according to EN 12390-3:2019 [39,40]. The loading rate was fixed at 0.5 mm/min based on the suggestion from the standard ASTM D2166-06 [41].

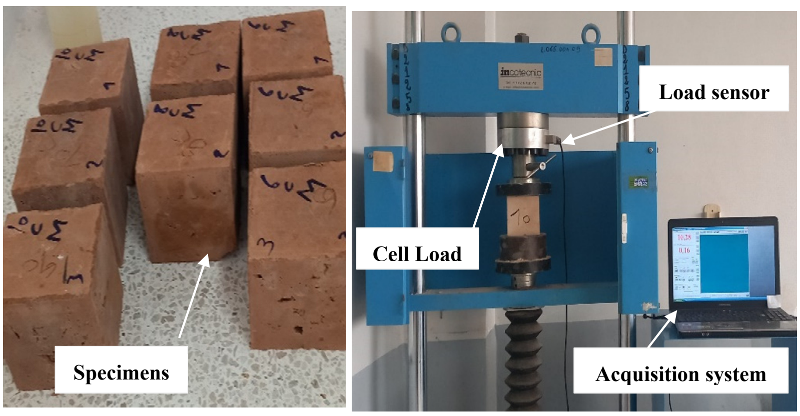

Figure 5. Compressive strength test.

2.3.2. Flexural Behavior

The flexural test was conducted on prismatic samples with the following dimensions $4 \times 4 \times 16$ cm^3, according to the standard NF EN 196-1 [42], as illustrated in Figure 6. The bending stress (σ_f) was calculated using Equation (2):

$$\sigma_f = \frac{3FL}{2bh^2} \quad (2)$$

where F is the maximum force at which the sample breaks, b is the height of the sample, h is the width, and L is the length.

Figure 6. Flexural strength test.

2.3.3. Total Absorption

The total water absorbed by the clay is crucial, as it indicates the clay's water interaction and reflects its porosity. These parameters significantly influence the mechanical strength of clay. The water absorption test was carried out by immersing the sample in water for periods ranging from 1 to 4 days. The weight difference between the sample's dry state and its state after being removed from the water was measured every 24 h. The amount of water absorbed was then calculated using Equation (3) [29,43]:

$$A = \frac{(W_h - W_s)}{W_s} \times 100 \quad (3)$$

where W_h and W_s, represent the sample's weight after removal from water and its dry weight, respectively.

2.3.4. Capillary Water Absorption

The capillary water absorption was calculated according to the standard XP P13-901 [44]. The surface was immersed in 5 mm of water for 10 min. After this period, the mass difference was measured to determine the amount of water absorbed by the sample. The water absorption (WA) coefficient was then calculated using Equation (4):

$$C_b = \frac{(M_1 - M_0)}{S\sqrt{t}} \times 100 \quad (4)$$

where C_b, M_0, M_1, S, and T represent the capillary rise coefficient of water, the initial mass before immersion in water, the mass after immersion, the submerged surface area, and the duration for which the sample was left in water, respectively.

3. Results and Discussion

The behavior of stabilized clay brick blocks, made from different soil types (A, B, and C), stabilized with varying ratios of cement and lime, was investigated. For each treatment, three specimens were prepared to evaluate the cement and lime impact on the bricks' mechanical properties. The results of these tests were analyzed and are discussed in the following section.

3.1. Results of Compressive Strength Test

3.1.1. Mixtures Containing Lime

The mechanical properties of construction materials are the most significant characteristics. The compressive strength (CS) test was conducted on dry samples with dimensions of $10 \times 10 \times 10$ cm^3 at the laboratory LTPE, Spa (Laboratoire des Travaux Publics de l'Est), according to the standard EN 12390-3 [39]. Figure 7 illustrates the average compressive strength of the tested blocks. The compressive strength tests were carried out in triplicate. For soils A and B, it is noteworthy that for the clay–lime mixture, the compressive strength increased with the increasing lime ratio up to 8%. Beyond this ratio, the compressive strength decreased. The highest strength gains were 48% and 101% for soils A and B, respectively, compared to the reference specimen. These results were in good agreement with previous studies [29–31]. For soil C, the maximum strength gain was achieved at a 6% lime ratio, and its obtained strength gain was 44%.

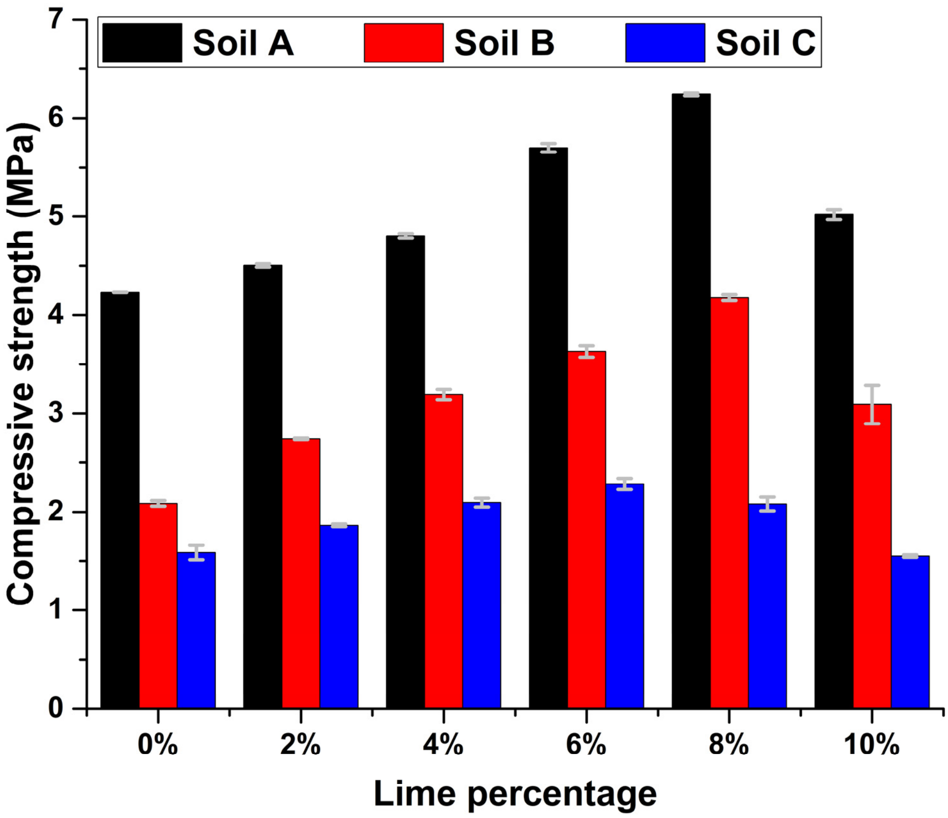

Figure 7. Compressive strength of lime.

Soil Awas characterized by its chemical balance, which included high percentages of silica (SiO_2), calcium (CaO), and a significant percentage of alumina (Al_2O_3); that balance facilitated the reaction of lime with silica to form calcium silicate ($CaSiO_3$) and calcium aluminate ($CaAl_2O_4$), which significantly increased the strength of the bricks. The following chemical equations illustrate these processes:

$$Ca(OH)_2 + SiO_2 \rightarrow C - S - H \quad (5)$$

$$Ca(OH)_2 + Al_2O_3 \rightarrow C - A - H \quad (6)$$

Soil A achieved the highest compressive strength of 6.24 MPa at 8% of lime, an increase of 47.47% compared to the specimen without lime. This reflects the ability of soil A to use lime effectively to enhance clay bricks' strength. However, when 10% lime was used, the compressive strength value decreased from 6.24 MPa to 5.02 MPa, a decrease of 19.55% compared to the specimen containing 8% of lime. This decrease was due to the formation of structurally undesirable compounds within the clay bricks such as excessive CaO deposits that may cause excessive brittleness. Excessive use of lime may also increase production costs. This highlights the importance of the lime ratio in ensuring the optimal properties of clay bricks. Despite this ratio of 8%, the compressive strength remained greater that of reference specimen (18.64%).

For soil B, the achieved compressive strength was 4.18 MPa at 8%. An increase of 101% was obtained in comparison with the specimen of reference. However, when 10% of lime was used, the compressive strength value decreased by 26% from 4.18 MPa to 3.09 MPa. It also appears that the excessive use of lime in soil B may lead to a reduction in clay bricks properties.

Soil C was characterized by a high calcite and quartz content with kaolinite traces. We observed that the addition of 6% of lime led to the maximum compressive strength of 2.28 MPa, with a strength gain of 44%. Beyond that ratio, the compressive strength decreased to 1.55 MPa (the observed decrease in compressive strength was 1.9%). This can be attributed to the following: (1) when excessive lime is added (e.g., 10%), the amount of $Ca(OH)_2$ produced exceeds the capacity of the soil to react with it. This leads to an accumulation of unreacted $Ca(OH)_2$, which does not contribute to strength and can even weaken the structure and (2) the accumulation of unreacted $Ca(OH)_2$ can lead to the formation of large crystalline structures within the clay matrix. These crystals are brittle and can create microcracks in the brick structure, reducing its overall strength. Additionally, excess lime can cause internal stresses due to the expansion of these crystals, further contributing to microcracking and weakening the material [45].

Regardless of the amount of lime added, it was observed that soil A exhibited higher mechanical strength, followed by soil B, and then soil C in decreasing order. This difference in performance can be attributed to the higher kaolinite content ($Al_2Si_2O_5(OH)_4$, see Table 2) in soil A compared to soils B and C [46]. Kaolinite reacts more effectively with lime, promoting the formation of a greater quantity of calcium silicate hydrates (C-S-H) and calcium aluminate hydrates (C-A-H). These reaction products, particularly C-S-H, are responsible for improving the mechanical properties of the material by ensuring better binding between soil particles and contributing to the cohesion and densification of the material's structure.

3.1.2. Mixtures Containing Cement

Figure 8, shows the average compressive strength achieved for the earthen blocks treated with cement initially decreased across all types of earthen blocks (A, B, and C), and then started to increase as the percentage of cement increased. These results were consistent with previous studies on clay mortars [47] and earthen blocks [27]. It can be noted that the greatest compressive strength was obtained for soil A, regardless of the added cement ratios. The addition of 2% of cement decreased the compressive strength by 77%. This can be explained by the fact that the small amount of cement was not enough to form effective chemical bonds with the clay components. Beyond the ratio of 4%, cement addition consequently increased the compressive strength. The maximum obtained value for a 10% ratio was 5.23 MPa, representing a strength gain of 24%. These enhancements can be attributed to a more uniform microstructure, with smaller pores and the absence of microcracks, when the calcium silicate hydrates (C-S-H) form links between isolated particles [48]. Kalifala Dao et al. [26] confirmed that the cement improved the compressive strength of adobe blocks.

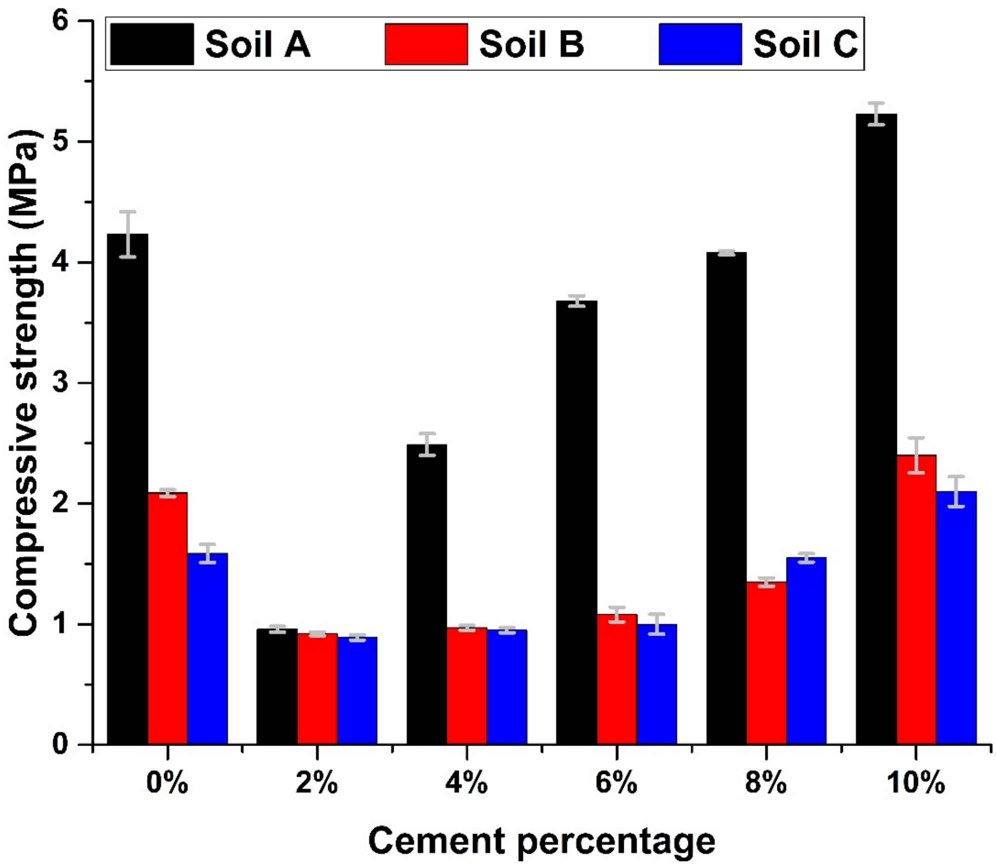

Figure 8. Compressive strength of cement.

The reaction of cement with water leads to the formation of calcium hydroxide ($Ca(OH)_2$). This compound reacts with silica (SiO_2) and alumina (Al_2O_3) in the soil to form calcium silicate hydrate (C-S-H) and calcium aluminate hydrate (C-A-H), which contribute to the structure and strength of the brick.

Soil B presented low values of compressive strength compared to soil A but had the same behavior as soil A when cement was added. The only difference was that the increase in strength started at the 8% ratio. The incorporation of 2% of cement led to a 56% decrease in compressive strength. Therefore, adding from 4% to 6% of cement yielded the same reduction. After the 8% ratio, the compressive strength was enhanced, and the maximum obtained value was 2.4 MPa, representing a strength gain of 15%.

Soil C also presented the same behavior as soil B. The lowest ratio of cement led to a 44%reductionin compressive strength. Adding from 4% to 6% of cement maintained practically the same drop in strength. After exceeding an 8% ratio, the compressive strength increased, reaching a maximum value of 2.1 MPa, which represented a 33% improvement in strength.

By comparing the studied soils, it appeared that soil A demonstrated significant results in terms of initial strength and improvement with cement addition. However, it also exhibited a rapid reaction even at relatively low cement proportions (above 4%). The main results regarding the compressive strength of cement-stabilized bricks were similar to those reported by Boffoué et al. [27].

3.2. Flexural Strength Test

3.2.1. Mixtures Containing Lime

The obtained values are the average of three specimens for each test. A three-point bending test was carried out to examine the mechanical properties of the tested specimens containing different lime ratios (0%, 2%, 4%, 6%, 8%, 10%), according to NF EN 196-1 [42]. Figure 9 shows the obtained flexural strength for all tested soils. It can be noted that for all investigated soils, flexural strength followed the same mechanical behavior compared to the compressive test results. It started to increase with the incorporation of lime until an 8% ratio. Beyond that ratio, the flexural strength decreased.

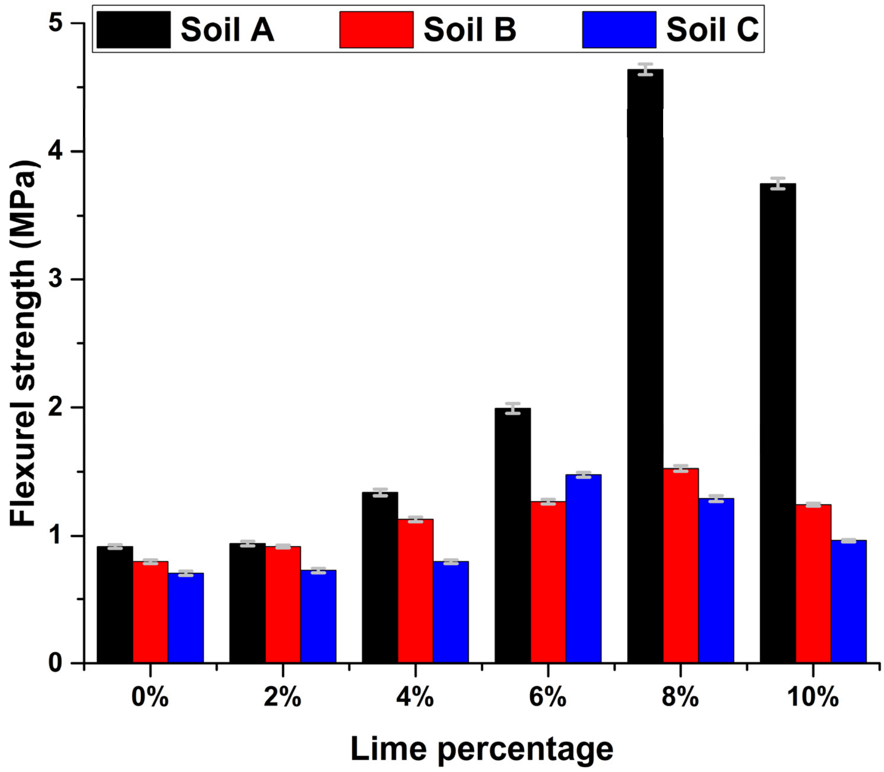

Figure 9. Flexural strength of lime.

These observations were in good accordance with those obtained by Koadri et al. [49]. In their study, the authors found that adding 9% of lime resulted in higher flexural strength. Beyond that point, the flexural strength decreased significantly.

In the case of soil A, a significant improvement in flexural strength was observed from 0.91 MPa at 0% of lime to 4.64 MPa at 8% of lime, representing an improvement of 400%. In contrast, increasing the ratio to 10% resulted in a decrease in flexural strength to 3.75 MPa, representing a 19% reduction compared to the mix with 8% of lime. Nevertheless, this value remained significantly higher than the reference mixture. In the case of soil B, a slight enhancement in flexural strength was obtained from 0.8 MPa to 1.52 MPa, representing an improvement of 90%.

For soil C, an improvement in flexural strength was observed up to 6%, where the flexural strength increased from 0.7 MPa to 1.48 MPa, representing an improvement of 112%. However, when the lime content was increased to 8% for soils A and B, and 6% for soil C, a decrease in flexural strength was observed. This decrease could be due to increased reactions that may lead to the formation of undesirable compounds or unexpected effects on some minerals in the soil when lime is used at a high percentage. It can be concluded that lime has a beneficial effect on enhancing the mechanical properties of earth blocks, provided that the optimal lime ratio is related to each soil type.

3.2.2. Flexural Strength Cement

Figure 10 shows the results obtained for the flexural strength of the tested specimens. It can be observed that the soils under investigation had the same behavior. They presented a reduction in flexural strength with the addition of cement at well-determined ratios. After that, the increase in cement ratios led to a decrease in flexural strength.

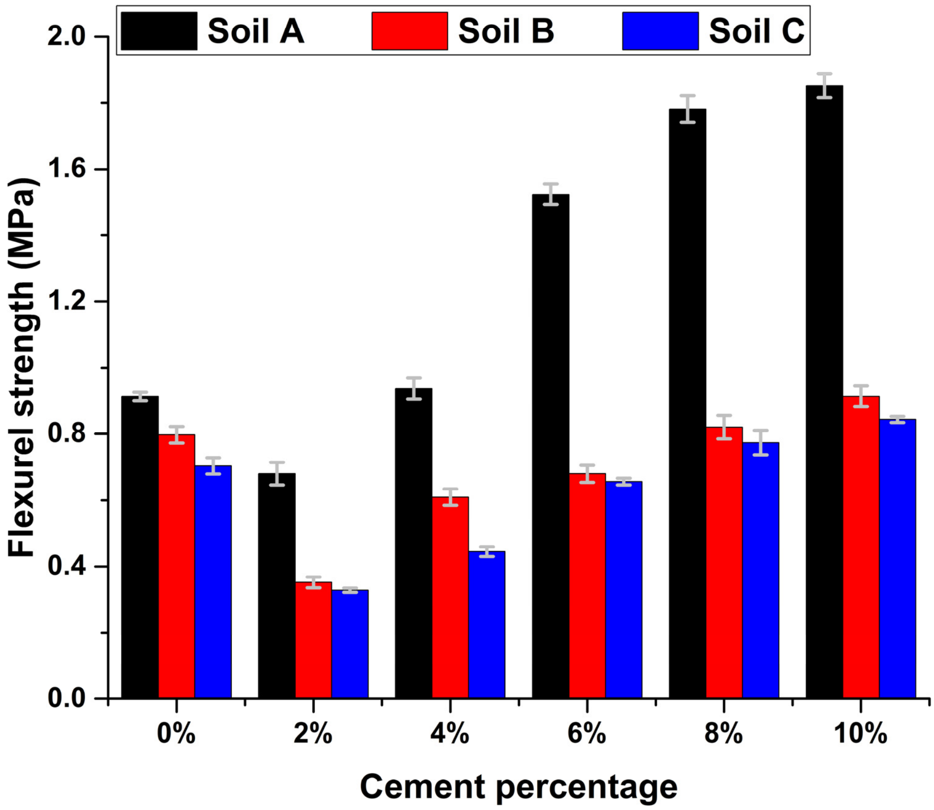

Figure 10. Flexural strength of cement.

For soil A, the addition of 2% of cement reduced the strength by 25%. Beyond a ratio of 4%, the strength started to increase, and the maximum value reached was obtained for 10%, with a strength gain of 103%. This can be explained by the fact that soil A was rich in kaolinite compared to soils B and C. The kaolinite reacted with lime, promoting the formation of a greater quantity of calcium silicate hydrates (C-S-H) and calcium aluminate hydrates (C-A-H). These reaction products contributed to the structure and strength of the bricks. This compound contributed to the formation of a solid and stable matrix, binding the clay particles and enhancing the mixture's cohesion. The obtained results were in good agreement with previous research elaborated by Pkla et al. [47].

In the case of soil B, the addition of 2% of cement decreased flexural strength by 56%. However, the increase in cement percentage (up to 4%), increased flexural strength. The maximum obtained strength at 10% was 0.91 MPa, showing a strength gain of 15%. The chemical reaction between cement and soil B constituents, such as quartz and calcite, resulted in the formation of strong chemical bonds, enhancing the flexural strength of clay bricks and improving their overall structural properties. A similar strength reduction was observed in soil C with the addition of 2% of cement. The highest was achieved at a 10% cement content, showing a 20% increase in strength. This can be attributed to the same mechanisms observed in soil B.

It was clearly observed that soil A had significant responses to cement addition compared to the other studied soils, where the strength gain reached 103%. This was attributed to its high calcite ($CaCO_3$) content.

3.3. Results of Total Absorption

3.3.1. Total Absorption of Specimens Containing Lime

The total water absorption (WA) tests revealed important information: the blocks containing lime remained cohesive throughout the 4-day immersion period, maintaining their initial shape without any noticeable changes.

Figure 11 shows the study results of the lime effect on the water absorption properties of clay bricks. In soil A, the addition of lime to the mixtures decreased the water absorption (WA). An excessive drop in absorption was observed at an 8% cement ratio. The water absorption coefficient ranged between 11.96% and 19.14%. The increase in lime content decreased WA. The lowest water absorption coefficient was found at 8%, and the reduction amount was 36%. It can be explained by the fact that adding lime to clay yields to the formation of C-S-H, which fills the pores in the bricks and consequently, the water absorption decreases [25,28]. A similar behavior was observed in soil B as in the previous soil. The water absorption coefficient ranged from 15.48% to 20.54%. At the same lime ratio of 8%, soil B exhibited a low water absorption coefficient of 15.48%, indicating a reduction of 25%. This can be explained by the presence of quartz, a chemically inert mineral, which does not contribute to the densification process of the mixture's matrix. As a result, the clay's porosity remains higher, allowing water to penetrate more easily, leading to increased water absorption. In the case of soil C, a considerable change in WA was observed with the increasing lime content. The absorption decreased from 22.34% to about 16.77% with the application of 6% of lime, before rising again to around 19.17% when 10% of lime was added.

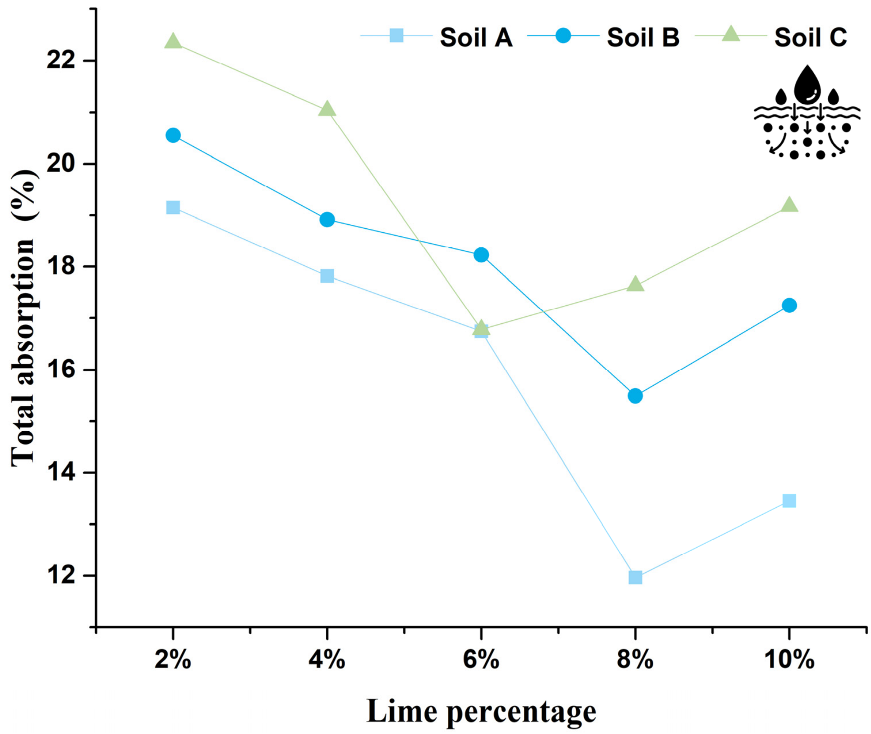

Figure 11. Variation of total absorption with respect to lime content.

The test results showed a decrease in water absorption, accompanied by increases in compressive strength, as the lime content was increased. These results were in good accordance with those reported by Shubbar et al. [50]. It can be concluded that for common clays, a lime content of 5% to 8% is recommended to ensure effective stabilization and reduce water absorption (WA). For clays that are less plastic or contain a higher proportion of calcite, a lower lime content of 2% to 5% may be sufficient.

3.3.2. Total Absorption of Specimens Containing Cement

Figure 12 shows the total absorption of all tested specimens containing cement. Soils A and B exhibited similar patterns. For 2% of added cement, the values were 16.84% and 17.80% for soils A and B, respectively. Total water absorption decreased with increasing cement content, reaching its lowest value at 10%. For soils A and B, the recorded values were 11.95% and 13.07%, respectively. Soil C showed the same behavior as indicated in previous soils. Although soil C presented a high WA compared to the others, it gave the same pattern when the cement ratio was increased. The water absorption coefficient was 29.05% at 2% of cement and then gradually decreased to 18.82% at 10%. These results can be explained by the fact that soils A and B were rich in calcite, which presents an excellent reactivity with cement, forming stabilized components (C-S-H) and densifying the mixture structure, which reduced the porosity. However, soil C, characterized by its high quartz content, exhibited limited reactivity with the cement components, as discussed earlier. This reduced the formation of stabilizing compounds, thereby limiting the efficiency of the cement as a stabilizer.

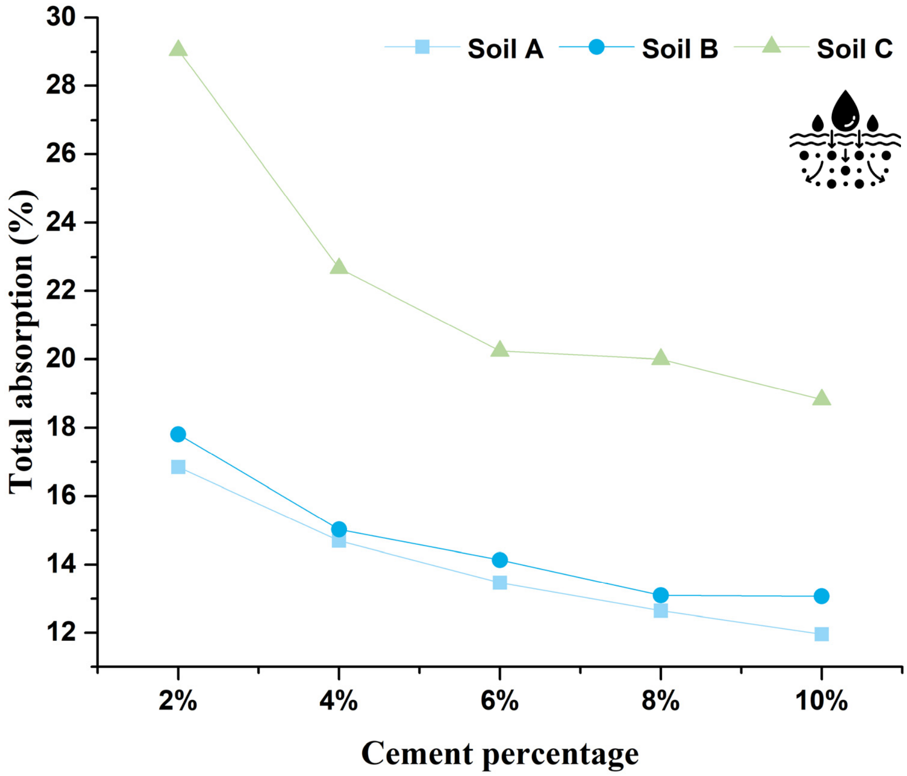

Figure 12. Variation of total absorption with respect to cement content.

When comparing the effect of lime and cement on water absorption in clay bricks for all investigated soils, it was observed that cement was more effective in reducing absorption across all soil types compared to lime. For example, for soil A, the water absorption ratio decreased continuously with the increasing cement content, reaching 11.95% at 10% of cement, while the absorption ratio with lime decreased to 8% to reach 11.96%, then increased slightly at 10%. In soil B, cement showed an increasing effect in reducing the WA coefficient, reaching 13.07% at 10%, while lime reduced the absorption ratio at an 8% ratio to 15.49% but increased it to 17.25% at 10%. Lastly, in soil C, the cement effect was greater, where the absorption ratio decreased significantly from 29.05% at 2% of cement to 18.82% at 10%, while lime reduced the WA coefficient significantly starting from a 6% ratio to 16.78% and then increased it to 19.17% at 10%. In general, cement has a more regular and stable effect on reducing water absorption.

3.4. Capillary Absorption

3.4.1. Bricks Containing Lime

Figure 13 illustrates the capillary absorption (CA) of specimens containing lime. It can be clearly observed that the patterns of capillary absorption were similar with those of total absorption.

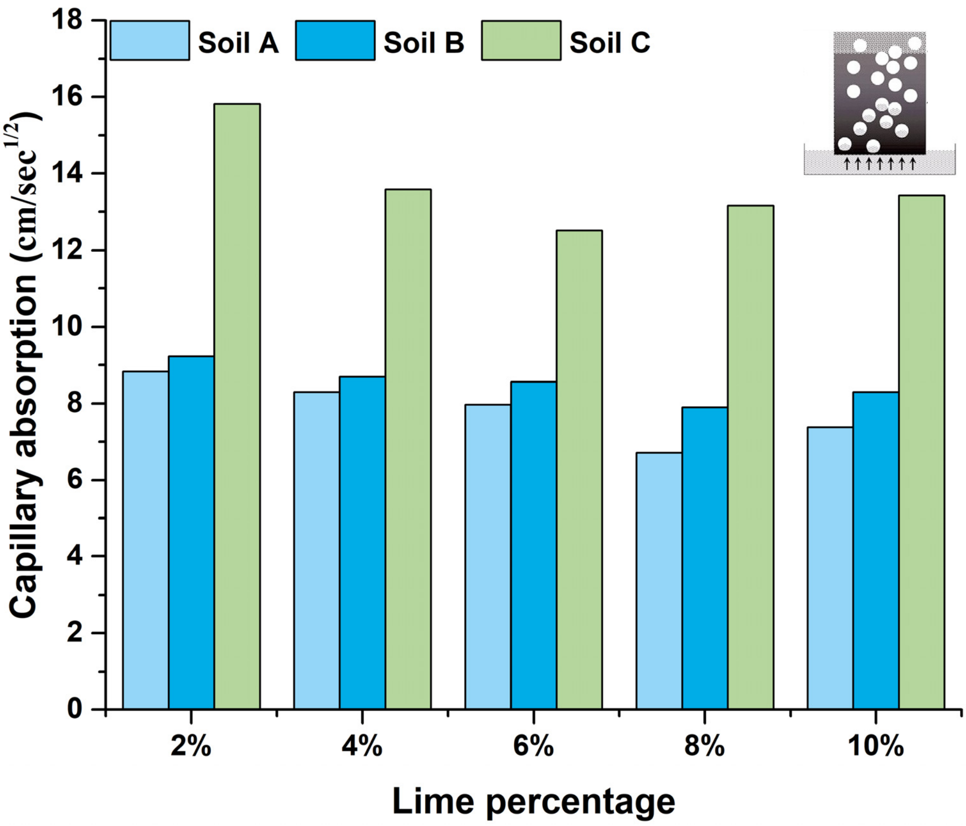

Figure 13. Variation in capillary absorption as a function of lime function content.

By increasing the lime content from 2% to 8%, we observed a significant decrease in the capillary absorption coefficient in both soils A and B. Specifically, in soil A, the CA values decreased from 8.82 cm/s$^{1/2}$ at 2% of lime to 6.71 cm/s$^{1/2}$ at 8% of lime, while soil B experienced a decrease from 9.22 cm/s$^{1/2}$ to 7.90 cm/s$^{1/2}$ for the same lime ratios. After that decrease, a slight increase in CA could be seen when lime was increased to 10% for both soils (A and B), reaching 7.38 cm/s$^{1/2}$ and 8.30 cm/s$^{1/2}$, respectively. For soil C, the pattern was similar but with different CA levels. The CA coefficient decreased from 15.81 cm/s$^{1/2}$ at 2% of lime to 12.51 cm/s$^{1/2}$ at 6% of lime but increased again to 13.44 cm/s$^{1/2}$ at 10% of lime. This indicates that adding lime up to a certain percentage can improve the soil's resistance to water absorption, but exceeding this percentage may lead to negative effects and an increase in capillary absorption coefficient.

It can be concluded that incorporating lime at a ratio between 6% and 8% is effective in reducing capillary absorption, reflecting an enhancement in clay properties. The lime effect varies depending on the soil type and its chemical and mineral composition.

3.4.2. Bricks Containing Cement

Figure 14, illustrates the capillary absorption (CA) of specimens containing cement. The same patterns of capillary absorption for all tested soils were observed. The behavior was characterized by high CA values at 2% of cement and decreasing values at 10%. In the case of soil A, the CA coefficient gradually decreased as the cement content increased from 2% to 10%. The values at 2% were 14.49 cm/s$^{1/2}$, 14.75 cm/s$^{1/2}$, and 17.13 cm/s$^{1/2,}$ for soils A, B, and C, respectively. On the other hand, at 10%, they were 8.56 cm/s$^{1/2}$, 8.82 cm/s$^{1/2}$, and 10.67, respectively. These results indicate that cement is an effective option for improving soil quality in applications that require high water resistance.

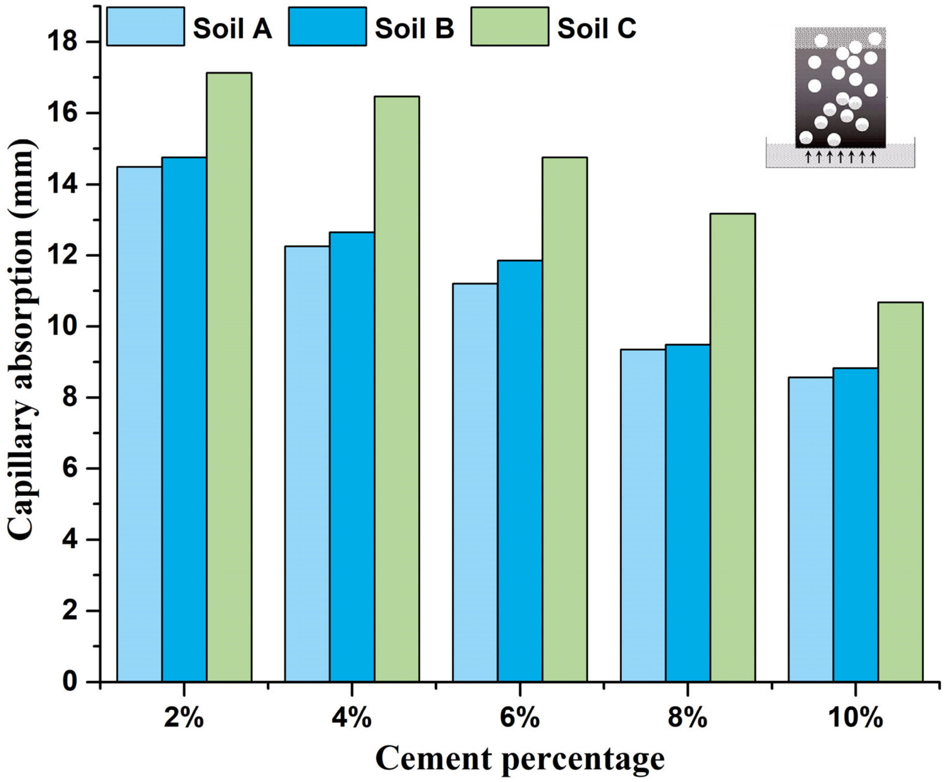

Figure 14. Variation in capillary absorption as a function of cement content.

The results indicated that lime and cement had significant effects on CA for all investigated soils. However, there were clear differences between their effects. When using lime, it was observed that the CA decreased with the increasing lime content until it reached a certain limit (between 6% and 8%), after which it rose again. This indicates that lime improves the water resistance of the clay bricks. On the other hand, the results showed that the use of cement was more effective in reducing the percentage of CA continuously as its ratio increased. Increasing the cement ratio from 2% to 10%, a gradual and continuous decrease in CA was observed. This indicates that cement effectively enhances the moisture-resistant properties of the soil.

4. Conclusions

The main objective of this paper was to investigate the effect of lime and cement on clay bricks. The study was conducted on three types of soil. The investigated ratios of stabilizers were 0%, 2%, 4%, 6%, 8%, and 10% of the total mass. From the obtained results, the following conclusions can be listed:

- The lime incorporation in clay bricks with an 8% ratio significantly enhanced the compressive strength by 47% and 100% for soils A and B, respectively. However, for soil C, only 6% of lime gave a strength gain of 44%.
- Cement addition of up to 10% enhanced the compressive strength by 24%, 15%, and 33% for soils A, B and C, respectively.
- Clay's flexural strength was improved with the addition of 8% of lime by 400% and 90%, respectively, and 112% at a 6% cement ratio for soil C. However, the highest FS

values were obtained at a ratio of 10% of cement. The gains were 103%, 15%, and 20%, for soils A, B, and C, respectively.

- A significant reduction in total water absorption was obtained at 8% of lime for all soils. Beyond that ratio, the WA started to increase. However, cement addiction decreased proportionally with the water absorption for all soils.
- With the addition of cement or lime, the capillary absorption tests for all soils exhibited a similar behavior as observed with total water absorption.

The results of this study can be applied in the manufacturing of clay bricks for producing sustainable products. Based on the findings of this study, the following recommendations can be made for application in clay brick production:

For lime stabilization, the optimal lime ratio for soil A (M'sila) is 8%, which significantly enhances compressive strength and flexural strength by 47% and 400%, respectively. For soil B (Bordj Bou Arreridj), the optimal lime ratio is also 8%, increasing compressive strength and flexural strength by 101% and 90%, respectively. However, in the case of soil C (Sétif), the optimal ratio is 6%, improving compressive strength and flexural strength by 44% and 12%, respectively.

For cement stabilization, the optimal cement ratio for all tested soils (soils A, B and, C) is 10%. This ratio enhances compressive strength by 24%, 15%, and 33%, respectively. The flexural strength was enhanced by 103%,15%, and 20%, respectively.

It would be desirable to complement this study through further experimental studies by extending the investigation to other types of clays available in Algeria. Additionally, it would be beneficial to explore alternative stabilization techniques that could improve the structural integrity, durability, and environmental impact of the bricks.

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Nomenclature

CS	Compressive strength
FS	Flexural strength
UCS	Unconfined compressive strength
W_L	Liquid limit
P_L	Plastic limit
P_I	Plastic index
σ_f	Bending stress
WA	Water absorption
C_b	Capillary coefficient
C-S-H	Calcium silicate hydrates
C-A-H	Calcium aluminate hydrates

References

1. Husnain, A.; Qazi, I.A.; Khaliq, W.; Arshad, M. Immobilization in cement mortar of chromium removed from water using titania nanoparticles. *J. Environ. Manag.* **2016**, *172*, 10–17. [CrossRef] [PubMed]
2. Miller, S.A.; John, V.M.; Pacca, S.A.; Horvath, A. Carbon dioxide reduction potential in the global cement industry by 2050. *Cem. Concr. Res.* **2018**, *114*, 115–124. [CrossRef]
3. Khaiyum, M.Z.; Sarker, S.; Kabir, G. Evaluation of carbon emission factors in the cement industry: An emerging economy context. *Sustainability* **2023**, *15*, 15407. [CrossRef]
4. Habert, G.; Miller, S.A.; John, V.M.; Provis, J.L.; Favier, A.; Horvath, A.; Scrivener, K.L. Environmental impacts and decarbonization strategies in the cement and concrete industries. *Nat. Rev. Earth Environ.* **2020**, *1*, 559–573. [CrossRef]
5. Norton, J. *Building with Earth*; Intermediate Technology Publications Ltd. (ITP): London, UK, 1997.
6. Mansouri, S.; Triki, L.; Zeghichi, S. Sustainable building materials and technologies of stabilized earth. *Mod. Environ. Sci. Eng* **2017**, *3*, 355–363. [CrossRef]
7. Turgut, P. Manufacturing of building bricks without Portland cement. *J. Clean. Prod.* **2012**, *37*, 361–367. [CrossRef]
8. Mian, A.; Bendig, M.; Piazzesi, G.; Manente, G.; Lazzaretto, A.; Maréchal, F. Energy Integration in the cement industry. In *Computer Aided Chemical Engineering*; Elsevier: Amsterdam, The Netherlands, 2013; Volume 32, pp. 349–354.
9. Zaghez, I.; Attoui, R.; Saou-Dufrêne, B.N. Restoration and Sustainability of Earthen Architecture: Ksar Khanguet Sidi Nadji in the Algerian Sahara as a Case Study. *Res. Sq.* **2023**. [CrossRef]
10. Leiermann, T. Rehabilitation of historic Shibam and Zabid, Yemen as an impulse for community and economy. *Built Herit.* **2021**, *5*, 20. [CrossRef]
11. El-Mahllawy, M.S.; Kandeel, A.M. Engineering and mineralogical characteristics of stabilized unfired montmorillonitic clay bricks. *HBRC J.* **2014**, *10*, 82–91. [CrossRef]
12. Luo, Y.; Yang, M.; Ni, P.; Peng, X.; Yuan, X. Degradation of rammed earth under wind-driven rain: The case of Fujian Tulou, China. *Constr. Build. Mater.* **2020**, *261*, 119989. [CrossRef]
13. Mohamed, A.E.M.K. Improvement of swelling clay properties using hay fibers. *Constr. Build. Mater.* **2013**, *38*, 242–247. [CrossRef]
14. Hnaihen, K.H. The appearance of bricks in ancient mesopotamia. *Athens J. Hist.* **2020**, *6*, 73–96. [CrossRef]
15. Millogo, Y.; Aubert, J.-E.; Séré, A.D.; Fabbri, A.; Morel, J.-C. Earth blocks stabilized by cow-dung. *Mater. Struct.* **2016**, *49*, 4583–4594. [CrossRef]
16. La Noce, M.; Lo Faro, A.; Sciuto, G. Clay-based products sustainable development: Some applications. *Sustainability* **2021**, *13*, 1364. [CrossRef]
17. Dawood, A.O.; Mussa, F.I.; Al Khazraji, H.; Abd Ulsada, H.A.; Yasser, M.M. Investigation of compressive strength of straw reinforced unfired clay bricks for sustainable building construction. *Civ. Environ. Eng.* **2021**, *17*, 150–163. [CrossRef]
18. Vakili, A.; Selamat, M.; Moayedi, H.; Amani, H. Stabilization of dispersive soils by pozzolan. In *Forensic Engineering 2012: Gateway to a Safer Tomorrow*; ASCE: Reston, VA, USA, 2013; pp. 726–735.
19. Harichane, K.; Ghrici, M.; Kenai, S. Stabilization of Algerian clayey soils with natural pozzolana and lime. *Period. Polytech. Civ. Eng.* **2018**, *62*, 1–10. [CrossRef]
20. Bose, B. Geo engineering properties of expansive soil stabilized with fly ash. *Electron. J. Geotech. Eng.* **2012**, *17*, 1339–1353.
21. Ünsever, Y.S.; Diallo, M.L. Stabilization of Clay Soils Using Fly Ash. *Black Sea J. Eng. Sci.* **2019**, *2*, 81–87. [CrossRef]
22. Saidate, I.; Rikioui, T. Stabilization of gypsum clay soil by adding lime. *Civ. Eng. J.* **2022**, *8*, 2511–2520. [CrossRef]
23. Singh, J.; Singh, U.; Singh, R. Stabilization of clayey soil using gypsum and calcium chloride. *Int. J. Recent Technol. Eng.* **2020**, *9*, 668–673. [CrossRef]
24. Iskandar, R.; Hastuty, I.; Lubis, A. A study of the effectiveness of the use of gypsum and volcanic ash against the stability of clay soil in terms of UCT and CBR values. *IOP Conf. Ser. Mater. Sci. Eng.* **2018**, *309*, 012025.
25. Barman, D.; Dash, S.K. Stabilization of expansive soils using chemical additives: A review. *J. Rock Mech. Geotech. Eng.* **2022**, *14*, 1319–1342. [CrossRef]
26. Dao, K.; Ouedraogo, M.; Millogo, Y.; Aubert, J.-E.; Gomina, M. Thermal, hydric and mechanical behaviours of adobes stabilized with cement. *Constr. Build. Mater.* **2018**, *158*, 84–96. [CrossRef]
27. Boffoue, M.O.; Kouadio, K.C.; Kouakou, C.H.; Assande, A.A.; Dauscher, A.; Lenoir, B.; Emeruwa, E. Influence de la teneur en ciment sur les propriétés thermomécaniques des blocs d'argile comprimée et stabilisée. *Afr. Sci. Rev. Int. Des Sci. Technol.* **2015**, *11*, 35–43.
28. Wang, S.; Gainey, L.; Baxter, D.; Wang, X.; Mackinnon, I.D.; Xi, Y. Thermal behaviours of clay mixtures during brick firing: A combined study of in-situ XRD, TGA and thermal dilatometry. *Constr. Build. Mater.* **2021**, *299*, 124319. [CrossRef]
29. Khoudja, D.; Taallah, B.; Izemmouren, O.; Aggoun, S.; Herihiri, O.; Guettala, A. Mechanical and thermophysical properties of raw earth bricks incorporating date palm waste. *Constr. Build. Mater.* **2021**, *270*, 121824. [CrossRef]

30. Layachi, S.; Izemmouren, O.; Dakhia, A.; Taallah, B.; Atiki, E.; Almeasar, K.S.; Layachi, M.; Guettala, A. Effect of incorporating Expanded polystyrene beads on Thermophysical, mechanical properties and life cycle analysis of lightweight earth blocks. *Constr. Build. Mater.* **2023**, *375*, 130948. [CrossRef]
31. Zaidi, A.; Izemmouren, O.; Taallah, B.; Guettala, A. Mechanical and durability properties of adobe blocks filled with date palm wastes. *World J. Eng.* **2022**, *19*, 532–545. [CrossRef]
32. Khalil, U.; Aslam, B.; Kazmi, Z.A.; Maqsoom, A.; Qureshi, M.I.; Azam, S.; Nawaz, A. Integrated support vector regressor and hybrid neural network techniques for earthquake prediction along Chaman fault, Baluchistan. *Arab. J. Geosci.* **2021**, *14*, 2192. [CrossRef]
33. *ISO 17892-4:2016*; Geotechnical Investigation and Testing—Laboratory Testing of Soil—Part 4: Determination of Particle Size Distribution. AFNOR: La Plaine Saint, France, 2018; p. 41.
34. Wang, S.; Gainey, L.; Mackinnon, I.D.; Xi, Y. High-and low-defect kaolinite for brick making: Comparisons of technological properties, phase evolution and microstructure. *Constr. Build. Mater.* **2023**, *366*, 130250. [CrossRef]
35. Abbas, S.N.; Qureshi, M.I.; Alkharisi, M.K.; Alturki, M.; Ahmad, Z. Combined effect of silica fume and various fibers on fresh and hardened properties of concrete incorporating HDPE aggregates. *Constr. Build. Mater.* **2024**, *445*, 137940. [CrossRef]
36. Ouedraogo, M.; Dao, K.; Millogo, Y.; Aubert, J.-E.; Messan, A.; Seynou, M.; Zerbo, L.; Gomina, M. Physical, thermal and mechanical properties of adobes stabilized with fonio (*Digitaria exilis*) straw. *J. Build. Eng.* **2019**, *23*, 250–258. [CrossRef]
37. Millogo, Y.; Hajjaji, M.; Ouedraogo, R. Microstructure and physical properties of lime-clayey adobe bricks. *Constr. Build. Mater.* **2008**, *22*, 2386–2392. [CrossRef]
38. Ho, L.S.; Nakarai, K.; Duc, M.; Le Kouby, A.; Maachi, A.; Sasaki, T. Analysis of strength development in cement-treated soils under different curing conditions through microstructural and chemical investigations. *Constr. Build. Mater.* **2018**, *166*, 634–646. [CrossRef]
39. *EN 12390-3:2019*; Testing Hardened Concrete—Part 3: Compressive Strength of Test Specimens. iTeh Standards: San Francisco, CA, USA, 2019.
40. Suparp, S.; Ejaz, A.; Khan, K.; Hussain, Q.; Joyklad, P.; Saingam, P. Load-bearing performance of non-prismatic RC beams wrapped with carbon FRP composites. *Sensors* **2023**, *23*, 5409. [CrossRef] [PubMed]
41. *ASTM D2166-06*; Standard Test Method for Unconfined Compressive Strength of Cohesive Soil. ASTM: West Conshohocken, PA, USA, 2013.
42. *NF EN 196-1*; Méthodes d'essais des Ciments-Partie 1: Détermination des Résistances Mécaniques. AFNOR: La Plaine Saint, France, 2006.
43. Taallah, B.; Guettala, A.; Guettala, S.; Kriker, A. Mechanical properties and hygroscopicity behavior of compressed earth block filled by date palm fibers. *Constr. Build. Mater.* **2014**, *59*, 161–168. [CrossRef]
44. *XP P13-901*; Briques et Blocs de terre crue pour murs et cloisons—Définitions—Spécifications—Méthodes d'essai—Conditions de réception. AFNOR: La Plaine Saint, France, 2022; p. 35.
45. Rosone, M.; Megna, B.; Celauro, C. Analysis of the chemical and microstructural modifications effects on the hydro-mechanical behaviour of a lime-treated clay. *Int. J. Geotech. Eng.* **2021**, *15*, 447–460. [CrossRef]
46. Boonjaeng, S.; Chindaprasirt, P.; Pimraksa, K. Lime-calcined clay materials with alkaline activation: Phase development and reaction transition zone. *Appl. Clay Sci.* **2014**, *95*, 357–364. [CrossRef]
47. Pkla, A.; Mesbah, A.; Rigassi, V.; Morel, J. Comparaison de méthodes d'essais de mesures des caractéristiques mécaniques des mortiers de terre. *Mater. Struct.* **2003**, *36*, 108–117.
48. Usman, M.; Yaqub, M.; Auzair, M.; Khaliq, W.; Noman, M.; Afaq, A. Restorability of strength and stiffness of fire damaged concrete using various composite confinement techniques. *Constr. Build. Mater.* **2021**, *272*, 121984. [CrossRef]
49. Koadri, Z.; Benyahia, A.; Deghfel, N.; Belmokre, K.; Nouibat, B.; Redjem, A. Étude de l'effet du temps de traitement alcalin de fibres palmier sur le comportement mécanique des matériaux à base d'argile rouge de la région de M'sila. *Matériaux Tech.* **2019**, *107*, 404. [CrossRef]
50. Shubbar, A.A.; Sadique, M.; Kot, P.; Atherton, W. Future of clay-based construction materials—A review. *Constr. Build. Mater.* **2019**, *210*, 172–187. [CrossRef]