ISSN 1807-1929
Revista Brasileira de Engenharia Agrícola e Ambiental
v.21, n.8, p.543-549, 2017
Campina Grande, PB, UAEA/UFCG – http://www.agriambi.com.br

DOI: http://dx.doi.org/10.1590/1807-1929/agriambi.v21n8p543-549

Quality evaluation of soil-cement-plant residue bricks by the combination of destructive and non-destructive tests

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Key words:
soil stabilization
rice husk
anisotropic resistance

ABSTRACT

Residues from agricultural activity can be used to improve the quality of soil-based bricks, constituting an interesting alternative for their destination. The technical quality of soil-cement-plant residue bricks was evaluated by the combination of non-destructive and destructive methods. A predominant clayey soil, Portland cement and residues of husks of both rice and *Brachiaria brizantha* cv. Marandu (0, 10, 20, 30 and 40%, in mass, in substitution to the 10% cement content) were used. The bricks were submitted to destructive (water absorption and compressive strength) and nondestructive (ultrasound) tests for their physical and mechanical characterization. Results from both destructive and non-destructive tests were combined to determine the quantitative parameter named "anisotropic resistance" in order to evaluate the quality of the bricks. The addition that promoted best technical quality was 10% residue content, regardless of the residue type. The anisotropic resistance proved to be adequate for the technical quality evaluation of the bricks.

Palavras-chave:
estabilização de solos
casca de arroz
resistência anisotrópica

Avaliação da qualidade de tijolos de solo-cimento-resíduos vegetais por meio da combinação de testes destrutivos e não-destrutivos

RESUMO

Resíduos provenientes da atividade agrícola podem ser utilizados para a melhoria da qualidade de tijolos, constituindo-se como interessante alternativa de sua destinação. Avaliou-se a qualidade técnica de tijolos de solo-cimento-resíduos vegetais pela combinação de testes destrutivos e não-destrutivos. Utilizou-se um solo predominantemente argiloso, cimento CP II-F 32 e resíduos das cascas de arroz e de braquiária (*Brachiaria brizantha* cv. Marandu) nos teores (em massa) de 0, 10, 20, 30 e 40% em substituição ao teor de 10% do cimento. Os tijolos foram submetidos a ensaios destrutivos (absorção de água e compressão simples) e não-destrutivos (ultrassom) para sua caracterização físico-mecânica; em seguida, os resultados dos ensaios destrutivos e não-destrutivos foram combinados para se determinar o parâmetro "resistência anisotrópica" utilizado na avaliação da qualidade técnica dos tijolos, tendo sido obtido o melhor resultado com o teor de 10% de resíduo em substituição ao cimento, independentemente do tipo do resíduo. Concluiu-se que a resistência anisotrópica se mostra adequada para a avaliação da qualidade técnica dos tijolos.

Ref. 101-2016 – Received 1 Jul, 2016 • Accepted 24 Feb, 2017 • Published 29 Jun, 2017

Introduction

The agricultural activity generates residues that can be used to manufacture unconventional construction materials. Because of the problem of searching adequate disposal, recent studies have reported the use of agro-industrial residues in the manufacture of pressed bricks (Faria et al., 2012; Madurwar et al., 2013; Zhang, 2013; Ganga et al., 2014; Laborel-Préneron et al., 2016).

Rice husk has been object of studies to improve the physical-mechanical characteristics of mortar and/or construction materials based on raw earth (Ferreira et al., 2008). The major advantage of using rice husk as alternative aggregate lies in the fact that its generation is concentrated in few places, which facilitates its marketing. In addition, the granulometry of the material is relatively uniform, which facilitates the dosage of the composite. A similar situation occurs with the residues originated from processing plants of seeds of forage species, such as Brachiaria grass (*Brachiaria brizantha*). The husk that involves the seed is, most of the times, discarded, due to the inexistence of more adequate use. On the other hand, Ferreira et al. (2008) report the need of previous procedures aiming at the utilization of these residues in the manufacture of raw earth-based materials. Such treatments include grinding the husks in hammer mill grinder, sieving to eliminate fine material, standardization and improvement of biomass adhesion to the soil-cement system and immersion in 5% concentrated lime solution, for a period of 24 h. This pre-treatment favors the minimization of the incompatibility between the vegetal biomass and Portland cement, besides allowing to remove extractives that solubilize in the water and inhibit cement hydration.

In general, the quality of soil-cement mixtures is evaluated through destructive tests, such as those of simple compression and water absorption. Likewise, quality can be evaluated through non-destructive tests, such as the ultrasonic wave propagation technique (Cazalla et al., 1999; Qasrawi, 2000; Cultrone et al., 2001; Ferreira & Freire, 2004; Brozovsky, 2014; Carrasco et al., 2014; Ganga et al., 2014).

Cultrone et al. (2001), studying the influence of different raw materials on the quality of fire bricks, proposed the concept of "anisotropic resistance" as a quantitative parameter to evaluate brick quality, combining the results of simple compression (destructive method) and structural anisotropy (non-destructive method).

The use of anisotropic resistance to measure the quality of a brick is based on the relationship between the physical stress produced on the brick during the compression test and a mathematical parameter (its anisotropic structure). The higher its value, the better the quality of the material (Carrasco et al., 2014).

Thus, the present study investigated the effect of the addition of plant residues on the mechanical and elastic-acoustic properties of soil-cement bricks and evaluated the combination of quantitative and qualitative criteria, respectively, through the utilization of the results of compressive strength and water absorption capacity, and total anisotropy and anisotropic resistance for the analysis of the quality of these bricks.

Material and Methods

The experiment was carried out at the Laboratories of Soil Mechanics and Construction Materials, of the Civil Engineering School, and at the Laboratory of Biosystems Engineering, of the Agronomy School, both of the Federal University of Goiás (16° 35' 47" S; 49° 16' 47" W, 730 m).

The experiment used the soil and plant residues previously characterized by Ferreira & Oliveira (2007). The soil had clayey texture, predominant of the municipality of Goiânia, Goiás. The samples were collected at depth of 1.0 m to avoid the surface layer, due to the excessive presence of organic matter and alteration in the quantity of fine material through leaching.

Firstly, the collected soil proved to be inadequate for utilization in soil-cement mixtures, with limits of consistency and clay content in disagreement with the ABNT (1989). Thus, its granulometry was corrected through the addition of sand, to make it meet the norm (100% passing through 4.78 mm mesh sieve, 10 to 50% passing through 0.075-mm-mesh sieve, liquid limit ≤ 45% and plasticity index ≤ 18%). The mixture received Portland cement CP II-E-32 (ABNT, 1991), which is composed by blast furnace slag, combining good results of low hydration heat with increase of resistance. This type of cement is commonly used in soil-cement mixtures to promote relatively slow heat release and be tolerant to the attack of sulfates from the soil (Cruz & Jalali, 2010).

The plant residues (rice and Brachiaria seed husks) were obtained in rice and forage seed processing plants of the municipality of Goiânia, Goiás. In its natural condition, rice husk was characterized as a light material, with bulk density of 0.086 g cm^{-3} and uniform granulometry (89% between the sieves of 2.00 and 1.19 mm mesh). On the other hand, after undergoing the processes of fractionation, sieving and pre-treatment, rice husk bulk density increased to 0.152 g cm^{-3}. The pre-treatment consisted in the immersion of rice husks in 5% hydrated lime solution (24 h) and subsequent drying in an oven at 80 °C (48 h) (Ramakrishna & Sundararajan, 2005) to minimize the chemical incompatibility between the cement and the husks. Approximately 90% of its mass showed diameter ranging from 1.19 to 0.42 mm. Brachiaria seed husks, in their natural condition, were characterized as a light material, with bulk density of 0.059 g cm^{-3} and uniform granulometry (91% between the sieves of 2.00 and 1.19 mm mesh). After undergoing the processes of fractionation, sieving and pre-treatment with hydrated lime solution, the bulk density increased to 0.096 g cm^{-3}, and 83% of its mass showed diameter ranging from 2.00 to 0.105 mm.

In order to add maximum amount of residues and reduce the cement consumption in the soil-cement-residue mixture, the content of 10% of the cement-residue combination was adopted, considered in relation to the dry soil weight in the fraction smaller than 4.78 mm and in its natural moisture content, according to the procedures adopted by Milani & Freire (2006).

The contents of cement and residue varied from 100% cement + 0% residue to 60% cement + 40% residue (in relation to the content of 10% cement), totaling nine mixtures (treatments), as follows: T_1 – soil + 0% of additions (0%

residue + 100% cement) - control; T_2 – soil + 10% of additions (10% rice husk + 90% cement); T_3 – soil + 10% of additions (20% rice husk + 80% cement); T_4 – soil + 10% of additions (30% rice husk + 70% cement); T_5 – soil + 10% of additions (40% rice husk + 60% cement); T_6 – soil + 10% of additions (10% Brachiaria seed husk + 90% cement); T_7 – soil + 10% of additions (20% Brachiaria seed husk + 80% cement); T_8 – soil + 10% of additions (30% Brachiaria seed husk + 70% cement) and; T_9 – soil + 10% of additions (40% Brachiaria seed husk + 60% cement).

The bricks were molded according to ABNT (1989) in a manually operated brick making machine (Brand: Tecmor) with capacity for three bricks (23 x 11 x 5 cm^3) per pressing (ABNT, 1992a). To reach maximum apparent specific weight of the bricks, for the molding, the present study adopted the values of optimum moisture obtained in the Normal Proctor compaction tests, previously conducted by Ferreira et al. (2008) (Table 1). After molding, the bricks were cured in humid chamber at 23 ± 2 °C and relative humidity of 90 ± 2%, for 7 days, and then stored in the open air and protected from inclement weather until the age of 182 days.

At 7, 28, 56, 91 and 182 days, test specimens (prismatic) were prepared by sawing the bricks in half (transversely to their length), joining both halves and coating of the working sides with Portland cement paste of plastic consistency, with the minimum thickness necessary to obtain flat and parallel faces. Then, the test specimens were ruptured under simple compression in a universal test machine (Dynatest) with capacity for 2.500 kN, adopting the loading speed of 1 mm min^{-1}. Resistance was calculated by dividing the rupture load by the transverse section area of the brick and the mean resistance obtained in three replicates. The water absorption test was performed at the age of seven days. Both tests were conducted according to ABNT (1992b).

The ultrasonic wave propagation velocity was obtained using an ultrasound device (Steinkamp/BP7, Germany) with emission of ultrasonic pulse at frequency of 45 kHz and equipped with two flat-section transducers (Figure 1A), one emitter and the other receiver of the pulse. Previous studies (Cazalla et al., 1999; Ferreira & Freire, 2004; Carrasco et al., 2014) have demonstrated that it is possible to relate the wave velocity in the three directions and, thus, characterize the structural anisotropy (total anisotropy) of the bricks (Eq. 1).

$$\Delta M = 100\left[1 - \frac{2V_1}{(V_2 + V_3)}\right] \quad (1)$$

where:

ΔM - total anisotropy (%); and,

V_1, V_2 and V_3 - ultrasonic wave velocity (m s^{-1}), respectively measured in the shortest distance (thickness), transverse distance and longitudinal distance (Figure 1B).

The parameter "anisotropic resistance" - R_A, (MPa $\%^{-1}$) Cultrone et al. (2001) was used to measure the technical quality of bricks in physical-mechanical and elastic-acoustic terms (Eq. 2). Higher R_A values indicate low anisotropy of the crystalline structure of the bricks, associated with the low presence of

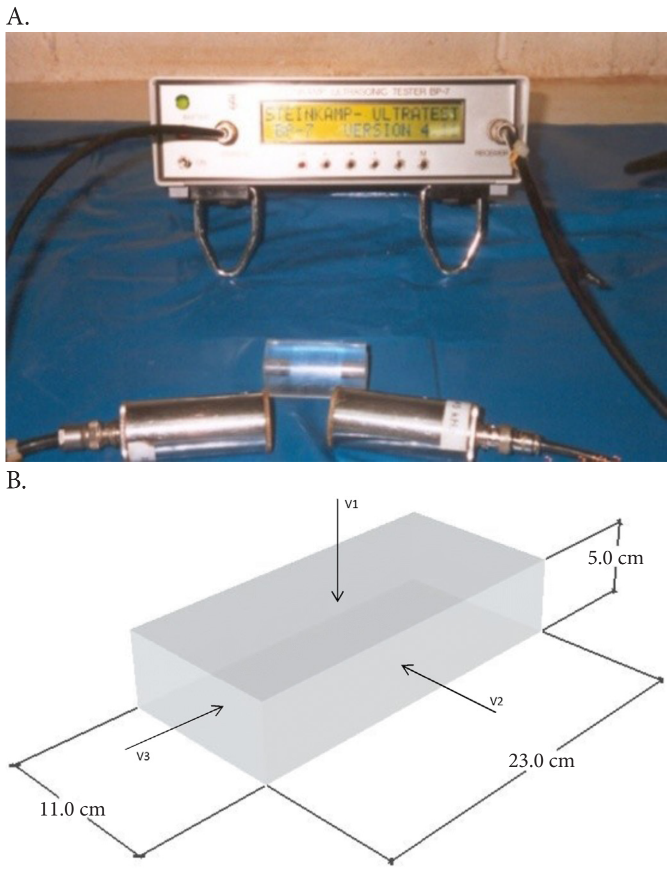

Figure 1. Non-destructive evaluation of the bricks: portable ultrasound device (A), Reading directions of ultrasonic pulse propagation velocity, dimensions in cm (B)

empty spaces, with higher values of mechanical resistance (R_c) and durability and, consequently, better quality.

$$R_A = \frac{R_C}{\Delta M} \quad (2)$$

Tests were also conducted to determine the dynamic modulus of elasticity (Ed), according to the recommendations of Naik et al. (2014), who relate ultrasonic wave velocity through solid materials to the physical properties of these solids (Eq. 3).

$$Ed = \rho V^2 \frac{(1+\mu)(1-2\mu)}{(1-\mu)} \quad (3)$$

where:

ρ - apparent specific weight of the brick, kg m^{-3};

V - ultrasonic pulse velocity, m s^{-1}; and,

μ - Poisson coefficient.

Since it is impossible to obtain the Poisson coefficient experimentally, the value of 0.19 was used (Mosalam et al., 2009).

The experiment was conducted in completely randomized design, in a 2 x 5 factorial scheme. ANOVA was used to study the effects of the interactions between the types of residue (rice and Brachiaria seed husks), contents of residue (0, 10, 20, 30 and 40%) and ages (7, 28, 56, 91 and 182 days) on the response variables R_C and R_A. The results were compared by Tukey test at 0.01 probability level ($p < 0.01$) using the mean of three replicates.

Results and Discussion

The presence of residues caused greater energy dissipation during the molding of the bricks, leading to reduction in the maximum dry apparent specific weight and increase in optimal moisture of compaction, following the same behavior observed in the Normal Proctor compaction tests previously performed by Ferreira et al. (2008) (Table 1).

ABNT (1992a) establishes that the cement content to be employed in the manufacture of bricks is the one that gives minimum resistance of 2.0 MPa and maximum water absorption of 20%, at 7 days. For non-normed bricks, as in the present study, the norm suggests minimum of 1.5 MPa for sealing purposes. As the residue content increased the resistance, the simple compression significantly decreased (Table 2).

Khedari et al. (2005) claimed that the presence of aggregates and vegetal fibers can cause reduction in the resistance of bricks due to the weak adhesion between the particles and the matrix. The best mechanical performances were achieved by the treatments T_2 and T_6. The addition of rice husk resulted in higher values of resistance to compression compared with Brachiaria seed husk, at the equivalent contents and at all ages. The more residues incorporated to the matrix, the greater the difference of resistance in favor of rice husk, compared with the addition of Brachiaria seed husk. Jauberthie et al. (2003) reported that this advantage can be attributed to the modification in the organic part of the rice husk, due to the high alkalinity of the water in the pores in the region of the rice husk, whose silica content is higher than that of Brachiaria seed husk. Such modification in the chemical composition of the husk allows greater interaction of the cement with the silica present in the rice husk, which probably eliminates starch remnants still adhered to the husk, favoring the formation of calcium silicate hydrate (C-S-H). The C-S-H's have porous structure and large specific surface (Yu et al., 1999), which contributes to the increase of the bonds between oxides present in the soils (iron sesquioxides, Fe_2O_3), aluminates (alumina, Al_2O_3) and iron-aluminates (tetracalcium iron-aluminates, C_4AF). Like the C-S-H's, these oxides are products of the Portland cement hydration, which positively influence also the physical and mechanical properties of matrices based on soil-cement.

The increment in the residue content increased the water absorption due to the lower apparent specific weight; higher values occurred in the treatments with greater addition of residue.

Table 1. Maximum dry apparent specific weight and optimal moisture of compaction of the soil-cement-residue mixtures in Normal Proctor compaction tests

Specific weight (g cm^{-3})									Optimal moisture of compaction (%)								
T_1	T_2	T_3	T_4	T_5	T_6	T_7	T_8	T_9	T_1	T_2	T_3	T_4	T_5	T_6	T_7	T_8	T_9
1.8	1.7	1.7	1.7	1.7	1.8	1.7	1.7	1.7	16.7	17.7	18.6	18.2	19.3	16.9	18.5	19.0	19.9

Source: Ferreira et al. (2008)
T_1 – Soil + 0% of additions (0% residue + 100% cement) - control; T_2 – Soil + 10% of additions (10% rice husk + 90% cement); T_3 – Soil + 10% of additions (20% rice husk + 80% cement); T_4 – Soil + 10% of additions (30% rice husk + 70% cement); T_5 – Soil + 10% of additions (40% rice husk + 60% cement); T_6 – Soil + 10% of additions (10% Brachiaria seed husk + 90% cement); T_7 – Soil + 10% of additions (20% Brachiaria seed husk + 80% cement); T_8 – Soil + 10% of additions (30% Brachiaria seed husk + 70% cement) and; T_9 – Soil + 10% of additions (40% Brachiaria seed husk + 60% cement)

Table 2. Resistance to simple compression and total water absorption capacity of soil-cement- plant residues bricks

Treat.	Resistance to simple compression (MPa) – days					Total water absorption (%) 7 days
	7	28	56	91	182	
T_1	3.00 ± 0.27 (9.08) a C[1]	3.07 ± 0.05 (1.68) a C	4.80 ± 0.52 (10.88) a A	3.83 ± 0.09 (2.23) a B	4.96 ± 0.35 (7.10) a A	11.42 ± 3.41 (29.90)
T_2	1.82 ± 0.09 (4.91) b C	2.25 ± 0.05 (2.30) b B	2.89 ± 0.16 (5.59) b A	2.52 ± 0.05 (1.96) b B	2.74 ± 0.10 (3.55) b A	12.97 ± 3.06 (23.59)
T_3	1.34 ± 0.05 (3.86) c C	1.52 ± 0.04 (2.57) c BC	2.21 ± 0.06 (2.92) c A	1.77 ± 0.07 (3.81) c B	2.40 ± 0.13 (5.63) c A	13.78 ± 3.75 (27.20)
T_4	1.07 ± 0.07 (6.28) cd C	1.21 ± 0.04 (3.21) cd BC	1.40 ± 0.18 (12.73) d B	1.54 ± 0.03 (2.09) c A	1.75 ± 0.05 (2.95) d A	16.42 ± 5.79 (35.27)
T_5	0.98 ± 0.02 (1.99) d B	1.03 ± 0.00 (0.00) d B	1.00 ± 0.13 (13.42) e B	1.15 ± 0.03 (2.82) de B	1.63 ± 0.04 (2.40) d A	18.51 ± 4.97 (26.88)
T_6	1.53 ± 0.15 (10.11) b D	2.16 ± 0.07 (3.25) b C	2.61 ± 0.28 (10.78) b B	2.35 ± 0.11 (4.83) b BC	2.99 ± 0.12 (3.96) b A	12.33 ± 2.80 (22.75)
T_7	1.07 ± 0.07 (6.28) cd B	1.17 ± 0.05 (4.40) d B	1.58 ± 0.06 (4.08) d A	1.33 ± 0.05 (3.70) d B	1.75 ± 0.07 (4.01) d A	12.71 ± 1.46 (11.50) ab
T_8	0.83 ± 0.07 (8.16) de B	0.91 ± 0.03 (3.71) de B	0.91 ± 0.12 (12.80) e B	1.16 ± 0.07 (5.79) de A	1.29 ± 0.07 (5.42) e A	15.14 ± 4.51 (29.79) ab
T_9	0.62 ± 0.03 (5.44) e B	0.69 ± 0.07 (10.20) e B	1.00 ± 0.15 (15.23) e A	1.01 ± 0.07 (6.62) e A	0.69 ± 0.04 (5.66) f B	19.96 ± 7.47 (37.42) b

T_1 – Soil + 0% of additions (0% residue + 100% cement) - control; T_2 – Soil + 10% of additions (10% rice husk + 90% cement); T_3 – Soil + 10% of additions (20% rice husk + 80% cement); T_4 – Soil + 10% of additions (30% rice husk + 70% cement); T_5 – Soil + 10% of additions (40% rice husk + 60% cement); T_6 – Soil + 10% of additions (10% Brachiaria seed husk + 90% cement); T_7 – Soil + 10% of additions (20% Brachiaria seed husk + 80% cement); T_8 – Soil + 10% of additions (30% Brachiaria seed husk + 70% cement) and; T_9 – Soil + 10% of additions (40% Brachiaria seed husk + 60% cement)
[1]Mean values + standard deviation (coefficient of variation, in %); Means followed by the same lowercase letter in the columns do not differ by Tukey test ($p < 0.01$); Means followed by the same uppercase letter in the rows do not differ by Tukey test ($p < 0.01$)

The ultrasonic wave propagation velocity increased with the age (Table 3) because of the gradual increment in the compounds resulting from cement hydration with the age, leading to crystalline structure of better quality and higher compacity and, consequently, favoring higher ultrasonic wave velocity (Brozovsky, 2014).

As a rule, the increase of age favored the decrease of total anisotropy (Table 3) through the reduction in the differences between the velocities in the three directions of the bricks, i.e., the gradual chemical stabilization by the cement, along the ages, favored the occurrence of lower differences between velocities, interpreted by the greater homogeneity of the physical-mechanical and elastic-acoustic behaviors evaluated in the three directions of the bricks.

There was a trend of increase in R_A with the increment of age (Table 4). As already mentioned (Cultrone et al., 2001),

Table 3. Ultrasonic wave velocity in the three directions and total anisotropy of the bricks

Age	Velocity (m s^{-1})	T_1	T_2	T_3	T_4	T_5	T_6	T_7	T_8	T_9
7 days	V_1	1766	813	395	296	260	803	460	296	120
	V_2	1650	1206	883	653	576	1170	746	550	260
	V_3	1696	1313	973	460	340	1176	666	265	200
28 days	V_1	1340	830	701	336	225	795	445	210	161
	V_2	1466	1133	986	730	575	1200	653	330	210
	V_3	1496	1173	1106	823	516	1246	666	355	276
56 days	V_1	1531	1238	951	688	511	983	730	420	236
	V_2	1743	1533	1240	946	726	1340	1030	680	443
	V_3	1783	1576	1303	1103	673	1410	1110	743	576
91 days	V_1	1536	1160	793	576	430	1016	630	506	311
	V_2	1633	1320	1030	816	676	1196	786	710	376
	V_3	1730	1430	1116	830	723	1410	830	703	443
182 days	V_1	1650	883	1206	653	576	1170	746	550	260
	V_2	1830	1186	1400	886	740	1353	990	693	525
	V_3	1880	1536	1283	963	716	1483	1186	846	556

Treatment	Total anisotropy (%) – days				
	7	28	56	91	182
T_1[1]	11.93	9.57	13.15	8.61	14.46
T_2	35.41	28.09	20.37	15.38	22.36
T_3	57.55	32.92	25.18	26.08	19.27
T_4	46.63	56.44	32.82	29.94	36.51
T_5	43.28	58.83	26.76	38.52	31.33
T_6	31.49	34.93	28.45	21.85	21.98
T_7	34.79	37.01	31.65	17.69	31.03
T_8	27.35	38.10	44.22	28.12	24.19
T_9	47.83	33.48	53.13	15.32	48.90

T_1 – Soil + 0% of additions (0% residue + 100% cement) - control; T_2 – Soil + 10% of additions (10% rice husk + 90% cement); T_3 – Soil + 10% of additions (20% rice husk + 80% cement); T_4 – Soil + 10% of additions (30% rice husk + 70% cement); T_5 – Soil + 10% of additions (40% rice husk + 60% cement); T_6 – Soil + 10% of additions (10% Brachiaria seed husk + 90% cement); T_7 – Soil + 10% of additions (20% Brachiaria seed husk + 80% cement); T_8 – Soil + 10% of additions (30% Brachiaria seed husk + 70% cement) and; T_9 – Soil + 10% of additions (40% Brachiaria seed husk + 60% cement)

Table 4. Anisotropic resistance of the bricks (R_A)

Treatment	Anisotropic resistance (MPa %$^{-1}$) - days				
	7	28	56	91	182
T_1[1]	0.27 ± 0.05 (20.82) a C[1]	0.35 ± 0.09 (24.85) a B	0.37 ± 0.06 (16.19) a B	0.49 ± 0.14 (29.30) a A	0.34 ± 0.03 (7.38) a B
T_2	0.05 ± 0.00 (5.76) b B	0.08 ± 0.01 (13.13) b AB	0.14 ± 0.01 (4.94) b A	0.14 ± 0.04 (21.42) b A	0.12 ± 0.01 (9.80) b AB
T_3	0.02 ± 0.00 (7.85) b B	0.05 ± 0.00 (8.79) b AB	0.09 ± 0.01 (6.69) bc AB	0.07 ± 0.00 (7.26) bc AB	0.12 ± 0.01 (5.63) b A
T_4	0.02 ± 0.00 (9.82) b A	0.02 ± 0.00 (6.86) b A	0.04 ± 0.01 (12.44) c A	0.05 ± 0.00 (7.83) c A	0.05 ± 0.00 (9.45) c A
T_5	0.02 ± 0.00 (1.30) b A	0.02 ± 0.00 (4.90) b A	0.04 ± 0.00 (8.20) c A	0.03 ± 0.00 (3.26) c A	0.05 ± 0.01 (14.38) c A
T_6	0.05 ± 0.00 (8.35) b B	0.06 ± 0.00 (7.13) b B	0.09 ± 0.02 (17.60) bc AB	0.11 ± 0.01 (7.77) bc AB	0.14 ± 0.00 (2.65) b A
T_7	0.03 ± 0.00 (5.77) b A	0.03 ± 0.00 (14.77) b A	0.05 ± 0.00 (7.24) c A	0.08 ± 0.02 (19.51) bc A	0.06 ± 0.01 (17.36) c A
T_8	0.03 ± 0.01 (32.26) b A	0.02 ± 0.00 (17.04) b A	0.02 ± 0.00 (14.93) c A	0.04 ± 0.00 (6.11) c A	0.05 ± 0.01 (9.36) c A
T_9	0.01 ± 0.00 (5.44) b A	0.02 ± 0.00 (4.88) b A	0.02 ± 0.00 (17.58) c A	0.07 ± 0.02 (29.52) bc A	0.01 ± 0.00 (24.44) c A

T_1 – Soil + 0% of additions (0% residue + 100% cement) - control; T_2 – Soil + 10% of additions (10% rice husk + 90% cement); T_3 – Soil + 10% of additions (20% rice husk + 80% cement); T_4 – Soil + 10% of additions (30% rice husk + 70% cement); T_5 – Soil + 10% of additions (40% rice husk + 60% cement); T_6 – Soil + 10% of additions (10% Brachiaria seed husk + 90% cement); T_7 – Soil + 10% of additions (20% Brachiaria seed husk + 80% cement); T_8 – Soil + 10% of additions (30% Brachiaria seed husk + 70% cement) and; T_9 – Soil + 10% of additions (40% Brachiaria seed husk + 60% cement)

[1]Mean values + standard deviation (coefficient of variation, in %); Means followed by the same lowercase letter in the columns do not differ by Tukey test ($p < 0.01$); Means followed by the same uppercase letter in the rows do not differ by Tukey test ($p < 0.01$)

Table 5. Mean values of the dynamic modulus of elasticity of the bricks (Ed)

Treat.	Ed (MPa) – days				
	7	28	56	91	182
T_1	3497.97 ± 205.80 (5.88) a C[1]	2303.70 ± 263.21 (11.43) a D	4524.03 ± 647.24 (14.31) a B	3694.23 ± 561.10 (15.19) a C	4956.32 ± 90.68 (1.83) a A
T_2	1059.37 ± 20.18 (1.90) b C	633.20 ± 6.21 (0.98) b D	2045.20 ± 62.67 (3.06) b A	1675.93 ± 124.89 (7.45) b B	1373.56 ± 41.76 (3.04) b BC
T_3	395.20 ± 60.71 (15.36) c B	311.93 ± 37.19 (11.92) c B	961.83 ± 21.75 (2.26) c A	734.60 ± 81.19 (11.05) d AB	761.44 ± 62.31 (8.18) c AB
T_4	244.67 ± 5.18 (2.12) c A	215.07 ± 12.91 (6.00) c A	321.53 ± 41.89 (13.03) d A	369.37 ± 42.21 (11.43) de A	246.56 ± 6.09 (2.47) d A
T_5	325.57 ± 4.16 (1.28) c A	222.20 ± 0.00 (0.00) c A	214.60 ± 12.18 (5.68) d A	264.57 ± 21.43 (8.10) e A	223.26 ± 10.95 (4.90) d A
T_6	1308.40 ± 91.57 (7.00) b A	911.63 ± 36.11 (3.96) b B	1148.20 ± 12.70 (1.11) c AB	1185.50 ± 4.60 (0.39) c AB	1463.84 ± 28.50 (1.95) b A
T_7	542.30 ± 26.83 (4.95) c A	301.40 ± 11.76 (3.90) c A	521.20 ± 17.57 (13.37) d A	425.53 ± 42.95 (10.09) de A	586.19 ± 0.56 (0.10) c A
T_8	351.87 ± 20.05 (5.70) c A	203.37 ± 4.74 (2.33) c A	251.40 ± 12.92 (5.14) d A	287.00 ± 45.26 (15.77) e A	218.45 ± 1.27 (0.58) d A
T_9	273.67 ± 2.98 (1.09) c A	159.37 ± 0.53 (0.53) c A	244.70 ± 53.25 (21.76) d A	197.83 ± 29.82 (15.12) e A	99.11 ± 3.98 (4.02) d A

T_1 – Soil + 0% of additions (0% residue + 100% cement) - control; T_2 – Soil + 10% of additions (10% rice husk + 90% cement); T_3 – Soil + 10% of additions (20% rice husk + 80% cement); T_4 – Soil + 10% of additions (30% rice husk + 70% cement); T_5 – Soil + 10% of additions (40% rice husk + 60% cement); T_6 – Soil + 10% of additions (10% Brachiaria seed husk + 90% cement); T_7 – Soil + 10% of additions (20% Brachiaria seed husk + 80% cement); T_8 – Soil + 10% of additions (30% Brachiaria seed husk + 70% cement) and; T_9 – Soil + 10% of additions (40% Brachiaria seed husk + 60% cement)

[1]Mean values + standard deviation (coefficient of variation, in %); Means followed by the same lowercase letter in the columns do not differ by Tukey test ($p < 0.01$); Means followed by the same uppercase letter in the rows do not differ by Tukey test ($p < 0.01$)

high R_A indicates low anisotropy associated with the lower presence of voids, higher mechanical resistance and durability.

The residue contents that allowed to achieve highest and lowest R_A were those corresponding to 10% rice husk (T_2) and 40% Brachiaria seed husk (T_9), respectively. As the resistance to compression, the R_A of the treatments with rice husk was higher than that relative to Brachiaria seed husk.

The values of dynamic modulus of elasticity (Ed) tended to increase with the ages of the bricks (Table 5). Since the Ed strongly depends on the ultrasonic wave propagation velocity, because it varies with its square, Ed values followed the trend of increase of velocity over the storage time (Table 5). The highest Ed values were 4524 and 2045 MPa, for the treatments T_1 and T_2, respectively, which were much higher than those reported for the traditional adobes, which vary from 100 to 300 MPa (Piattoni et al., 2011; Adorni et al., 2013).

The obtained results confirm the positive effect of the processes of mechanical stabilization (pressing) and chemical stabilization (use of cement) on the quality of the bricks manufactured with incorporation of the studied residues, constituting an alternative that is adequate to the traditional adobes (manual molding) and to the ceramic fire bricks in technical and ecological terms, respectively, under equal conditions of use.

Likewise, the combination of the effects of the mechanical stress (destructive tests) and anisotropic structure of the bricks indicates the “anisotropic resistance” as a viable qualitative parameter to evaluate the quality of bricks made of mechanically and chemically stabilized raw earth.

Conclusions

1. Additions of rice husk resulted in higher values of resistance to simple compression, at all contents and ages, compared with those obtained with Brachiaria seed husk.

2. There were differences in the ultrasonic wave velocities measured in the three directions of the bricks, represented by the presence of structural anisotropy of these materials.

3. There was a reduction in the apparent specific weight of the bricks with the additions of plant residues, thus resulting in lower values of anisotropic resistance.

4. The values of anisotropic resistance of the treatments with rice husk were higher than those relative to Brachiaria seed husk.

5. The residue contents that led to best and worst technical quality, evaluated through the anisotropic resistance were, respectively, 10% rice husk (T_2) and 40% Brachiaria seed husk (T_9).

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