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Engineering and mineralogical characteristics of stabilized unfired montmorillonitic clay bricks



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Abstract This paper presents engineering and mineralogical characteristics of stabilized unfired montmorillonitic clay bricks treated by different curing methods. Quicklime (up to 30 wt.%) and Portland cement (up to 15 wt.%) at different proportions were used as stabilizers to Egyptian montmorillonitic clay in clay-based mixtures. Sand was used in the formulations of the unfired clay brick specimens. The formulated clay specimens were treated by moisture and spray techniques until 90 days of curing. The laboratory unfired stabilized clay specimens were identified using X-ray diffraction technique. In addition, physical and mechanical properties were measured according to the Egyptian Standard Specification (ESS) 1234-2005 and evaluated in accordance with the Egyptian Code for Building Units (ECP) 204-2005 to ensure the quality and impact of the made unfired clay specimens.

The quantification of the formed phases demonstrated a detrimental effect of calcium silicate hydrates (C-S-H), portlandite ($\text{Ca}(\text{OH})_2$) and calcite (CaCO_3) phases in the studied samples. The physico-mechanical results of the specimens cured by the moisture method were higher than those treated by the spray of the same sample. In all cases, the test results suggested that cement amended specimen properties rather than lime. Moreover, as explained from the obtained physico-mechanical properties, calcium hydroxide generated from the hydration of cement is more reactive than that from the hydration of the added lime. Also, it is recommended to use the suitable mixture for rural building construction in tropical countries.

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Introduction

Mud brick construction is not a new technology and dates back, in various forms, to several thousands of years ago. Clay has the ability to regulate the internal relative humidity level to the most comfortable level for humans. Also, it has a well insulated and airtight house which means only less heating is necessary, which is cheaper. The shortage of low cost and

affordable housing in Egypt has led to many investigations into new building masonry materials. Fired clay masonry bricks are conventionally used for mainstream masonry wall construction but suffer from rising price of energy plus other related environmental problems, such as high energy usage and carbon dioxide, fluorine, and sulfur emission. The use of stabilized unfired clay bricks for masonry construction may solve these problems. It may become a vital technology for the future of construction here in Egypt and especially in areas that have a good reserve of desert clays as source materials. Thus, allowing people to live in a healthy environment, with improved social, economic and environmental conditions.

In the past, unfired clay soil has been a traditional construction material in rural regions. This material was in various forms such as sun-baked bricks, mortars and plasters. This is because of its simplicity, low cost, good thermal and acoustic properties. In addition, the clay material can easily be reused by grinding and wetting without any interference with the environment aided this material's flexibility, as a sustainable material.

However, the main deficiency of unstabilized clay soil is its susceptibility to water damage but this problem is now overcome by the stabilization methods. Works on the use of some materials and waste types (Portland cement, lime, tea waste, GGBS, fly ash, cement kiln dust, recycled bassanite and coal ash, etc.) in order to study their feasibility in the unfired clay brick making or improving their properties, as stabilizers, have been conducted by many researchers [1–7]. The addition of lime ($\text{Ca}(\text{OH})_2$ or CaO) to soil in the presence of water will increase the pH due to the presence of OH^- ions up to a maximum value of about 12.4. Under these conditions of high pH, pozzolanic reactions occur, the Si and Al that form a part of the clay matrix dissolve and combine with the available free Ca^{2+} resulting in cementation compounds such as calcium silicate hydrate (C-S-H) and calcium aluminate hydrate (C-AI-H) gels [8]. These hydrated compounds are responsible for improving the mechanical properties of the clay soil. The improvement rate increases overtime as the pozzolanic reactions developed.

This paper presents an investigation on the engineering and mineralogical characteristics of stabilized montmorillonitic unfired clay bricks treated with two curing conditions. This paper is aimed at contributing toward the application of this unfired technology in the building industry and providing knowledge on the engineering performance of the unfired bricks, ensuring this is widely available to the fired clay sector and other building material manufacturers.

It is important to mention that this study is one of the earliest attempts in Egypt to use this technology accompanied with commercial binding agents in the stabilization of montmorillonitic clay for the unfired clay making.

Materials and methods

The starting materials used for the current research are clay, two different types of stabilizers [Portland cement (PC), and quicklime (QL)] and sand. The used clay sample was collected from a clay quarry located beside Kafr Homied village (50 km south of Cairo), Giza governorate, Egypt. It is grayish green, massive, damped and saliferous in some parts. It belongs to the claystone deposits of the Late Eocene age [9]. Use of the selected clay deposits is challenging because it is salty and of montmorillonitic type, as mentioned later. This type of clay

was selected since it is one of the most common clay deposits all over Egypt. The used Portland cement is of CEM (I) 42.5 type according to BS EN [10]. It was supplied by the Suez Cement Company, Suez city, Egypt. The quicklime (calcium oxide) was purchased from the Egyptian market.

The used clay raw material and the made unfired clay specimens were analyzed by powder X-ray diffraction (XRD) for mineralogical characterization. The used XRD apparatus was a X'Pert PRO PW3040/60 (PANalytical) diffractometer equipped with monochromatic $\text{Cu-K}\alpha$ radiation source. The test was run at 40 kV and 30 mA. A continuous mode was used for collecting data in the 2θ range from 3° to 30° at a scanning speed of $2^\circ/\text{min}$. The acquired data were identified using X'Pert high score software works with a PDF-2 database. The chemical composition (major oxides) of the starting materials was determined by X-ray fluorescence (XRF). Bogue's equations were used by the XRF to determine the approximate proportions of the main phases in Portland cement. The used XRF was an Axios sequential spectrometer manufactured by PANalytical, Netherlands. Also, traditional manual methods prescribed in the ASTM for determination of the loss on ignition [11], (LOI), and insoluble residue [12] were followed. The free swell test was determined for the used clay sample according to the method suggested by Holtz and Gibbs [13].

The prepared specimens were tested for water absorption, bulk density and compressive strength at the end of curing periods. These basic properties were carried out in accordance with the Egyptian Standard Specification [14]. The Egyptian code [15] was followed for assessment of the obtained results. In order to establish the durability of the test specimens in wet environments, water absorption test was used for this purpose. Particle size distribution for the used materials was determined using either dry sieve analysis for the quicklime and sand or laser diffraction analyzer (manufactured by Horiba, LA-950, France) for the dispersed materials of Kafr Homied clay and Portland cement samples with suitable treatments.

Mix compositions and specimen preparation

In order to investigate effect of the used stabilizer on the properties of the unfired stabilized clay specimens, four suggested mixtures, namely AM0, AM, AMII and AMIII, were designed for the study. Due to the high strength requirement in the building industry, high stabilizer dosages up to 30% were used as given in Table 1.

The reason for using quicklime was because it has been successfully used for stabilization of clays at low temperature regions for road construction for the improvement of slop stability. Quicklime removes water from the mix or surrounding soil providing them rapid stability [16]. Portland cement was encouraged for using in the stabilization because it acts as a material that binds together solid bodies like aggregate and soil by hardening after mixing with water. The rigidity was developed and then steadily increased in compressive strength (hardens) by chemical reactions with water (hydration). The sand as non-plastic material was used to make the final product durable [17] in addition, to reduce the effect of shrinkage of the clay that may occur as well as it may accelerate the formation of C-S-H phases. On the other hand, it is observed from Table 1 that as the PC content increased the required water for good consistency increased.

Table 1 Mix compositions of the unfired clay specimens, wt.%.

Mix code	Mix ingredients				Water/solid ratio
	Portland cement	Quicklime	Sand	Clay	
AM0	0	0	15	75	0.35
AMI	0	30	15	55	0.40
AMI	10	20	15	55	0.44
AMIII	15	15	15	55	0.50

The prepared mixtures were homogenized in a laboratory blender for 5 min, except the cement, then mixed with a suitable amount of water to reach a wetting mixture (first stage). The prepared mixtures were left in covered buckets for 3 days then the cement content was added and mixed with water to get the consistency needed (second stage). The water/solid ratio was adjusted to achieve ease molding as to match processing technology for the clay brick manufacturing in Egypt, the plastic method was adopted for making the specimens in the lab easy to be molded without a pressing machine. The prepared mixtures were hand molded in 5 cm-side length cube. After 24 h, the formed specimens were demolded and stacked covered under polythene sheets for 3 days, till initial hardening commences. Thereafter, a number of the prepared specimens were stored in a stainless steel container at $35\text{ }^{\circ}\text{C} \pm 2$ and $85\% \pm 2$ relative humidity for 7, 28 and 90 days. Such conditions are called the moisture method. The other specimens were sprinkled by water to be damped 3 times a day and placed uncovered at the normal lab environment of $20\text{ }^{\circ}\text{C} \pm 3$ and $50\% \pm 3$ relative humidity (winter season). Such treatment is called the spray method. At the end of the curing period, all the specimens were tested for water absorption, bulk density and compressive strength.

Results and discussion

Characteristics of the raw materials

The chemical composition, loss on ignition (LOI) and insoluble residue, if determined, of the raw materials used are depicted in Table 2. The used quicklime (QL) belongs to a non-fat class according to the Egyptian Standard Specification [18]. The chemical composition of used Portland cement (PC) and its corresponding phase composition (Table 3) achieved

Portland cement type of CEM (I) 42.5. The used clay matches average chemical and mineralogical compositions (Tables 2 and 4 and Fig. 1) of the Egyptian montmorillonitic clays. It is mainly composed of montmorillonite, kaolinite and illite minerals in descending order of abundance in addition to traces of non-clay minerals such as quartz, halite and feldspar. Results of the used sand got the expected chemical composition, consisted mainly of SiO_2 .

Table 5 shows that particles of the used QL and sand materials are totally passed through 10 mm sieve and retained on 0.150 mm sieve diameter. As given in Table 6, more than 90% of the PC grains are less than $45\text{ }\mu\text{m}$ and more than 87% of the KHC sample is within the clay size. The high specific surface, good material size distribution and good mix of pozzolanic oxides give better mechanical strength and hydration profile [19]. The tested clay sample attained 300% in the free swell test. According to Ahmed [20], it is an extreme high potential sample for swelling giving verification to the presence of high content of montmorillonite mineral.

Mineralogy of the unfired montmorillonitic clay specimen

Figs. 2–7 represent XRD patterns of the stabilized unfired montmorillonitic clay specimens treated by the moisture and spray methods as a function of curing time. It was observed that the examined specimens of mixture AMI (without cement addition) have the highest peak intensity of calcite and the lowest height one of quartz mineral. This can be attributed to the high content of added quicklime (30 wt.%) and its reaction with the atmospheric carbon dioxide where carbonation becomes predominant. The calcite phase in all patterns was developed in the specimens treated by the spray method due to carbonation effect. The excessive carbonation of the samples limited the formation of the cementing hydrated

Table 2 Chemical compositions in terms of oxide content, insoluble residue and loss on ignition of the raw materials, wt.%.

Oxide content (%)	Quicklime (QL)	Portland cement (PC)	Clay	Sand
SiO_2	1.61	20.49	60.14	93.88
Al_2O_3	0.39	4.02	9.69	3.76
Fe_2O_3	0.24	3.31	7.63	0.68
CaO	68.38	62.71	5.15	0.55
MgO	1.52	1.95	2.11	0.37
Na_2O	0.01	0.47	5.76	0.21
K_2O	0.05	0.18	0.88	0.09
SO_3	0.61	3.04	0.15	0.02
TiO_2	0.01	0.02	1.24	0.10
Insoluble residue	ND	0.64	ND	
L.O.I	26.82	3.81	6.28	0.23

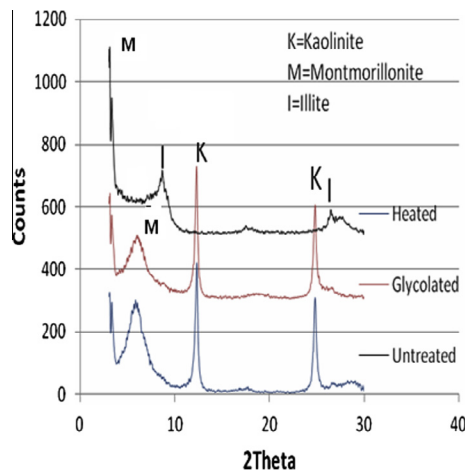
ND, Not determined.

Table 3 Phase composition of the Portland cement used as calculated by XRF.

Cement notation (Phase)	Oxide formula	% composition (calculated)
C ₃ S (Alite)	3 CaO·SiO ₂	58.88
C ₂ S (Belite)	2 CaO·SiO ₂	14.41
C ₄ AF (Ferrite)	4 CaO·Al ₂ O ₃ ·Fe ₂ O	10.07
C ₃ A (Celite)	3 CaO·Al ₂ O ₃	5.06

Table 4 Mineralogical composition of Kafr Homeid clay (KHC) sample.

Minerals	Chemical formula	% Composition in KHC
Montmorillonite	(Na, Ca) _{0.3} (Al, Mg) ₂ Si ₄ O ₁₀ (OH) ₂ ·n(H ₂ O)	57
Kaolinite	Al ₂ Si ₂ O ₅ (OH) ₄	26
Illite	(K, H ₃ O)(Al, Mg, Fe) ₂ (Si, Al) ₄ O ₁₀ [(OH) ₂ , (H ₂ O)]	5
Quartz	SiO ₂	7
Halite	NaCl	3
Feldspar	CaAlSi ₃ O ₈	2

**Fig. 1** XRD patterns of the heated, glycolated and untreated KHC fraction.**Table 5** Particle size analysis for quicklime and sand by dry sieving.

Sieve (mm)	Passing (%)	
	Quicklime (QL)	Sand
10	100.0	100.0
2.36	97.9	99.9
1.18	95.2	99.4
0.600	92.3	95.2
0.300	87.4	80.5
0.150	0.0	0.0

compound and forms heterogeneous microstructure [21]. It was confirmed in Figs. 2 and 3 whereas the C-S-H peaks exhibited as weak reflections. This could be assignable to poorly crystallized calcium silicate hydrates (C-S-H).

The decreasing of quartz crystallinity is presumably due its solubility in the medium which is linked to the increase of pH, due to lime addition. Also, it was found that lime addition tends to the development of calcite and poorly crystallized

Table 6 Grain size distribution of Kafr Homied clay and Portland cement as determined by laser diffraction analyzer.

Grain size (μm)	KHC (%)	Grain size (μm)	PC (%)
> 250	0.0	> 45	8.3
63–250	3.2	20–45	31.1
2–63	9.3	10–20	14.4
< 2	87.5	< 10	46.2

calcium silicate hydrate. This observation is in a good agreement with a previous study [21]. On the other hand, Millogo et al. [21] had found that the coarse grains of quartz in the mixture displayed surficial pits which apparently constituted preferential sites for C-S-H and/or calcite nucleation. This elucidated the importance of sand addition on the hydration product enlargement.

Also, it was noted that the portlandite phase development is decreased, and may be disappeared completely at 28 and/or 90 days of the specimens cured by the moisture method, with curing time at the expense of C-S-H formation. Altogether, the XRD patterns of Figs. 4–7 demonstrate that increasing of peak intensity of the formed C-S-H phase as well as decreasing of portlandite and calcite phases is associated with the increase of cement content and curing age as well as the treatment carried out by the moisture method. Thus, the highest peak intensity of the C-S-H phases and the lowest one of calcite phase as well as poorly developed portlandite phase were recorded in the XRD pattern of the mixture AMIII (15 wt.% PC and 15 wt.% QL) cured by the moisture method (Fig. 7).

Physico-mechanical properties of the unfired montmorillonitic clay specimens

Figs. 8 and 9 show the water absorption, bulk density, and dry/wet compressive strength of the stabilized unfired montmorillonitic clay specimens treated by the moisture and spray methods as a function of curing time. Wet compressive strength means the specimen was subjected to water submersion for 24 h before testing while dry one means specimens

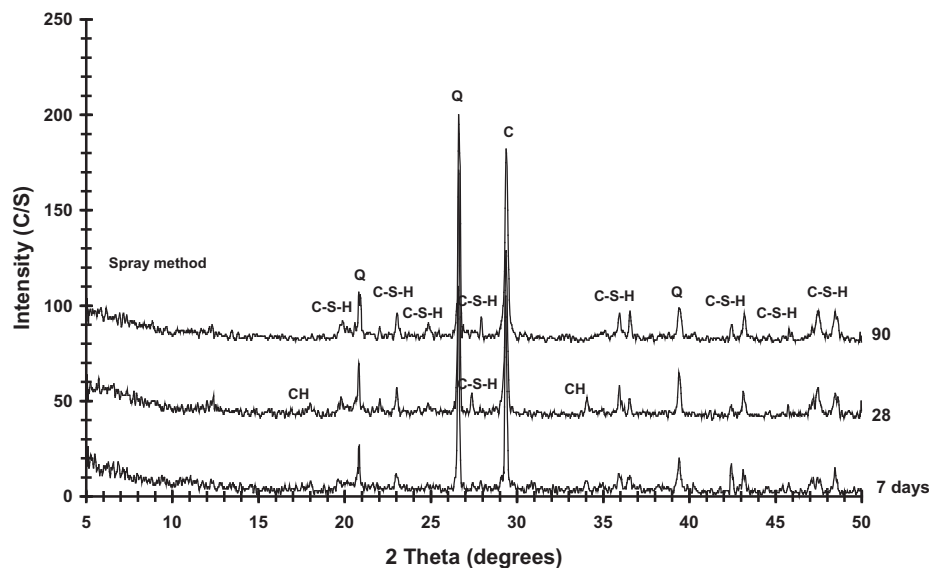


Fig. 2 XRD patterns of the AMI specimens treated by the spray method as a function of curing time (C-S-H, calcium silicate hydrates; Q, quartz; CH, portlandite).

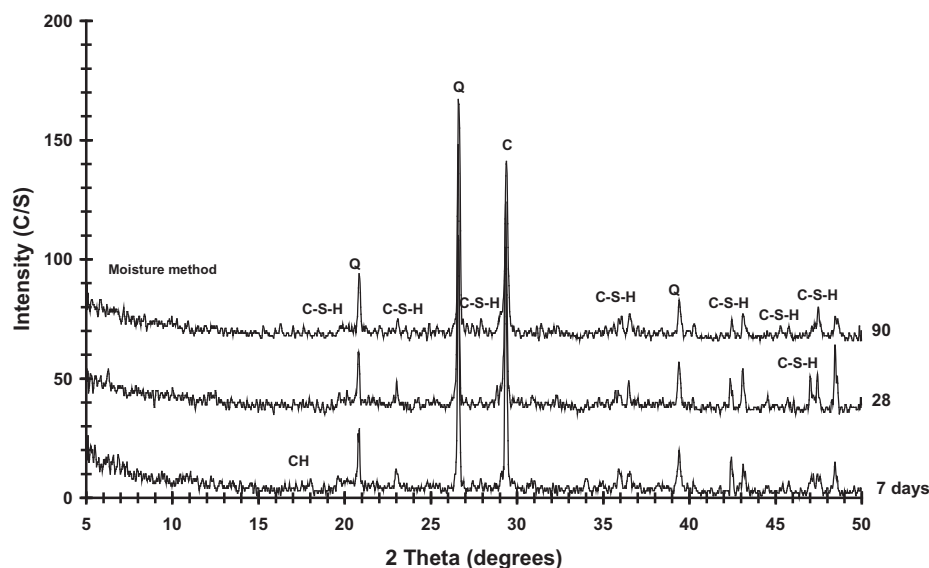


Fig. 3 XRD patterns of the AMI specimens cured by the moisture method as a function of curing time (C-S-H, calcium silicate hydrates; Q, quartz; CH, portlandite).

were dried in an electrical dryer at 60 °C for 8 h before performing the dry compressive strength test.

- All tested properties for specimens of the mixture AM0 cannot be determined at all curing times. This is due to that the specimens lost their geometrical shape during curing progress then distorted and finally collapsed, before 7 days.
- Water absorption test can be used as an indicator for the specimen's resistance to immersion in water. The results explained (Fig. 8) that amount of the absorbed water decreased as the cement dosage increased giving evidence that the cement plays a significant role in the impermeability of the tested specimens. It reached the best value (8.73%) in the AMIII specimens (15% PC + 15% QL)

cured by the moisture method. This is probably due to the increase of C-S-H phase development accompanied by portlandite phase decreasing, as detected obviously in the XRD patterns of the AMIII specimens cured by the moisture method (Fig. 7). Addition of cement promoted C-S-H formation which acts as cementing materials and binds the clay particles together, imparting strength to the clay body [22]. Also, for all specimens, water absorption decreased with curing time. This is attributed to transformation of the C-S-H after prolonged curing into a more crystallized calcium silicate hydrate as appeared in all XRD patterns of specimens cured by the moisture method rather than those treated by the spray method. This result goes parallel with the conclusions of James and Rao [23]. This is due to

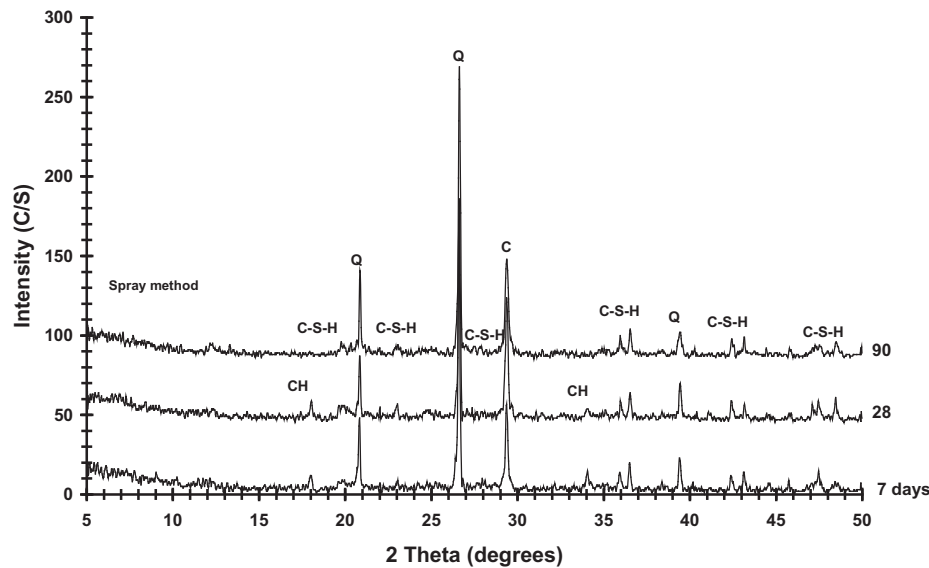


Fig. 4 XRD patterns of the AMII specimens treated by the spray method as a function of curing time (C-S-H, calcium silicate hydrates; Q, quartz; CH, portlandite).

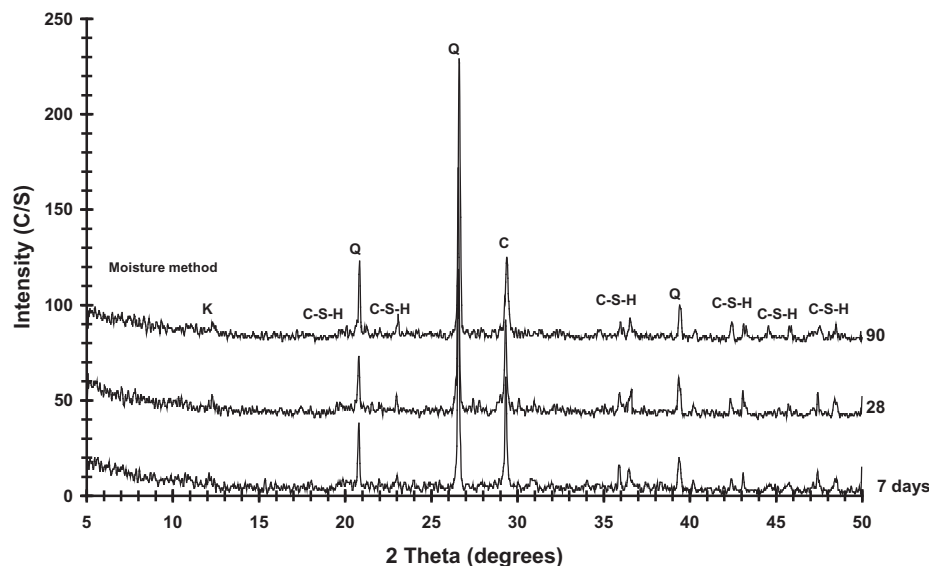


Fig. 5 XRD patterns of the AMII specimens cured by the moisture method as a function of curing time (K, kaolinite; C-S-H, calcium silicate hydrates; Q, quartz; CH, portlandite).

the formation and accumulation of the formed C-S-H and closes some of the open pores then decreases their affinity to absorb water.

Moreover, the specimens cured by the moisture method achieved better water absorption values compared to those treated by the spray method. This is confirmed by enhancement of the water absorption of the specimens cured by the moisture method with not less than 40% compared to specimens of the other method. This may be due to the carbonation effect in the specimens treated by the spray method giving an opportunity to excessive formation of calcite as appeared clearly in the XRD pattern of the AMI specimens (Fig. 2). It is worth mentioning that the water absorption readings of the AMI specimens (30% QL, without PC) treated by the

spray method cannot be determined due to their collapsing upon immersion in water. This indicates the efficiency of the moisture method on the development of durable specimens. The ECP [15] requires the maximum water absorption of 20% as a standard for clay masonry brick used for non-load bearing walls. Based on the test results, all stabilized specimens cured by the moisture method achieved the ECP requirements and only the AMIII specimens treated by the spray method and cured for 90 days fulfilled the ECP requirements.

- In terms of bulk density (Fig. 8) of the unfired stabilized clay specimens, it is increased with curing time. The highest value was achieved by specimens of the mixture AMIII (1.52 g/cm³) at the end of 90 days of moist curing period. In other words, as cement content increases at the expense

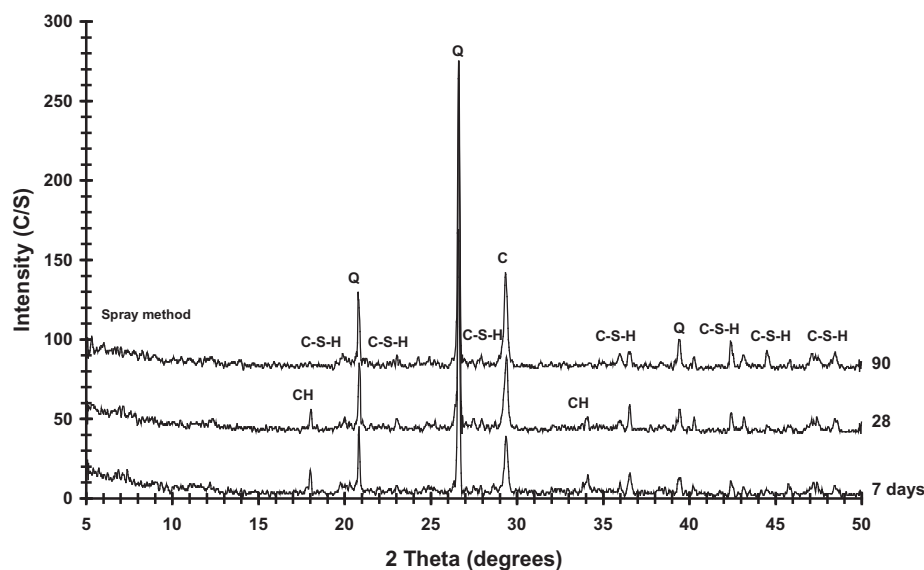


Fig. 6 XRD patterns of the AMIII specimens treated by the spray method as a function of curing time (C-S-H, calcium silicate hydrates; Q, quartz; CH, portlandite).

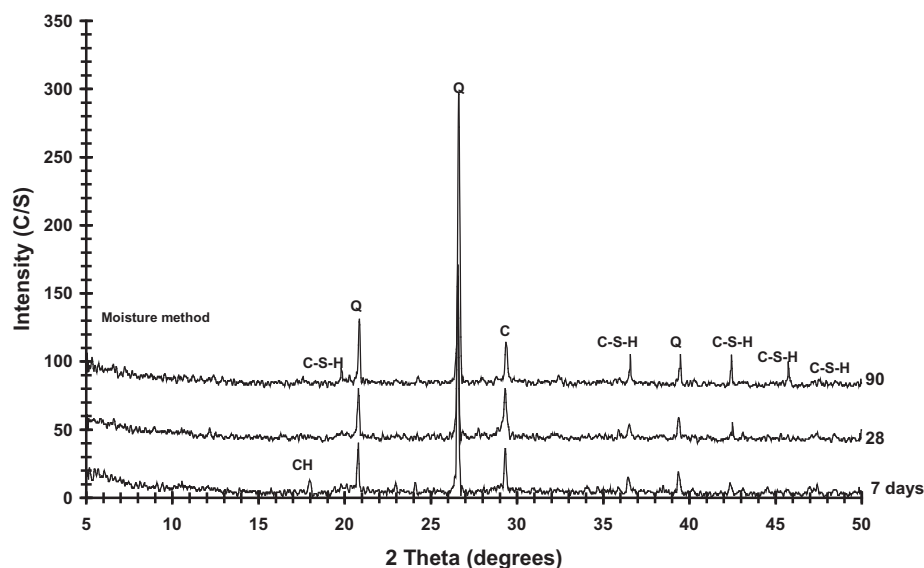


Fig. 7 XRD patterns of the AMIII specimens cured by the moisture method as a function of curing time (C-S-H, calcium silicate hydrates; Q, quartz; CH, portlandite).

of lime, the bulk density increases giving evidence for densification. As identified in the XRD patterns, C-S-H phases increased with the cement as well as curing time, C-S-H density is almost 2.0 g/cm^3 . These formed phases may fill the void spaces and blinds the materials in the stabilized clay specimens leading to a decrease in water absorption and increase in bulk density. Thus, the specimens of the mixture AMIII that have the highest content of the C-S-H phases have the lowest water absorption values (18.40% and 8.73%) and the highest bulk density values (1.42 and 1.52 g/cm^3) corresponding to the spray and moisture methods, respectively.

– Fig. 9 pointed that the compressive strength increases with prolongation of curing time. Dry compressive strength values are higher than those of the wet results. Wet

compressive strength of the specimens of AMI at all curing times, and of the specimens of the AMII at 7 days cannot be determined due to either their collapsing in water or softening. This is attributed to breakdown of weak chemical bonds between stabilized constituents. Also, as mentioned before at all tested properties the cured specimens by the moisture method got higher values than those treated by the spray method. The figure shows that maximum compressive strength is gained by the AMIII cured specimens by the moisture method due to the addition of cement that has a positive effect on the strength. This is attributed to the continuous hydration forming more C-S-H as binding agent. This is previously discussed that $\text{Ca}(\text{OH})_2$ has no cementing properties in comparison with Portland cement. Also, the results explained that the loss of strength

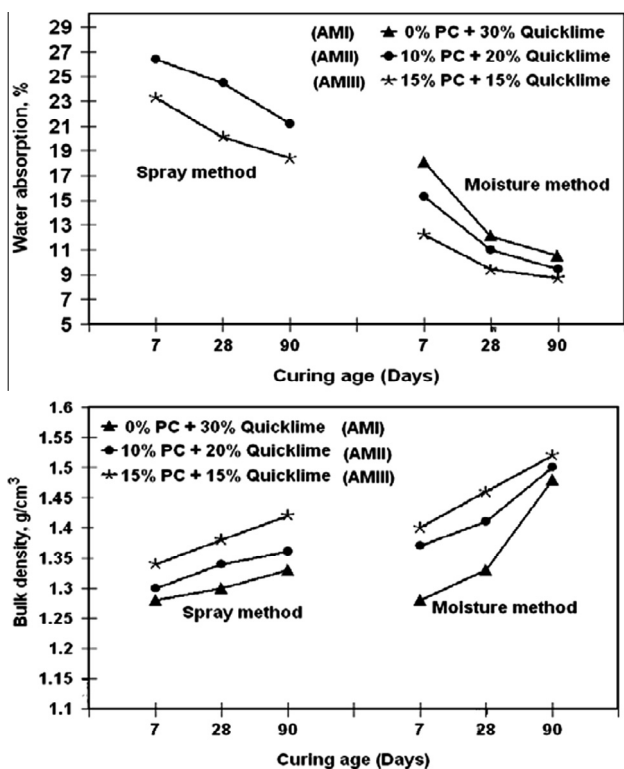


Fig. 8 Effect of stabilizer's percentage and curing time on water absorption and bulk density of the unfired stabilized test specimens at different treatment methods.

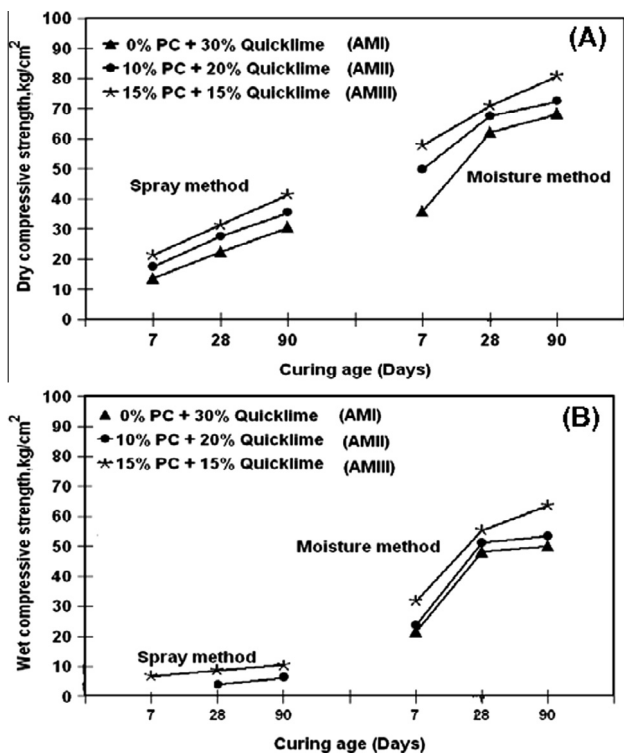


Fig. 9 Effect of stabilizer's percentage and curing time on dry (A) and wet (B) compressive strength of the unfired stabilized test specimens at different treatment methods.

increased with the lime content. This is due to lime that has a slow setting time and gains its strength overtime. In terms of comparing the strength development, cement is the more effective stabilizing agent compared to lime. The Egyptian code [15] requires the minimum wet compressive strength of 40 kg/cm² as a standard for clay masonry brick used for non-load bearing walls. Based on the test results, all stabilized specimens cured only for 28 and 90 days by the moisture method achieved the ECP requirements, on the contrary, all stabilized specimens treated the spray method did not fulfill the ECP requirements. However, when the lime dosage was too high, the strength gained was not as high because of a decrease in the dry density as occurred in specimens of the mixture AMI (30 wt.% QL).

On the whole, the improvement of the physico-mechanical properties is attributed to the cementing character of C-S-H and to the presence of minor amounts of calcite and portlandite phases. Too much formation of the latter compounds led to the reduction of the mechanical resistance and the increase of porosity, proved by an increase of water absorption. When cement is mixed with water and hydrates, the most important hydrated products of C-S-H and calcium hydroxide (CH) are formed. The C-S-H is responsible for binding the clay particles. The CH liberated during the hydration of Portland cement can react with C₃A and C₄AF forming other additional hydration products. Also, as the hydration proceeds more hydration products (C-S-H) are formed and accumulated within the pore system in the specimens. Therefore, the porosity decreases and then the compressive strength and bulk density increase.

The XRD patterns revealed that the portlandite phase (CH) decreases with curing time may disappear with long time, secondary cementing material is formed by the release of silicates from the clay and their combination with calcium from CH. Calcium hydroxide generated from hydration of cement is believed to be more reactive than that produced from lime hydration as observed from the obtained physico-mechanical results. CH created from the hydration of cement products is very fine and well dispersed throughout the soil [24].

In terms of the lime addition influence, it is worth mentioning that it was expected that lime plays a more important contribution than that obtained from results of the physico-mechanical properties of the stabilized clay specimens due to its short and long-term reactions. It was anticipated to induce a flocculation of the clay colloids by its high concentration of calcium and hydroxide ions which may transform the plastic clay into a granular state giving a profound influence of the properties of the stabilized unfired specimens. The reason for this may mainly be attributed to the type of the clay used. Montmorillonitic type is not reactive like kaolinite. The quicklime used may encounter some difficulties to continue its real role, such as its high content in some mixtures, especially in AMI (30 wt.%), and/or consuming of Ca²⁺ in encouraging formation of calcite mineral rather than C-S-H cementing phases. Also, many researchers [25–26] have reported that a low quantity of C-S-H gel is formed in a high pH of high alkaline system. However, effect of pH on the structure and composition of C-S-H gel is still controversial [4]. In other words, lime has an optimal content for the maximum possible strength gain, which mainly depends on clay type and mineralogy. Clays containing montmorillonite may require adequate con-

tent, not too high, to achieve higher strengths, because montmorillonite may be more receptive to pozzolanic reactions due to its high specific area which allows greater access to silica or alumina in the clay. It is suggested here to add pozzolana (siliceous or siliceous and aluminous material) with lime to advance its role by its pozzolanic reaction with calcium hydroxide in the presence of water forming insoluble calcium silicate hydrate and calcium aluminate hydrate compounds as cementing products.

Evaluation of the studied specimens with selected environmental concerns

Table 7 shows the energy and carbon dioxide emission values found in the literature for the most common stabilizers [27–28]. These values were used as inputs for the binder combinations in the current study using the dosage levels adopted. The given values clarified that PC has the highest sum of all the energy required to be produced simultaneous with CO₂ emission followed by lime than granulated ground blast-furnace slag (GGBFS).

Table 8 represents the calculated energy and CO₂ emission values for the binder combinations used in the study, taken into consideration values anticipated in Table 7. As clear that the mixture AMI containing 30% lime has the lowest energy consumption and CO₂ emission but still is not recommended to be used as a stabilizer for unfired clay bricks. Also, the

Table 7 Embodied energy and CO₂ emission of widely quoted binders of PC, lime and ground-granulated blast-furnace slag (GGBFS).

Stabilizer	Stabilizer (100%)	
	Energy (MJ/t)	CO ₂ (kg/t)
Lime	4000	800
PC	5000	1000
GGBFS	1300	70

Table 8 Calculated energy and CO₂ emission values for the binder combinations used in the study.

<i>(a) Stabilizer combinations</i>	
Binder combinations (Mix code)	Binder content (%)
Lime (AMI)	30
PC-Lime (AMII)	10 PC + 20 Lime
PC-Lime (AMIII)	15 PC + 15 Lime
<i>(b) Energy inputs</i>	
Binder combinations (Mix code)	Energy consumption (MJ/t)
Lime (AMI)	30% of 4000 = 1200
PC-Lime (AMII)	10% of 5000 + 20% of 4000 = 1300
PC-Lime (AMIII)	15% of 5000 + 15% of 4000 = 1350
<i>(c) CO₂ emission</i>	
Binder combinations (Mix code)	CO ₂ amount (kg/t)
Lime (AMI)	30% of 800 = 240
PC-Lime (AMII)	10% of 1000 + 20% of 800 = 260
PC-Lime (AMIII)	15% of 1000 + 15% of 800 = 270

Table 9 Quantification of energy usage and CO₂ emission for the lab made unfired stabilized specimens.

<i>(a) Analysis of energy usage</i>	
Brick type	Quantification of energy usage (MJ/t)
Fired clay bricks	4186.8 (Morton, 2008)
Sun-baked bricks	525.6 (Morton, 2008)
Unfired specimens of mix AMI	525.6 + 1200 = 1725.6
Unfired specimens of mix AMII	525.6 + 1300 = 1825.6
Unfired specimens of mix AMIII	525.6 + 1350 = 1875.6
<i>(b) Analysis of carbon dioxide emission</i>	
Brick type	Carbon dioxide emission (CO ₂ kg /t)
Fired clay bricks	202 (Morton, 2008)
Sun-baked bricks	25 (Morton, 2008)
Unfired specimens of mix AMI	25 + 240 = 265
Unfired specimens of mix AMII	25 + 260 = 285
Unfired specimens of mix AMIII	25 + 270 = 295

results explained that, as cement content increases the energy consumption and CO₂ emission increase.

Morton [29] estimated the energy input and CO₂ contribution for pressed sun-baked clay bricks to be 525.6 MJ/tonne and 25.0 kg CO₂ kg/tonne, respectively. Thus, extra inputs will be employed to the unfired clay specimens in the present research as shown in Table 9. This table presents energy inputs and emission outputs for the production process of 1 tonne of the unfired bricks and conventional fired bricks used as control. The total energy usage (MJ/t) for the studied mixtures was estimated between 1725.6 (AMI, 30 wt.% lime) and 1875.6 (AMIII, 15 wt.% PC + 15 wt.% QL). The carbon dioxide emissions (CO₂ kg/t) for the experimental unfired stabilized specimens were estimated between 265 (AMI) and 295 (AMIII). The studied mixtures have lower values than the fired bricks in the energy usage but they have higher values in the carbon dioxide emission. Furthermore, firing clay-based material generally results in the release of several gases besides carbon dioxide leading to further pollution rather than the studied mixtures. Traditional sun-baked bricks tend to have the least energy usage 525.6 MJ/tonne with emissions of 25.0 CO₂ kg/tonne. However, the main problem of sun-baked bricks is their weakness in contact with water; high susceptibility to water damage. In the current work, it is believed that the AMIII mixture (moisture method) may solve this problem due to its distinguished engineering properties for using for non-load bearing walls according to ECP [25]. Most notably, protection of the stabilized clay bricks from high humidity and prolonged wetness must be considered.

Conclusions

From the main research findings, it can be concluded that:

- (1) Excessive formation of portlandite, calcite and minor development of C-S-H affected negatively on the significant properties of the unfired stabilized montmorillonitic clay specimens as observed in the lime addition case (mixture AMI).
- (2) In terms of comparing the water absorption property and strength development, cement is more effective stabilizer compared to lime.

- (3) The physico-mechanical results of the specimens' moisture cured were higher than those treated by the spray method in the same mixture composition.
- (4) It is believed that the AMIII mixture (15 wt.% PC + 15 wt.% QL, moisture method) can be used successfully for non-load bearing walls according to ECP 204–2005. Most notably, protection of the stabilized clay bricks from high humidity and prolonged wetness must be considered.
- (5) Calcium hydroxide generated from the hydration of cement is found to be more reactive than hydrated lime.
- (6) It is recommended to reduce grain size of quartz, increase the duration of hydration and preserve the clay based pastes and specimens from air to improve physico-mechanical properties and decrease the carbonation affinity.
- (7) The unfired clay bricks exhibited respecting to the energy conscious and environmental concerns.
- (8) For extending this type of successful unfired clay bricks, the stabilized specimens must water cured to show their durability for water with curing time to be used for non-load bearing walls.

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