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MECHANICAL AND THERMAL BEHAVIORS OF STABILIZED COMPRESSED EARTH BLOCKS

COMPORTAMENTOS MECÂNICO E TÉRMICO DE TIJOLOS DE TERRA CRUA ESTABILIZADA

Regis de Castro Ferreira[1], **Maria Luiza de Carvalho Ulhôa**[2]
Universidade Federal de Goiás, Goiânia, GO.
[1]Doutor em Engenharia. E-mail: regisdecastroferreira@gmail.com
[2]Mestre em Engenharia do Meio Ambiente. E-mail: luizaled@gmail.com.

ABSTRACT

The effect of lime and Portland cement associated to sodium silicate (Na_2SiO_3) on the mechanical and thermal behavior of compressed earth blocks was analyzed. Mini panels were molded and their mechanical and thermal properties were determined in laboratory. For such, sandy and clayey soils were added with Portland cement and lime at 6% and 10% contents, and sodium silicate at dosage of 4%. The compressed earth blocks were cured in a humidity chamber for seven, 28, 56 and 91 days. At the ages of 28, 56 and 91 days the specimens were submitted to the compressive test and water absorption tests at seven days. The thermal conductivity was obtained by the guarded hot plate method and the specific heat value by the calorimeter method. Afterwards, the main thermophysical properties were calculated and analyzed by means of walls thermal behaviors. The best compressive strength and water absorption capacity results were reached by the sandy soil with addition of Portland cement or lime at 10% content, both added of sodium silicate. Regarding to the thermal behavior, the results pointed out that the stabilized compressed earth blocks reached the best thermal behavior when compared to the conventional ones under the same use conditions.

Keywords: Stabilized earth, Soil-cement, Mechanical properties, Thermophysical properties.

RESUMO

Foi analisado o efeito da adição de cimento e cal associados ao silicato de sódio (Na_2SiO_3) sobre o comportamento mecânico e térmico de tijolos prensados de terra crua. Mini painéis foram moldados e suas propriedades mecânicas e térmicas foram determinadas em laboratório. Para tal, cimento Portland e cal, nas dosagens de 6% e 10% e silicato de sódio, na dosagem de 4% foram adicionados a dois tipos de solos, um arenoso e outro argiloso. Os tijolos foram curados em câmara úmida por sete, 28, 56 e 91 dias. Os ensaios de compressão simples foram realizados nas idades de 28, 56 e 91 dias e os de absorção de água aos sete dias. A condutividade térmica foi obtida pelo método da placa quente e o calor específico foi determinado por calorímetro. As principais propriedades termofísicas foram calculadas e analisadas por meio do comportamento térmico de paredes. Os melhores resultados em termos de compressão simples e absorção de água foram alcançados pela mistura solo arenoso e cimento ou cal na dosagem de 10% associados ao silicato de sódio. Os resultados apontaram que os tijolos prensados de terra crua alcançaram melhor comportamento térmico comparados aos tijolos cerâmicos convencionais.

Palavras-Chave: Terra cura estabilizada, Solo-cimento, Propriedades mecânicas, Propriedades termofísicas.

1 – INTRODUCTION

For some time, due to economic, habitation and more recently energetic crises especially in developing countries, researchers have recovered techniques and materials offering appropriate solutions in the social, urban and rural dwellings constructions. The raw earth, that was of great accesses and low cost, has demonstrated to be an excellent technical and economic alternative for urban or rural constructions. The raw earth pressed blocks are unburned blocks and for that, have little energy consummation in their manufacturing process. In this way, great progress has been reached improving soil characteristic in construction material, especially by chemical additives as cement, lime, strong alkalis and fly ashes.

Even though Portland cement is more used and researched regarding soil stabilization as constructing material, currently, other alternatives, as lime have been researched (RAHEEM *et al.*, 2010; DEBOUCHA; HASHIM, 2011; OTI, KINUTHIA, 2012; CIANCIO; BECKETT; CARRARO, 2014; NAGARAJ *et al.*, 2014). Either cement or lime have noticeable distinctions on their active mechanisms and choices depend on which soil type will be stabilized. Lime stabilization refers to the process of adding either calcium oxide (*i.e.* quicklime) or calcium hydroxide ($Ca(OH)_2$) to soil in order to improve its properties (RAHEEM *et al.*, 2010). The stabilization results vary depending on the argil mineral nature and are better under high aluminium silicates, silk and iron hydroxide concentrations (OTI; KINUTHIA, 2012).

Soil treatment with strong alkalis favors quartz reacting with stabilized alkaline, same as for lime and Portland cement, making the initial resistance increase from 15% to 400% (FERREIRA; FREIRE, 2003). Sodium silicate

(Na_2SiO_3), sodium carbonate (Na_2CO_3) and sodium hydroxide (NaOH) are alkalis usually associated to cement for soil stabilization (FREIDIN; ERELL, 1995). The Na_2SiO_3 is used in soil stabilization because its reaction with soluble calcium salts in watery solutions to form insoluble calcium silicates. The hydrated calcium silicates are cement agents and improve soil stability filling in emptiness and expelling soil water (REN; KAGI, 1995).

The resurgence of renewed research interest in recent years in unfired clay building bricks may be partially due to its potential as a commercial construction material. Unfired clay bricks typically will not require painting and so can provide a structure with reduced life-cycle costs. The use of unfired clay bricks seems to have many benefits outside the obvious environment benefits of by-passing the firing process. The fact that a single element can fulfil several functions including structural integrity, thermal transmittance and durability in service makes the material an excellent walling material when compared to the bricks used in mainstream construction of today. With growing pressure on economic viability of buildings and new building regulations aimed at the reduction of the energy consumption, concern for thermal performance of internal enclosure has been on the increase. It can be stated therefore, that the unfired clay masonry bricks are among the feasible bricks for low to medium cost masonry wall construction. (OTI; KINUTHIA; BAI, 2010).

Mineral materials have a narrow relationship between thermal conductivity and dry density. However, for earth walls, both these requirements are generally opposed. Since density is usually required for other purposes, earth wall thermal performance depends more on thermal capacity than thermal resistance ASHOUR *et al.* (2015).

Researchers (DEMIRDA; GUNDUZ, 2008; SALA *et al.*, 2008; UTAMA; GHEEWAL, 2009) seem to agree that the thermal transmittance of a material used in building construction depends mainly on the material density, permanent moisture content and mineralogical composition.

Thus, the Colonial Building Notes n. 8 (BRS, 1952) reported a thermal conductivity value of 0.33 $W\ m^{-1}\ K^{-1}$ for rammed earth walls without any reference to density. Adam and Jones (1995) quoted that thermal conductivity values for earth products ranging from 0.33 to 2.20 $W\ m^{-1}\ K^{-1}$ failed to describe density with testing wall techniques.

Wall density values together with specific thermal heat values permit to determine the wall thermal capacity. The last value allows the thermal delay calculus of constructive elements. The knowledge of this thermophysical property is of great importance for building planning regarding thermal performance, principally in regions with high thermal amplitude. Likewise, earth construction systems have proven to be very efficient in maintenance of thermal comfort due to thermal insulation properties of earth as shown by Benardos; Athanasiadis; Katsoulakos (2014).

According the Brazilian Standard of thermal building performance (ABNT NBR 15220:2005b), the evaluation of thermal performance of a building can be made both in the design phase, and after the construction. Regarding building already constructed, the evaluating can be performed through *in-situ* measurements of representative variables performance, while at the design stage this assessment can be done by means of computer simulation or by checking compliance with constructive guidelines.

Table 1 presents construction recommendations, in thermal terms, for external walls of the eight Brazilian bioclimatic zones and the main cities and capitals for each zone. Such zones divide the Brazilian territory into eight relatively homogeneous climatic zones (Figure 1) and, for each one, there is a set of constructive and detailed recommendations strategies for a passive thermal condition.

Table 1 – External walls thermal recommendations for Brazilian bioclimatic zones

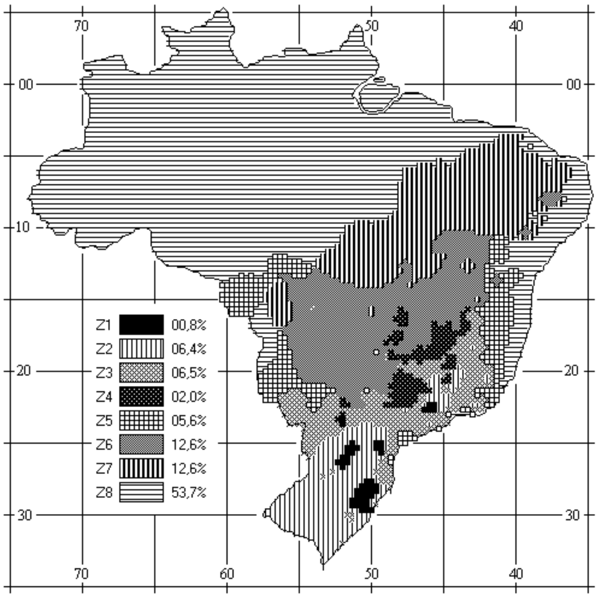
Zone	External walls	Main cities and capitals
1	Light	Curitiba, PR, Campos de Jordão, SP, Poços de Caldas, MG, São Joaquim, SC, Caxias do Sul, RS.
2	Light	Pelotas, RS, Piracicaba, SP, Ponta Grossa, PR, São João Del Rei, MG, Nova Friburgo, RJ, Laguna, SC.
3	Reflexive light	Belo Horizonte, MG, Ponta Porã, MS, Petrópolis, RJ, São Paulo, SP, Porto Alegre, RS, Florianópolis, SC, Foz do Iguaçu, PR.
4	Heavy	Brasília, DF, Patos de Minas, MG, Ribeirão Preto, SP, São Carlos, SP, Luziânia, GO,
5	Reflexive light	Vitória da Conquista, BA, Governador Valadares, MG, Niterói, RJ, Araçatuba, SP.
6	Heavy	Goiânia, GO, Campo Grande, MS, Montes Claros, MG, Presidente Prudente, SP.
7	Heavy	Cuiabá, MT, Teresina, PI, Imperatriz, MA, Petrolina, PE, Porto, Nacional, TO.
8	Reflexive light	Manaus, AM, Salvador, BA, Fortaleza, CE, São Luiz, MA, Belém, PA, Recife, PE, Aracajú, SE, Natal, RN, Porto Velho, RO, Rio de Janeiro, RJ

Source: ABNT NBR 15220:2005b.

Compared to Figure 1, Table 1 shows that great part of the Brazilian territory fits into zone 8 (53.7% of the territory). However, with exception to eastern seaside, this region has a smaller population density. The two bioclimatic regions of greater population density are in zone 3 (6.5%) followed by zone 2 (6.4%).

Thus, the aim of this paper is to investigate mechanical and thermal properties of stabilized soil blocks by determining effects of chemical additives incorporation (cement, lime and sodium silicate) and by their compliance with the Brazilian Standards of thermal building performance.

Figure 1 – Brazilian Bioclimatic chart



Source: ABNT NBR 15220:2005b

2 – MATERIALS AND METHOD

Physical and mechanic evaluations were done at the Laboratory of Test Material of the College of Agricultural Engineering and at the Laboratory of Building Structure of the College of Civil Engineering, both from the State University of Campinas in Campinas, São Paulo. The thermophysical experiments were conducted at the Hydrothermal Laboratory of the Institute of Technologic Research of São Paulo.

Two types of soils were studied with distinct textural classes, a granular texture soil ($A_{2,\,4(0)}$) and a fine texture one ($A_{5(6)}$). The soils were collected at the Sumaré city near to Campinas city.

Before collecting samples, the soils physical indexes (Table 2) were determined: grain size distribution (%) by ABNT NBR 07181:1984a; liquid and plastic limits (%) by ABNT NBR 06459:1984b and ABNT NBR 07180:1984c; maximum dry density (g cm^{-3}) and optimum moisture content (%) by ABNT NBR 07182:1986.

Portland cement (CPII E 32), hydrated calcic lime (CH, I) and commercial sodium silicate were used. Physical, chemic cement and lime characterization followed the ABNT NBR 11578:1997 and ABNT NBR 07175:2003, respectively. The Na_2SiO_3 chemical composition presented 63% of SiO_2 and 18% of Na_2O, and silicate by alkaline relation was 3,5:1.

Simple compression tests were performed in a DYNATEST universal press with carrying control gadget and 25,000 kN maximum capacity. The stabilized soil blocks were molded in CINVA, RAM block making press. The blocks produced were type II (23 by 11 by 5 cm^3) according to ABNT NBR 08491:1992a. Guarded Hot Plate apparatus was used to measure the stabilized soil blocks thermal conductivity value and calorimeter was used to obtain specific heat capacity.

Table 2 – Physical and mechanical characteristics of the two soil samples investigated

Characteristics	Soils	
	Sandy	Clayey
Water content (%)	3.75	17.01
Liquid limit (%)	Non plastic	44.67
Plastic limit (%)	Non plastic	36.28
Plastic index (%)	Non plastic	8.39
Sand (%)	68.35	39.35
Silt (%)	20.25	30.55
Clay (%)	11.50	30.00
δ (g cm^{-3}) – 0% stabilizer content	1.96	1.60
δ (g cm^{-3}) – 6% cement content	1.91	1.57
δ (g cm^{-3}) – 10% cement content	1.83	1.55
δ (g cm^{-3}) – 6% lime content	1.97	1.62
δ (g cm^{-3}) – 10% lime content	1.97	1.61
OMC – 0% stabilizer content	11.40	25.05
OMC – 6% cement content	11.67	25.00
OMC – 10% cement content	13.15	26.60
OMC – 6% lime content	11.14	24.49
OMC – 10% lime content	11.13	22.95
Bureau of Public Roads description	sandy	clayey
AASHTO classification	$A_{2\text{-}4(0)}$	$A_{5(6)}$
USAD classification	Sandy, loam Soil	Sandy, clayey

δ = Maximum dry density; OMC = Optimum moisture content.

2.1 Treatment definition

To accomplish this research, related treatments in Table 3 were studied. Although cement is not the best indicated stabilizer for fine soil treatment, and lime is not the more recommended additive for granular soil stabilization, it was decided to repeat the same treatment for both soils. Thereby, investigations were done to compare the sodium silicate incorporation effects associated to cement and lime regarding the physical, mechanic performance of the two studied soils.

Lime content of 6% and cement of 6% were chosen regarding the recommendations of Sherwood (2007) that defines minimum stabilizer content of 4% for chemical soil stabilization. According to the author, for lower than 4% contents, "stabilized soil" term becomes inadequate and "optimized soil" term should be adopted. Contents of 10% lime and 10% cement were chosen according recommendations of Milani and Labaki (2012). Additional 4% of sodium silicate associated to lime and cement contents was based on recommendations of Hendriks and Pietersen (2000).

Table 3 – Different soil, stabilizers studied mixtures

Sandy soil
T1 – natural soil, 0% stabilizer content;
T2 – soil + 6% cement content;
T3 – soil + 10% cement content;
T4 – soil + 6% cement content + 4% sodium silicate;
T5 – soil + 10% cement content + 4% sodium silicate;
T6 – soil + 6% lime content;
T7 – soil + 10% lime content;
T8 – soil + 6% lime content + 4% sodium silicate;
T9 – soil + 10% lime content + 4% sodium silicate;
Clayey soil
T10 – natural soil, 0% stabilizer content;
T11 – soil + 6% cement content;
T12 – soil + 10% cement content;
T13 – soil + 6% cement content + 4% sodium silicate;
T14 – soil + 10% cement content + 4% sodium silicate;
T15 – soil + 6% lime content;
T16 – soil + 10% lime content;
T17 – soil + 6% lime content + 4% sodium silicate;
T18 – soil + 10% lime content + 4% sodium silicate.

2.2 Molding specimen

The cement and lime content proportions (6% and 10%) were adopted to dry soil mass. The Na_2SiO_3 (4%) was related to the soil, additive mixture (lime or cement) dry mass and diluted in mashing water. The mashing water amount corresponded to the difference between optimized humidity and natural soil content.

Each treated block was molded according to the ABNT NBR 10832:1989 and submitted to a wet chamber for 14 days under 23 ($\pm$2) ºC temperature and 90 ($\pm$2)% relative humidity. In order to avoid cracking effects, foundation mortar composed of cement, lime and sandy soil (1:1:5) were prepared. Mini panels were obtained by laying four block rows with each row made of a block. The laying joints had a constant thickness of approximately 1 cm. The mini, panels were submitted to the wet chamber under temperature and humidity conditions previously described. After 28, 56 and 91 days they were submitted to a simple compression tests (Figure 2).

The compression resistance (R_C, in MPa) was obtained by the relation between maximum force (C, in kgf) applied to an area (A, in cm^2), through Equation 1.

$$R_C = \frac{0{,}1C}{A} \qquad (1)$$

Figure 2 – Mini panels submitted to simple compression

Water absorption measurements and the compressive tests were realized according to the ABNT NBR 08492:1992b. The blocks were taken to a stove with temperatures between 105 ºC and 110 ºC, until mass constancy, thus obtaining the dry block mass in stove (M_1), in grams. Following, the blocks were immerged in water for 24 hours. Afterwards, the blocks were removed, dried superficially and weighted, recording the saturated mass (M_2), in grams. The individual water absorption values (A), in percentage, were obtained by the Equation 2.

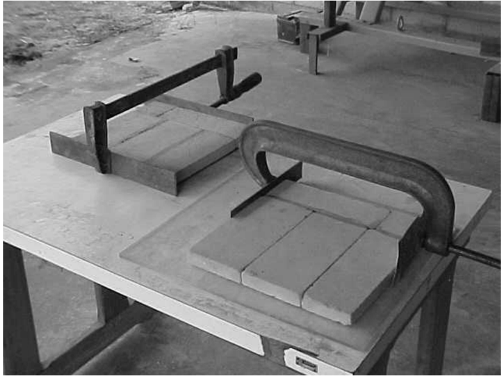
$$A = \frac{M_2 - M_1}{M_1} 100 \qquad (2)$$

2.3 Thermalphysics properties

Only the soil, additive mixture blocks with best results in terms of physic, mechanic performances were tested, that is, only the T5 mixture (sandy soil + 10% cement + 4% sodium silicate). Tests were done at 91 days. Procedures were conducted according to the ABNT NBR 15220:2005b, which deal with thermal resistance measurement (m K W^{-1}) and thermal conductivity (W m^{-1} K^{-1}) by the protected hot plate principle. Specific heat (kJ kg^{-1} K^{-1}) was obtained by the ASTM C – 351 – 92:1999.

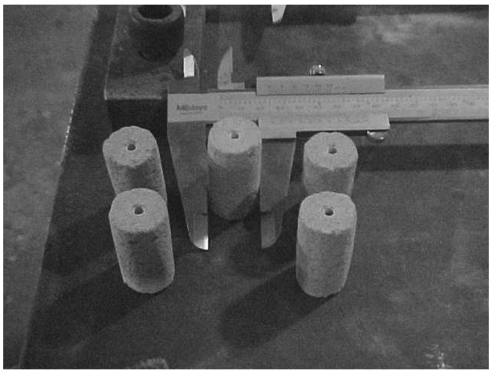
For thermal conductivity tests, the ABNT NBR 15220:2005b recommends 25 to 75 mm thickness specimen (plates). We adopted 25 mm plates. The width and length of the specimens were chosen according to the hot and cold experimental tool plates, dimensions of 305 mm by 305 mm. The blocks (230 mm by 110 mm by 50 mm) were longitudinally cut until 230 mm by 110 mm by 25 mm dimensions. Furthermore, pieces were polished with sandpaper and glued with polychloroprene obtaining 305 by 305 by 25 mm^3 plates. Two plates were built for thermal conductivity tests, one for the hot plate and another for the cold plate (Figure 3).

Figure 3 – Specimens for the guarded hot plate tests



According to the ASTM C – 351 – 92:1999, specific heat tests procedures must be conducted in tested material cylinders having the following characteristics: 24 mm diameter, 49 mm height, and 4.5 mm wide central hole with 20 mm depth (Figure 4).

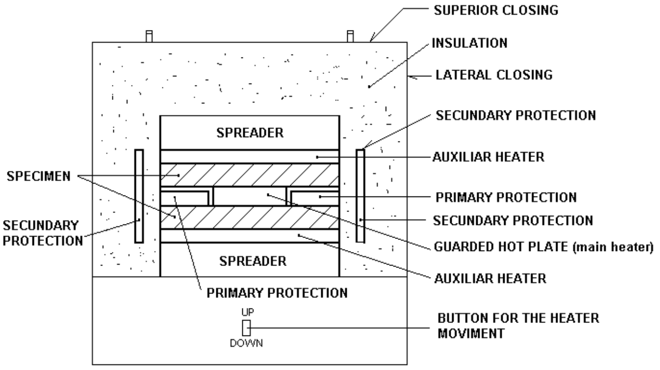
Figure 4 – Calorimeter essay of the specimens



The thermal conductivity determination by the protected hot box method involves medium temperature gradient specimen measures from certain heat flow in a permanent regime condition. A Holometrix GHP 300 Guarded Hot Plate was used. The equipment consists of three heating plates test module, two water circulation heat dissipaters, thermopars, feeding wires and an electro, mechanic moving plate device. Figure 5 shows the specimen schematic picture in between the guarded hot plates for essays.

The calorimeter measures the absorbed heat through itself, thus determines the specific heat. The equipment has a heat capacity well defined and calculated the quantity of energy from the recorded temperature increase. The testing material is placed in a double sided mirrored capsule (Dewar flasks). Thermopars are introduced into the cylinders holes. The cylinders capsules are heated up to around 95 ºC to 98 ºC, and later immersed in a deionized water container at room temperature. The capsules heat is transferred to water and, through a differential thermometer (Beckmann type), the water temperature increase curve is traced up to the equilibrium point. The specific heat is then obtained by a calculus sequence that considers several parameters such as water temperature, specific flask and water mass, cylinders mass etc.

Figure 5 – Schematic design of the specimens in the guarded hot plate



2.4 Obtaining the main thermophysical properties

From thermal conductivity and specific heat values, thermal resistance (R) (in m K W^{-1}), thermal capacity (T$_C$) (in kJ m^{-2} K^{-1}) and thermal delay (φ) (in hours) were calculated for the block as Equations 3 through 5:

$$R = \frac{t}{\lambda} \tag{3}$$

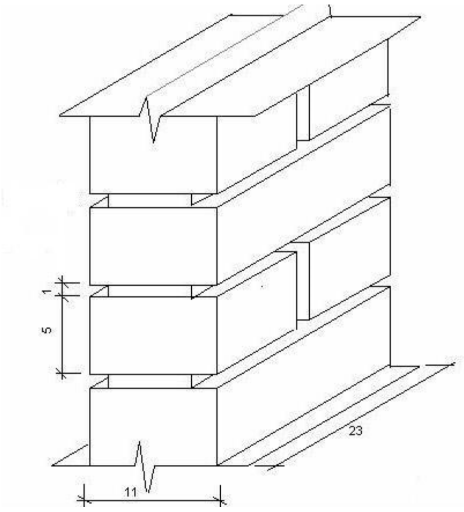
$$T_C = t\,c\,\rho \tag{4}$$

$$\varphi = 1.382t\sqrt{\frac{\rho.c}{3.6\lambda}} \tag{5}$$

Where:
t = test sample thickness (m);
λ = block thermal conductivity (W m^{-1} K^{-1});
c = block specific heat (kJ kg^{-1});
T$_C$ = thermal capacity (kJ m^{-2} K^{-1});
φ = thermal delay (h);
ρ = test sample density (kg m^{-3}).

Afterwards, a computational simulation was performed a hypothetic block wall built with the studied mixture (Figure 6). The Transmitância 1.0 software (LABEEE, 2003) was used for simulation. Calculated parameters were: Total thermal resistance R_T (m K W^{-1}); thermal transmittance U (W m^{-2} K^{-1}); wall thermal capacity T_{Cw} (kJ m^{-2} K^{-1}); wall thermal delay φ_w (hours); solar factor FS (%). Further, U, φ and FS were compared to the ABNT NBR 15220:2005c values for external walls. Finally, adequacy to each Brazilian bioclimatic zone was analysed for those values.

Figure 6 – Details of the stabilized soil block wall for simulation



2.5 Micro characterization

Sweep Electronic microscopy (SEM) was used to observe sodium silicate influence on the stabilized soil crystal structure. Coupled to the image acquisition, present elements analysis in the soil, additive mixture through energy dispersive spectroscopy (EDS) was realized. For that purpose, mini panel samples were collected just after 91 days age from rupture. Only two treatments were chosen for analysis; a) the T5 mixture (sand soil + 10% cement associated to sodium silicate), *i.e.*, the best physic, mechanic performance for the simple compression resistance and the water absorption; and b) the T3 mixture (sand soil + 10% cement) without sodium silicate addition considered as the control. The images were obtained by the Jeol JSM – 6360 LV electronic microscope and the EDS analysis was performed by the Jeol JSM – TM 300 equipment.

2.6 Experimental design

The essays were designed in a completely casual factorial experiment (2 by 9 by 3) with three repetitions, corresponding to: two soil types (sandy and clayey), nine soil, additive mixture types (Table 3) and three curing ages (28, 56 and 91 days). The results for compression and water absorption capacity were interpreted by variance analysis. The average value obtained was compared to Tukey at 5% probability.

3 – RESULTS AND DISCUSSION

The results in terms of physical, mechanical behavior of the mini panels, their thermophysical properties and the evaluation of the chemical stabilization by cement and sodium silicate through Sweep Electronic Microscopy are presented in the following sections.

3.1 Physical and mechanical properties

The highest medium resistance was 6,1 MPa obtained for sandy soil with 10% cement addition associated to 4% Na_2SiO_3, in 91 curing days (Table 4).

In general, resistance gain through time was observed for all treatments. Regardless soil type, Na_2SiO_3 incorporation to 6% and 10% cement and lime contents promoted excellent compression resistance gains when compared to resistance values for treatments without Na_2SiO_3.

Regarding water absorption capacity, all treatments applied to sandy blocks attended the NBR 08492 specifications, which determine maximum medium value of 20% and no value over 22%. Nevertheless, for the clayey soil, only 10% cement and Na_2SiO_3 addition attended the ABNT NBR 08492:1992b specifications. The main explanation for this behavior is the high porosity of clayey blocks, especially if treated with lime. Other strategies are suggested for these blocks treatment, like hydrofugant impregnation or addition products, as studied by Ren and Kagi (1995). According to them, sodium silicate addition solutions, silicone and siloxane reduces considerably water absorption of fine soils molded blocks.

The major increment for simple compression resistance was obtained by the Na_2SiO_3 incorporation to sandy soils, as noticed by others authors (FREIDIN; ERELL, 1995; FERREIRA; FREIRE, 2003) (Table 5). This behavior is due to a greater presence of the SiO_2 phase in sandy soil that becomes active when mixed to strong alkalis, such as NaOH, Na_2CO_3 and Na_2SiO_3. Free calcium, deriving from lime and cement hydration processes, reacts with Na_2SiO_3 added to soil, giving origin to the hydrated calcium silicates. Those compounds are responsible for mechanical resistance increase and better performance related to water action in raw soil pressed blocks (FREIDIN; ERELL, 1995).

Table 4 – Compressive strength and water absorption

Treat	Simple compression resistance (MPa)*		
	28 days	56 days	91 days
T1	1.0 ± 0.11 (11.28) ef A	0.6 ± 0.06 (10.41) h B	1.0 ± 0.02 (1.92) ij A
T2	0.7 ± 0.08 (11.94) ef A	0.9 ± 0.13 (13.66) h A	1.3 ± 0.06 (4.68) hij A
T3	1.2± 0.01 (0.74) de B	1.6 ± 0.06 (3.79) g AB	1.9 ± 0.14 (7.51) fgh A
T4	1.8 ± 0,20 (1.40) cd C	2.9 ± 0.47 (15.87) cd B	3.9 ± 0.26 (6.62) c A
T5	2.5 ± 0.16 (6.28) b C	5.4 ± 0.48 (8.79) a B	6.1 ± 0.41 (6.79) a A
T6	0.6 ± 0.01 (1.07) f A	0.6 ± 0.06 (9.96) h A	0.9 ± 0.01 (1,30) j A
T7	1.0 ± 0.07 (6.46) ef B	1.8 ± 0.11 (6.26) g A	1.8 ± 0.15 (8.40) fgh A
T8	1.2 ± 0.16 (2.87) de C	3.2 ± 0.41 (12.56) c B	4.4 ± 0.41 (9.12) bc A
T9	3.6 ± 0.40 (1.09) a B	4.3 ± 0.24 (5.57) b A	4.7 ± 0.69 (14.49) b A
T10	2.1 ± 0.00 (0.00) bc B	2.5 ± 0.02 (0.91) de AB	2.6 ± 0.13 (5.17) de A
T11	2.0 ± 0.12 (6.01) bc A	2.0 ± 0.11 (5.41) efg A	1.7 ± 0.13 (7.59) gh A
T12	2.1 ± 0.18 (8.38) bc AB	2.4 ± 0.21 (8.82) def A	2.0 ± 0.10 (5.34) fg B
T13	1.4 ± 0.10 (7.14) de C	2.0 ± 0.09 (4.54) efg B	2.8 ± 0.33 (11.76) de A
T14	1.6 ± 0.17 (10.83) cde B	3.4 ± 0.22 (6.59) c A	3.2 ± 0.22 (6.83) d A
T15	1.0 ± 0.09 (8.90) ef B	1.6 ± 0.12 (7.42) g A	1.4 ± 0.13 (8.85) ghij A
T16	1.0 ± 0.06 (5.59) ef B	1.8 ± 0.09 (5.04) fg A	1.6 ± 0.11 (6.93) ghi A
T17	1.0 ± 0.07 (6.93) ef B	2.2 ± 0.10 (4.72) efg A	2.3 ± 0.21 (8.81) ef A
T18	1.8 ± 0.08 (4.56) cd B	3.0 ± 0.27 (8.93) cd A	3.1 ± 0.11(3.67) d A

Treatments	Water absorption*
	7 days
T1	–
T2	11,86 ± 0,08 (0,65) a
T3	11,53 ± 0,14 (1,24) a
T4	14,43 ± 0,11 (0,74) c
T5	13,84 ±0,26 (1,85) bc
T6	13,79 ± 0,33 (2,42) bc
T7	13,40 ± 0,19 (1,25) b
T8	15,43 ± 0,19 (1,25) d
T9	16,06 ± 0,11 (0,66) d
T10	–
T11	26,09 ± 0,11 (0,43) h
T12	25,21 ± 0,03 (0,10) g
T13	23,72 ± 0,07 (0,31) f
T14	19,97 ±0,61 (3,05) e
T15	26,01 ± 0,36 (1,39) gh
T16	27,09 ± 0,58 (2,15) i
T17	25,70 ± 0,52 (2,01) gh
T18	23,50 ± 0,11 (0,48) f

*Medium values ± standard deviation (variation coefficient):

In each column, averages followed by the same small letter are not different from each other, according to Tukey test ($p < 0.05$);

In each line, averages followed by the same capital letter are not different from each other, according to Tukey test ($p < 0.05$).

On the other hand, some studies reveal the benefit effects using lime and cement in combination to reduce their quantity in the preparation of blocks of comparable strength to that prepared with cement alone (NAGARAJ *et al.*, 2014). This would be added benefit not only reducing the cost of the blocks, but also has serious implications in terms of the reduction of energy consumed in the manufacture of blocks when done in large scale.

Table 5 – Gain in mechanical resistance by sodium silicate incorporation

Soil	Stabilizer content		Resistance gain (%) 28 days	56 days	91 days
Sandy	Cement	6%	162.69	208.42	203.10
		10%	106.00	246.77	218.95
	Lime	6%	115.79	429.51	405.68
		10%	244.23	146.02	157.61
Clayey	Cement	6%	31.34	1.96	68.86
		10%	26.17	40.00	62.00
	Lime	6%	2.06	36.42	61.81
		10%	77.45	65.00	88.48

The sodium silicate incorporation associated to cement in clayey soil was what promoted the smaller resistance gain values (Table 5). This result can be attributed to the higher specific surface of this soils associated to the minor presence of the SiO_2 phase and free calcium content during the cement hydration process.

When executing loads on the mini panels simple compression essays, the first cracks appeared in the foundation mortar, propagating horizontally through this region and then vertical crack occurred. This behavior shows the good capacity of the plastic mortar in absorbing the deformations, as demonstrated by Nascimento and Helene (1993). Table 6 presents measurement results for mini panels foundation mortar characterization.

Table 6 – Measurement results for mini panels foundation mortar characterization

Age(days)	Compression strength (MPa)*	Dry density (kgm^{-3})*
14	2.4 ± 0.13 (5.63)	1,929.4 ± 79.59 (4.13)
42	4.9 ± 0.24 (4.96)	1,724.5 ± 22.11 (1.28)
77	6.6 ± 0.33 (4.93)	1,789.5 ± 72.57 (4.06)

*Medium values ± standard deviation (variation coefficient)

3.2 Thermophysical properties

Tables 7 and 8 present, respectively, the results for thermal conductivity and specific heat applied to the specimens. Table 9 presents the values for main block and foundation mortar thermophysic properties, calculated by Equations 3, 4 and 5. The foundation mortar thermophysical characteristics were assumed the values contained in ABNT NBR 15220:2005a. Table 10 presents the thermophysical properties from computational simulated wall. Table 11 presents the acceptable values of thermophysical properties for different types of walls according to the ABNT NBR 15220:2005a.

Table 7 – Thermal conductivity essay results

Mortar^{I} (kg)	ρ^{II} (kg m^{-3})	Temperatures (ºC) Hot plate	Cold plate	Thermal conductivity (W m^{-1} K^{-1})
4.34	1,868	35.00	16.10	0.49

^{I}Plate dimensions: 30.5 by 30.5 cm^2 and 2.5 cm thickness. ^{II}Dry density.

Table 8 – Specific heat essay results

Cylindrical specimens	Average temperature (ºC)	Specific heat (kJ kg^{-1} K^{-1})
1	61.2	0.80
2	61.0	0.77
3	61.2	0.69
Average	61.13 ± 0.12 (0.19)*	0.75 ± 0.06 (7.55)*

*Medium values ± standard deviation (variation coefficient).

Comparing the thermal conductivity values obtained during essay (Table 7) with the related values for ceramic materials in Table 12, thermal property of soil, additive mixtures is observed that this favors good performance in thermal comfort. The thermal conductivity value was approximately half the average value related in Table 12 for conventional ceramic blocks. On the other hand, differently from thermal conductivity occurrence, the specific heat value (Table 8) compared to the related value in Table 12, does not favor a good thermal performance. In this case, the material would need a smaller amount of heat (expressed in Joules) for temperature increase. This behavior is due, mainly to a greater glass phase presence caused by the sodium silicate addition (Figure 8).

Table 9 – Block and mortar thermophysic properties

Material	ρ (kg m^{-3})	λ (W m^{-1} K^{-1})	c (kJ kg^{-1} K^{-1})	R (m K W^{-1})	T_C (kJ m^{-2} K^{-1})	φ (h)
Block^1	1,868	0.49	0.75	0.22	154.11	4.3
Mortar	2,000	1.15	1.00	0.27	220.00	2.9

^{1}Block dimensions = 23 by 11 by 5 cm^3

Table 10 – Wall thermalphysic properties^1

Total thermal resistance (m K W^{-1})	Thermal capacity (kJ m^{-2} K^{-1})	Thermal transmittance (W m^{-2} K^{-1})
0.3612	162.21	2.77
Thermal delay (h)	Solar heat factor (%)	
4.00	7.20%	

^{1}Wall laid in half blocks (block dimensions: 23 by 11 by 5 cm^3).

The Brazilian Standard ABNT NBR 15220:2005a relates 0.70 to 1.05 W m^{-1} K^{-1} values for thermal conductivity and 0.92 kJ kg^{-1} K^{-1} for specific heat of conventional block and ceramic tiles with 1,000 to 2,000 kg m^{-3} variable density (Table 12).

Table 11 – Transmittance thermal delay and solar heat factor for external walls

Wall type	Thermal transmittance (W m^{-2} K^{-1})	Thermal delay (hours)	Solar heat factor (%)
Light	$U \leq 3.00$	$\varphi \leq 4.3$	$FCS \leq 5.0$
Reflexive light	$U \leq 3.60$	$\varphi \leq 4.3$	$FCS \leq 4.0$
Heavy	$U \leq 2.20$	$\varphi \geq 6.5$	$FCS \leq 3.5$

Source: ABNT NBR 15220:2005a.

For chemically stabilized raw soil blocks (lime and cement) made from soils with similar characteristics to those studied here, Adam and Jones (1995) found thermal conductivity values ranging between 0.26 and 0.41 W (m^{-1} K^{-1}) with apparent dry specific mortar of 1,540 to 1,860 kg m^{-3}, for lime stabilized blocks. For cement stabilized blocks, the thermal conductivity values stayed between 0.41 and 0.55 W (m^{-1} K^{-1}), with apparent dry specific mortar of 1,820 to 1,920 kg m^{-3}. Therefore, inverted relation between thermal conductivity and block density is noticed. Milani and Labaki (2012), testing stabilized soil, cement blocks (10% cement content) added with rice husk ash mixture (92.5% soil + 7.5% ash and 100% soil + 0% ash), found values of thermal conductivity of 0.65 and 0.80 W (m^{-1} K^{-1}), with apparent dry specific of 1,600 to 1,700 kg m^{-3}, respectively.

Table 12 – Density (ρ), thermal conductivity (λ) and specific heat (c) of ceramic building materials

Material	ρ (kg m^{-3})	λ(W m^{-1} K^{-1})	C(kJ kg^{-1} K^{-1})
Conventional	1,000 – 1,300	0.70	0.92
Ceramic	1,300 – 1,600	0.90	0.92
Blocks and tiles	1,600 – 1,800	1.00	0.92
	1,800 – 2,000	1.05	0.92

Source: ABNT NBR 15220:2005a.

Since essays were performed for the T5 mixture (sandy soil + 10% cement + 4% sodium silicate), the different mixture effects in the thermal conductivity values was not possible to evaluate. Nevertheless, thermal conductivity of materials is known to have a close relation to apparent dry specific mass. In that way, due to the smaller apparent specific mass in comparison to the cement stabilized blocks, it would be reasonably affirm lime stabilized blocks would reach smaller thermal conductivity values than those obtained by the T5 mixture (Table 7) within same soil type and chemical additive content.

For apparent block walls (without coating) similar to the blocks studied here, the ABNT NBR 15220:2005a relates 3.70 W m^{-2} K^{-1}, 149 kJ m^{-2} K^{-1} and 2.4 hours values, respectively for transmittance, thermal capacity and thermal delay (Table 11). Comparing calculated thermal transmittance, thermal capacity and thermal delay values for the wall (Table 10) to those in Table 11 for apparent compact blocks, thermal properties of the studied soil, additive mixture shows that good thermal performance is favored for walls with same material. The 2.77 W m^{-2} K^{-1} thermal transmittance value for the stabilized soil wall (Table 10) fulfills building criteria (Table 11) for light walls (bioclimatic zones 1 and 2) and reflexive light walls (bioclimatic zones 3 and 5). For heavy walls, typical of zones where greater thermal inertia is needed (bioclimatic zones 4, 6, 7 and 8), the thermal transmittance of the stabilized soil wall fulfills demands (Table 10) only if blocks are laid in their larger length (23 cm thickness). Thus, the transmittance value will pass from 2.77 to 1.65 W m^{-2} K^{-1} and the thermal delay values will change from 4 to 6.5 hours. However, this procedure would increase costs, resting to consider other strategies for adjusting the wall to building recommendations for bioclimatic zones 4, 6, 7 and 8 (high thermal inertia walls), for instance using mortar covering on external and internal wall faces.

3.3 Micro characterization

Figures 7 and 8 present images obtained by the scanning electronic microscope, respectively for the T3 (sand soil + 10% cement) and T5 (sand soil + 10% cement and 4% sodium silicate) mixtures at 91 days. The sodium silicate effect is observed by the images through the general crystal like structure of the analyzed samples.

Figure 7 – Sweep electronic microscopic image for the T3 mixture with no sodium silicate at 91 days (10,000 times amplifications)

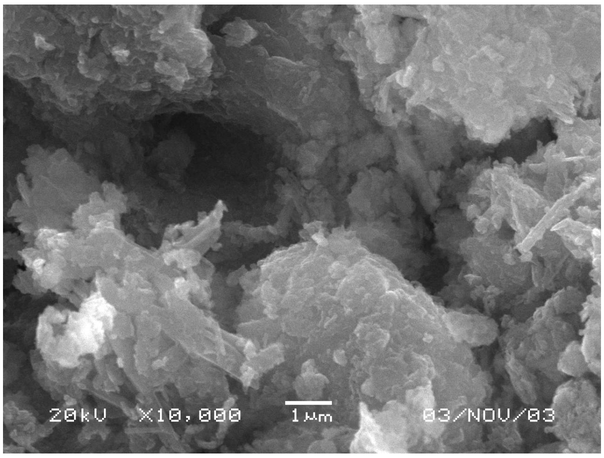
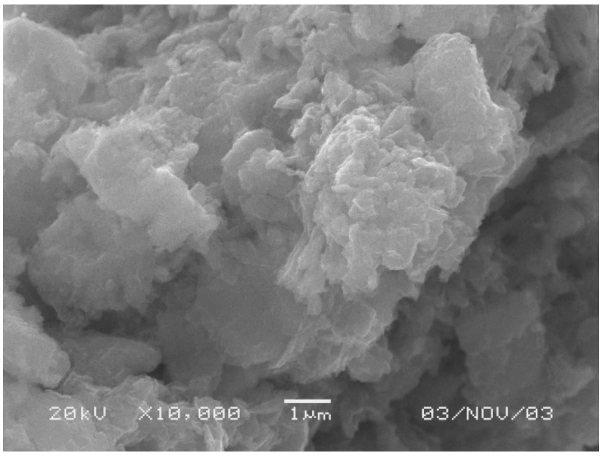


Figure 8 – Sweep electronic microscopic image for the T5 mixture with sodium silicate at 91 days (10,000 times amplifications)



As reported previously, hydrated calcium silicates are cement agents and improve soil stability, filling in blank spaces and consequently expelling soil water. In Figure 8, a smaller amount of empty spaces and concavities is noticeable making evident a greater formation of hydrated calcium silicates and a better quality crystal like structure results. The main elements detected by the EDS analysis were Al, Si, Ca and Fe for both mixtures.

CONCLUSION

The calcium silicate affected strongly the mechanical behavior of both soils, promoting considerable gains in terms of simple compression resistance. Independently of the soil type, the sodium silicate produced better simple compression resistance. Only the sandy soil treatments fulfilled the technical specifications for water absorption.

The highest simple compression resistance value was obtained at 91 days by the sandy mini panels with 10% cement content and associated lime to sodium silicate.

The plastic mortar used in the blocks demonstrated capable of absorbing imposed deformations during the simple compression essays.

The thermophysical properties demonstrated that the blocks have a better thermal performance when compared with ceramic blocks under the same use conditions.

The soils with similar characteristic to the studied sandy soil, treated with cement or lime associated or not to sodium silicate, showed to be promising to appropriate technology demands regarding optimized soil use as building material, energy conservation and costs reduction.

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