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RESEARCH ARTICLE

Physical and mechanical characterization of traditional Brazilian clay bricks from different centuries

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Abstract

Destructive and non-destructive tests were performed to characterize clay bricks from 18th to 20th century from vernacular historic constructions placed at Ceará State, Brazil. The present work has as the main aim to characterize the physical and mechanical properties of Brazilian historical clay bricks, namely water absorption index, ultrasonic pulse velocity and compressive strength. In general, cases of ancient materials characterization out of Europe zone are rarely reported at the literature. For that, samples from vernacular constructions placed at different regions of the Ceará State were tested. The results point to similarities between the clay bricks analyzed, and an evolution in the quality of the properties analyzed. Additionally, the results of the present paper are good contributions to development of numerical models and as well to the understanding about the loading capacity of historic Brazilian masonries. Also, the results allowed to state a correlation between physical and mechanical characteristics of the Brazilian clay bricks based on ultrasonic pulse velocity and the periods of the bricks manufacturing.

Keywords Historic masonry · Brazilian historic clay bricks · Physic and mechanic characterization · Ultrasonic characterization · Heritage constructions

1 Introduction

Preservation of historic buildings has become a relevant topic in the recent decades. Nonetheless, to preserve historic building it is important to consider the cultural value and the material properties as well the material behavior under loading action and environmental effect. That consideration is a good combination of factors in all well-designed rehabilitation procedures. How does an efficient rehabilitation can be designed if exist a lack of information on ancient materials? To overcoming this issue, this topic has demanding a comprehensive investigation about physical and mechanical properties of heritage constructions and put it systematically available for designers. Information on physic, mechanic and durability parameters are essential to understand the global behavior and are relevant information to maintenance and rehabilitation designs.

However, even that information on material properties be essentially relevant to keep in safe historic structure, especial attention should be taken during the characterization and experimental test on historic buildings, namely in order of to avoid the introduction of new damage in the structure. That restriction on employment of characterization tests has contribute to development of non-destructive techniques (NDT), such as sonic testing and monitoring techniques [1–3].

Between all NDT, ultrasonic test is reported in the literature as the most employed. The advances on ultrasonic techniques occurred as result of its functionality. Ultrasonic test is a non-destructive technique that can be used to estimate mechanical properties, as compressive strength and modulus of elasticity, as well to assess the material homogeneity. Basically, the experimental consist into measure the time taken for the ultrasonic wave to go from one point to another through a certain material. The measurements can be done in the same point over and over without introduces damage to the assessed structure. Thus, allowing the monitoring of the measured point over the time.

The applicability of ultrasonic testing on different types of materials has been studied worldwide, as concrete [4–7], mortar [8] and timber [9]. The results demonstrate that

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even for heterogeneous materials, as masonry components, ultrasonic pulse velocity (UPV) can be useful to detect vaults, to assess the walls quality and estimate mechanical parameters [10–13]. Additionally, recent studies proposed new approaches and its application to characterize historic buildings [14, 15].

Experimental tests were carried out in order to understand the mechanical properties of masonries from Aveiro downtown, in Portugal [16, 17]. In these studies samples of adobe were produced and destructive tests were performed in order to collect information on compressive strength and mechanical behavior of abode. Also, a correlation between different testing procedures and the final deformations under compression of the adobe masonries were identified. In this context, the application of ultrasonic tests could be useful to state new correlations between ultrasonic pulse and the mechanical properties of the adobe masonry and guarantee its application in similar masonry without destructive test necessity. In the other hand, in [18] UPV is employed to analyses clay bricks properties. The results demonstrate that is possible the establishment of a relation between UPV and mechanical properties of clay bricks. This application can assist the on-site UPV testing of clay brick masonry ancient buildings.

Sonic and ultrasonic tests have been each more reported in the literature, especially in Europe zone, due to the possibility into establish a correlation between mechanical parameters, such as compressive strength, and ultrasonic pulse velocity. Concerning concrete, correlations between mechanical and UPV are very well knew by technical community. But, concerning masonries samples, especially from historic buildings, correlations between mechanical and VPU are still a challenge for the technical field [19].

In a study presented by [20], the influence on clay bricks durability on the behavior of ultrasonic waves velocities was analyzed. The paper correlates the porosity of the samples and compressive strength with UPV. Through experimental procedures, the authors determine a direct correlation between UPV and the material durability: for velocity higher than 3500 m/s the bricks would be considered durable, while for velocity below 1000 m/s the bricks would be classified as not durable. However, for the range that comprises these two velocities, it was not possible to determine the durability of the samples by considering only the ultrasonic velocity as a parameter of analysis.

While several efforts have been made by the technical community in order to enlarge the information available on NDT masonry characterization, especially by UPV, as the contribution provided by [12, 18, 21–24], and showed by Fig. 1, more reliable data is needed to be collected, especially out of Europe zone.

Considering the necessity, the present paper has as the main aim to characterize physical and mechanical properties of the historic clay bricks from representative sites of the Ceará State (from North to South) and provides representative functions for estimating the compressive strength of the historic clay bricks based on UPV.

For this study samples were collected from Sobral, Icó, Irauçuba and Beberibe cities, as showed by Fig. 2, in order to cover considerable area of the Ceará State. The samples were collected all from vernacular 2-floors constructions, during the rehabilitation of the respective historic buildings heritage. The samples of Icó are dated from the 18th century, while the samples from Sobral are dated from the first half of the 19th century, and the samples from Irauçuba are dated from the second half of the 19th century and the samples from Beberibe are dated from the 20th century. The experimental characterization of the samples comprised to determination of water absorption index, compressive strength, UPV and the quantification of anisotropy expressed as a statistical parameter based on UPV measurements.

According to Institute of National Historical and Artistic Heritage (IPHAN), the Ceará State, located in the Northeast of Brazil, and presents four historic centers. Namely, these historic centers are located in the cities of Aracati, Icó, Sobral, and Viçosa do Ceará. However, heritage buildings can be found distributed in all cities of Ceará State, such as the cities of Irauçuba and Beberibe. The major and

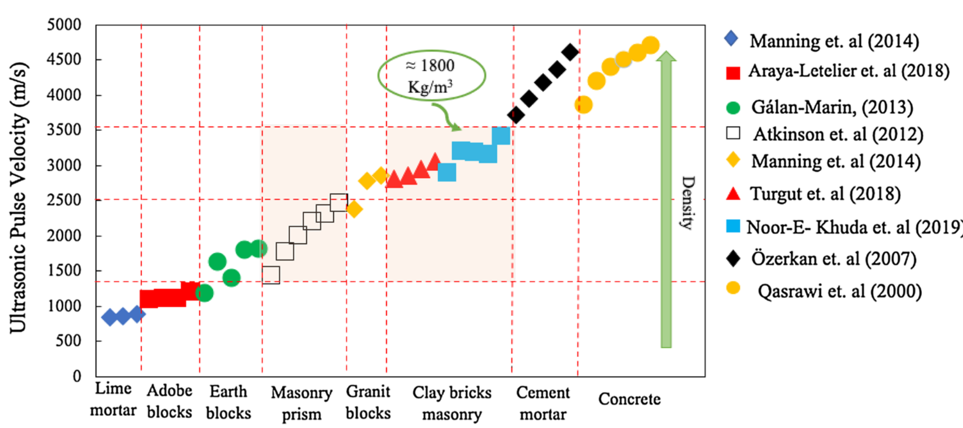

Fig. 1 Variation of the ultrasonic pulse velocity according to material analyzed

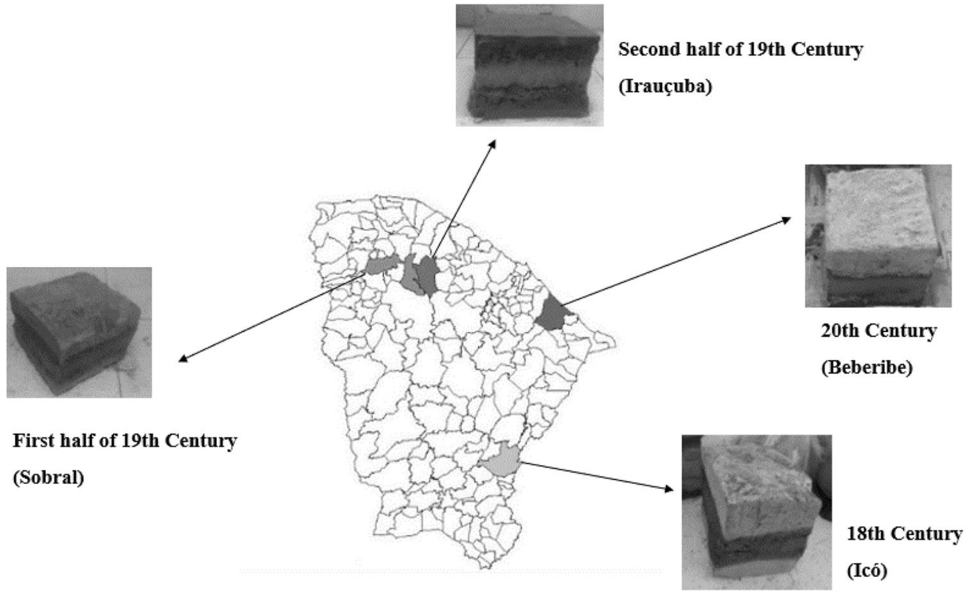

Fig. 2 Distribution of the places in the Ceará State were the samples of historic clay bricks were collected

minor presence of heritage constructions in the Ceará cities matches with the history of development of the Ceará, result of the Portuguese colonization. This way, to study the materials and the properties of the Ceará historic buildings and its elements is a necessary step to tell the history of the Ceará formation.

2 Ultrasonic method analysis

Non destructive techniques are each time more reported in the literature, especially in the characterization of building materials. In fact, non-destructive techniques (NDT) are attractive due to the fact that it does not introduces new damage to assessed structure, allowing repeatability of the measurements in the same point. Other attractive point on NDT is the fact that the test procedures can be easily performed in a short time. Between all NDT, ultrasonic is one of the most employed to assess concrete, mortar, timber and masonry structures. Fundamentally, by UPV measurements mechanical properties can be estimated and the heterogeneities detected [25, 26].

Waves can be classified into two basic groups: mechanic and electromagnetic. Ultrasonic waves are in the first group, because ultrasonic waves need a physical environment to its propagation, and thus, to transport energy. Mechanical waves can further be subdivided into two classes, body waves and surface waves [27]. There are two basic types of body waves, the longitudinal waves (P waves), which follow a longitudinal direction through compressive motions, and the transverse waves (S waves), which propagate in a perpendicular direction by vibration movements. Surface waves include Rayleigh waves, with elliptical motions, and Love waves, which appear in less common situations.

For a more detailed physical and mathematical point of view, consider a crystalline solid material which is made of atoms arranged in a precise precisely periodic in space. In addition, these atoms are not in the rest, but they own a spontaneous Kinect energy, i.e., they own a small random oscillation movement around their equilibrium position, vibrating like individual oscillators. One can observe collective and coherent movements (that can be longitudinal or transverse) of these atoms when mechanical waves propagate through the periodic crystal. It is worth to note that mechanical longitudinal and transverse waves can propagate within homogeneous solid materials in an independent way each other and with different velocities, namely, c_L and c_T for longitudinal and transverse, respectively. If the displacement vector from the equilibrium position is represented by $\boldsymbol{u}(\boldsymbol{r}, t)$, the mathematical equations that describe transverse and longitudinal plane propagating waves are the mechanical wave Eq. 1, where $\gamma = L$, for longitudinal waves, and $\gamma = T$, for transverse waves.

$$\nabla^2 \boldsymbol{u}_\gamma = \frac{1}{c_\gamma^2} \frac{\partial^2 \boldsymbol{u}_\gamma}{\partial t^2}, \quad (1)$$

It is also important to say that if the size of the medium is compared to the interatomic distance, then the displacement vector is the real atomic displacement and the wave must be described from an atomistic point of view. But, if the size of the solid material is larger than the interatomic distance, the microscopic structure can be ignored and the material must be considered as a macroscopic body and, as a consequence, the displacement vector represents, in a given time, the position of a volume element, with many atoms, of the solid.

The simplest solution for any wave equation in a given homogenous medium is a plane wave, i.e. Eq. 2,

$$\boldsymbol{u}_\gamma(\boldsymbol{r},t) = \mathrm{Re}\left[\boldsymbol{u}_{\gamma 0} e^{i(\boldsymbol{k}\cdot\boldsymbol{r}-\omega t)}\right], \tag{2}$$

which is the real part of the displacement amplitude vector $\boldsymbol{u}_{\gamma 0}$, that, in principle, is a space–time dependent complex vector. Here, $\boldsymbol{k}$ and ω means he wave-vector, related to the direction of propagation of the wave, and angular frequency, respectively. By replacing Eq. (2) in (1), the relation dispersion is obtained. This relation relates the angular frequency and the wave-vector, of a mechanical plane wave in a homogeneous solid material, as showed by Eq. 3.

$$k = |\boldsymbol{k}| = \frac{\omega}{c_\gamma}. \tag{3}$$

Finally, it is well-known that the both velocities c_L and c_T depend on the most basic mechanical properties of solids. In fact, they are given by the following equations

$$c_L = \sqrt{\frac{\mu}{\rho}} \tag{4a}$$

and

$$c_T = \sqrt{\frac{\lambda + 2\mu}{\rho}} \tag{4b}$$

where ρ is the density, and λ and μ are the Lame coefficients, which in turn are defined as

$$\lambda = \frac{E\nu}{(1+\nu)(1-2\nu)} \tag{5a}$$

and

$$\mu = \frac{E}{2(1+\nu)} \tag{5b}$$

Here, E and ν are, respectively, Young's modulus and Poisson's ratio, which are all time independent. In addition, we found that c_L is larger than c_T.

The ultrasonic method uses ultrasonic wave transmitter and receiver transducer to evaluate the path traveled by the wave, as well as velocity variations along the propagation. This procedure allows evaluating the different effects caused by the decrease or increase of the pulse speed.

In order to reduce interferences on the measures of UPV it is necessary to state frequency of the wave. If the frequency is sufficiently high, the wavelength values will be minimized, making difficult to capture it through the receiver transducer. Once the frequency is reduced, the detection of cracks within the material will became difficult. This fact can be explained due to the need of the wavelength be smaller than the crack length for be detected though analyzing the data collected.

There are three basic arrangements for measuring UPV. The first, the direct method, makes use of two transducers on opposite faces, and is ideal for characterizing material samples. The second, the semi-direct method, consists of using transducers on perpendicular faces, and the third, the indirect method, consists of using transducers on the same face, varying the distance between them. In this research the direct method of UPV measurement was adopted for the sample characterization.

The analysis and interpretation of the results obtained in the ultrasonic tests can allow the estimation of important material characteristics. Concerning heritage constructions assessment, the use of the ultrasonic method can be considered a relevant contribution. As can be observed in the studies performed by [15, 20], the method provided qualitative and quantitative data, enabling the establishment of a correlation between UPV and porosity index. The results also enabling to detect voids inside the materials.

In this research, the correlation between ultrasonic velocity and compressive strength was identified, and new parameters such as structural anisotropy and anisotropic resistance were also obtained through UPV measurements.

3 Experimental procedures

The clay bricks samples were obtained from vernacular historic constructions from Ceará State from different periods. For the sample collecting, the historic clay bricks were selected from four different periods: 5 clay bricks samples from a vernacular construction from 18th century were collected from Icó; 3 clay bricks samples from the first half of the 19th century were collected from Sobral; 5 clay bricks samples were collected from an ancient building from the second half of the 19th century from Irauçuba; and 3 clay bricks samples from the 20th century were collected from Beberibe. The bricks dimensions are presented by Table 1.

The bricks samples were prepared by removing mortar residues attached on clay bricks surfaces. The detailed information on the samples are presented in the Table 1.

3.1 Water absorption

The water absorption test was performed according to the procedures of [28]. First, each sample was submitted during 24 h to water immersion, for achieve the saturation condition. Following, the samples were weighed and them dry mass was determined. The water absorption index was calculated by the Eq. 6.

Table 1 Physical characteristics of the traditional Brazilian clay brick, where TA18, TB19, TC19 and TD20 are the samples from 18th century, first half of the 19th century, second half of the 19th century and 20th century

	Width (mm)	Length (mm)	Thickness (mm)	Weight (kg)
TA18-1	170	340	45	2.826
TA18-2	170	155	50	1.823
TA18-3	150	120	40	0.845
TA18-4	180	180	45	1.708
TA18-5	170	205	50	2.583
TB19-1	170	360	45	4.878
TB19-2	170	350	50	4.954
TB19-3	170	355	50	4.789
TC19-1	205	135/170	45	2.712
TC19-2	205	181/224	50	3.415
TC19-3	204	160/185	45	2.676
TC19-4	203	359	49	5.830
TC19-5	200	163/199	54	3.168
TD20-1	259	145	59	2.432
TD20-2	251	140	51	2.358
TD20-3	247	147	47	2.405

$$w = \frac{Saturated\ mass - Dry\ mass}{Dry\ mass} * 100 \tag{6}$$

3.2 Samples preparation for compressive strength and ultrasonic pulse velocities testing

The samples were divided to the half (Fig. 3) and were assembled using a limestone mortar in the proportions of 1:5 (in mass). The water/limestone ratio was fixed in 0.45. Following, a layer of mortar was applied to regularize the upper and lower surfaces of the blocks. The regularization enables the use of transducers properly, as well as contributes to the positioning of the samples during the experimental.

Fig. 3 Clay brick divided in two parts

3.3 Ultrasonic test and compressive strength

To perform the ultrasonic test, the Proceq® PUNDIT 2000® 54 kHz equipment was used, with two transducers, a transmitter and a receiver, allowing the transport, capture and measurement of UPV.

UPV measurements were performed based on direct measurement by positioning the transmitter and receiver transducers on opposite sides, procedure illustrated by Fig. 4. Ultrasonic measurements were performed in the three orthogonal directions of the samples. Each measurement procedure comprised three measures in each one orthogonal direction and the average was calculated and taken as the result.

Compressive strength tests were performed on the samples following the [29].

The nomenclature assigned to the samples is shown in Tables 2 and 3.

4 Results

4.1 Water absorption index

Concerning the analysis of the water absorption index of the samples, the bricks of the first half of the 19th century (TB19-1, TB19-2 and TB19-3) presented the lowest value, with an average of 6.40% of water absorption index, while the 20th century samples (TD20-1, TD20-2, TD20-3) presented the highest value, with an average of 27.34%. The 18th century samples (TA18-1, TA18-2, TA18-3, TA18-4

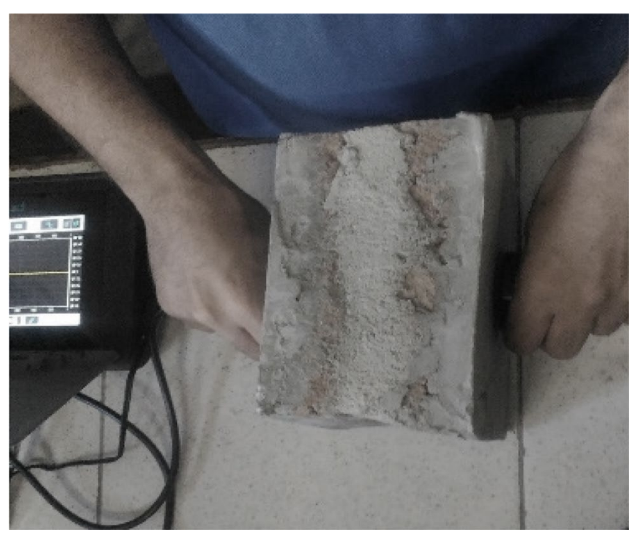

Fig. 4 UPV measurements in a sample

Table 2 Correlation between period and brick samples used in the absorption test

Identification	Bricks
18th century	TA18-1
	TA18-2
	TA18-3
	TA18-4
	TA18-5
First half of 19th century	TB19-1
	TB19-2
	TB19-3
Second half of 19th century	TC19-1
	TC19-2
	TC19-3
	TC19-4
	TC19-5
20th century	TD20-1
	TD20-2
	TD20-3

Table 3 Correlation between period and block samples used in ultrasonic and compressive strength tests

Identification	Blocks
18th century	A18-1
	A18-2
	A18-3
First half of 19th century	B19-1
	B19-2
	B19-3
Second half of 19th century	C19-1
	C19-2
	C19-3
20th century	D20-1
	D20-2
	D20-3

and TA18-5) and the samples of the second half of the 19th century (TC19-1, TC19-2, TC19-3, TC19-4 and TC19-5) presented an average of 12.52% and 10.46%, respectively (Fig. 5).

TB19-2 samples presented the lowest water of absorption index, with a value of 5.89%, while the TD20-1 specimen presented the highest value, of 32.01%. The absorption index of the samples from 18th century and for the second half of the 19th century is in the range between 10.14 and 13.58%, illustrating a homogeneity between them. According to [29], the water absorption index should not be less than 8% and not higher than 22%. In this way, the samples from the 18th century and from the second half of 19th century meet the

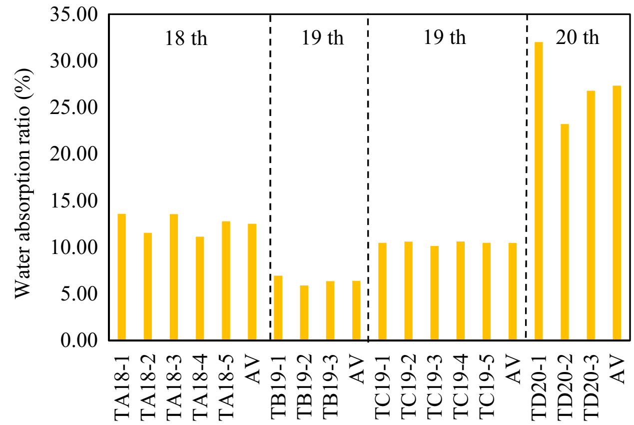

Fig. 5 Ration of the historic clay bricks water absorption

limits established by the standard, while the samples from the first half of 19th century were below the minimum value of absorption index, and the samples from the 20th century were above the maximum value standardized.

The homogeneity between the samples properties was performed by analyzing the standard deviation. Thus, the absorption index of the samples TA18-1, TA18-2, TA18-3, TA18-4 and TA18-5 from the 18th century, with values were 13.58%, 11.54%, 13.54%, 11.13% and 12.79% respectively, presented a standard deviation of 1.1324. Thus, the existence of similarity between these samples is proved due to the proximity between those values. The samples from the first half of the 19th century, TB19-1, TB19-2 and TB19-3 showed respectively, 6.95%, 5.89% and 6.35% of absorption index presenting a standard deviation of 0.5315. Also indicating a similarity between these samples, verified by the low standard deviation. The samples from the second half of the 19th century, TC19-1, TC19-2, TC19-3, TC19-4 and TC19-5, presented absorption values of 10.47%, 10.60%, 10.14%, 10.62% and 10.47% respectively and standard deviation of 0.1922. Finally, the samples from the 20th century, TD20-1, TD20-2 and TD20-3 showed water absorption values of 32.01%, 23.21% and 26.79% respectively, with a standard deviation of 4.4253. Therefore, it was observed that the bricks from second half of the 19th century presented the lowest standard deviation among the analyzed samples, comprising a correlation of this property, as well as the samples from the 18th century and from the first half of the 19th century. However, the samples from the 20th century, presented the highest standard deviation, which can be justified by the different bricks used in the sampling procedure.

4.2 Ultrasonic pulse velocity

For analyze of the ultrasonic pulse velocity measurements on the clay brick length, thickness and width

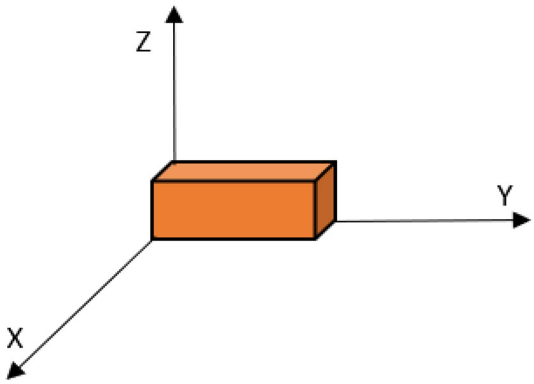

Fig. 6 Orthogonal axis representation of the VPU measurements

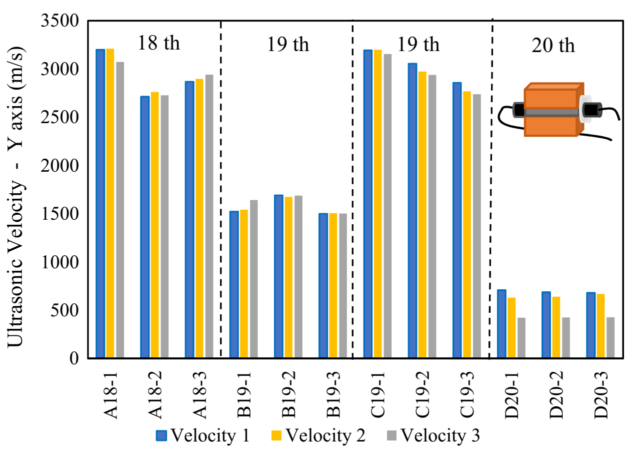

Fig. 7 Ultrasonic velocities measured in the Y axis

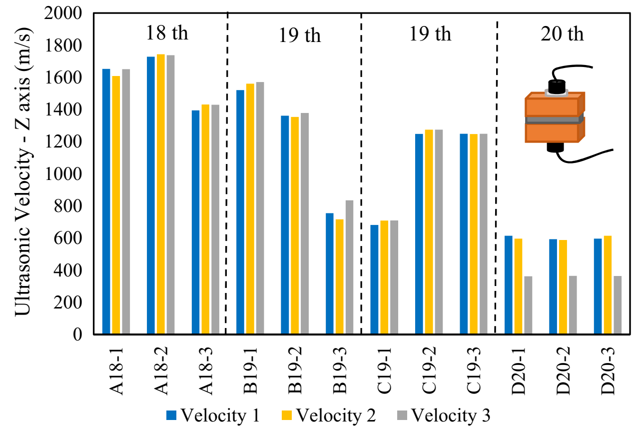

Fig. 8 Ultrasonic velocities on the Z axis

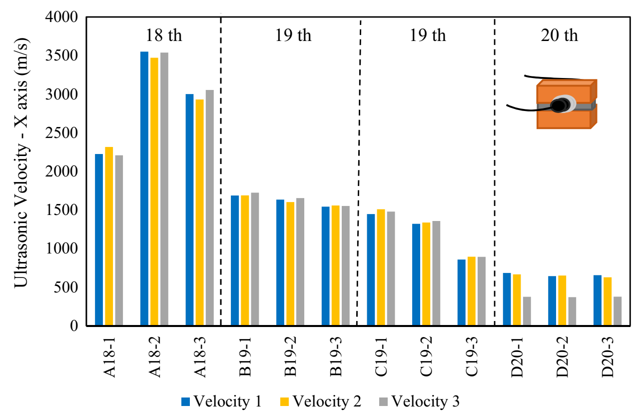

Fig. 9 Ultrasonic velocities on the X axis

measurements were performed, associated with the Y, Z and X axes respectively (Fig. 6).

In order to reduce error, three ultrasonic velocity measurements were performed in all samples face, being the result the average of the measured values. Only three samples from the 18th and three samples from the second half of the 19th century were tested because the other samples cracked during the experimental preparation. In the measurement of the Y axis (Fig. 7), it was observed in the samples of all periods assessed variation between the ultrasonic velocities. The samples from the 18th century and from the second half of the 19th century showed close ultrasonic pulse velocities, with a variation of 2733.67 m/s in the sample A18-2 to 3183 m/s in sample C19-1.

The samples from the first half of the 19th century, presented UPV values close to those from the 18th century and from the second half of the 19th century, ranging from 1503 m/s in B19-3 to 1684 m/s in B19-2. The lowest values found came from the samples from the 20th century, varying from 585.33 m/s in D20-2 to 593.33 in D20-3.

The measurements performed on the Z axis (Fig. 8) showed a different behavior in the UPV of the samples from the 18th century and from the second half of the 19th century, which had a considerably variation in relation to the X axis measurement (Fig. 9). In addition, there was a decrease in the samples average values, varying between 700 m/s in C19-1 and 1736.33 in A18-2. Observing the UPV values in the samples from the 18th century, there is a variation of 1418.33 m/s in A18-3 to 1736.33 m/s in A18-2, while the values from the samples of the 19th century are in the range between 700.33 m/s in C19-1 and 1266 m/s in C19-2. The samples from the first half of the 19th century also showed variation in the UPV values, ranging from 769 m/s in B19-3 to 1551 m/s in B19-1. Otherwise, the UPV measured in the samples from the 20th century presented similar values them the length measurement (Y axis), varying from 515.33 m/s in D20-2 to 525 m/s in D20-3.

Regarding the X axis (Fig. 9), samples from the first half of the 19th century presented similar values them the UPV measured on the other axes, ranging from 1550.33 m/s in

B19-3 to 1700 m/s in B19-1. The variation of the samples from 18th century and from the second half of the 19th century was superior, ranging from 881 m/s in C19-3 to 3519.67 m/s in A18-2. Analyzing the UPV of the samples from the 18th century is a range of 2249.33 m/s in A18-1 to 3519.67 m/s in A18-2, while the UPV values from the second half of the 19th century samples presented an average of 881 m/s in C19-3 and 1478.33 m/s in C19-1. Additionally, an average of 553 m/s in D20-3 to 575 m/s in D20-1 was observed in 20th century samples.

The ultrasonic velocities found in the samples from the 20th century may be associated with the higher water absorption values obtained of its bricks. These values ranged from 23.21 to 32.01%, indicating the high presence of voids, thus contributing to the reduction of ultrasonic pulse velocity in these blocks.

4.3 Compressive strength

Following the experimental, the information on compressive strength is shown by Table 4. Table 4 illustrates these values for each of the samples.

Regarding the compressive strength values, it was found that samples A18-1, A18-2 and A18-3 presented the lower values, with an average of 4.27 MPa, while samples C19-1, C19-2 and C19-3 presented the highest values, with an average of 11 MPa. Intermediate values were found in samples B19-1, B19-2 and B19-3, which obtained an average of 8 MPa; the samples D20-1, D20-2 and D20-3 presented a compressive strength average of 7.9 MPa (Fig. 10).

Samples B19-1 and B19-3 presented respectively 6.529 MPa and 7.065 MPa, while the B19-2 samples presented 10.583 MPa. The samples from the 18th century presented the lowest values, with A18-1 equal to 3.783 MPa, A18-2 equal to 2.860 MPa and A18-3 to 6.328 MPa. A18-2 sample obtained the lowest compressive stress found in the analyzed samples. The samples from the second half of the 19th century presented the smallest variation, with C19-1, C19-2 and C19-3 equal to 9.434 MPa, 11.867 MPa and 11.717 MPa respectively. The samples from the 20th century namely D20-1, D20-2 and D20-3 presented 7.10 MPa, 6.40 MPa and 10.20 MPa, respectively of compressive strength.

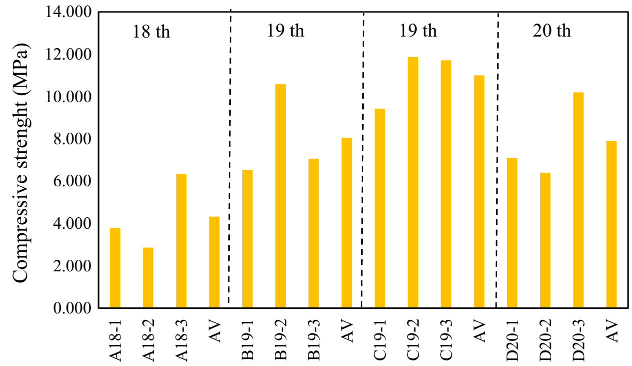

Fig. 10 Values of the compressive strenght of the specimens

Table 4 Definition of compressive strain values

	Area (mm^2)	Force (kgf)	Compressive strength (MPa)
A18-1	7050	2667	3.783
A18-2	14,410	4121	2.860
A18-3	18,906	11,964	6.328
B19-1	31,096	20,303	6.529
B19-2	28,336	29,989	10.583
B19-3	30,096	21,262	7.065
C19-1	18,957	17,884	9.434
C19-2	18,060	21,431	11.867
C19-3	12,006	14,067	11.717
D20-1	2150	1526.5	7.100
D20-2	2016	1290.24	6.400
D20-3	2451	2500.02	10.200

4.4 Correlation between the compressive strength and UPV

The results from compressive strength and UPV of each group of samples were analyzed and processed in order to point for a function of correlation between these two variables.

For this, due to the low correlation between the data from the samples of the 18th century, these were removed from the study, as well as the data of the samples B19-1, C19-1 and D20-3 for the same reason. For the Y axis measurement, which refers to the block length, the linear relationship degree or correlation index (R^2) equal to 0.8394 was obtained, representing a high correlation between both analyzed parameters (Fig. 11).

Based on correlation between UPV measured on Y axis and the compressive strength, Eq. 7 was found, where V is the ultrasonic pulse velocity, and fc is the compressive strength of the respective samples.

$$Vy = 374.21fc - 1723.9 \quad (7)$$

Performing the same data process in the other axes, the study between correlation of UPV measured on Z axis (block thickness) and the compressive strength was obtained a correlation index equal to 0.8865 (Fig. 12).

Following, the correlation between UPV measured on Z axis and the compressive strength, Eq. 8 was obtained,

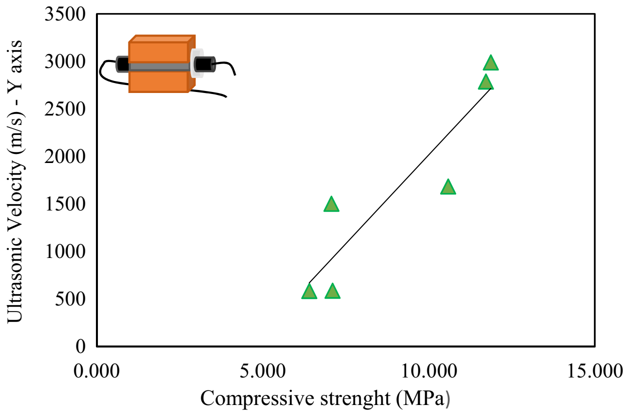

Fig. 11 Correlation between ultrasonic velocities of the Y axis and compressive strength

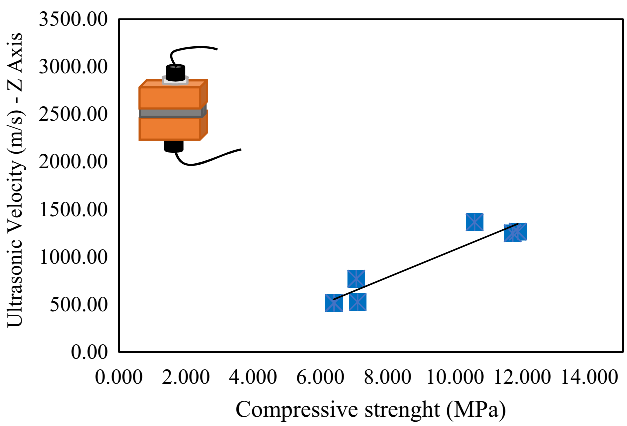

Fig. 12 Correlation between ultrasonic velocities of the Z axis and compressive strength

where V is the ultrasonic pulse velocity, and fc is the compressive strength of the respective samples.

$$Vz = 145.12fc - 375.91 \tag{8}$$

For the X axis (block width), a low correlation index between ultrasonic velocity and compression stress was observed, equal to 0.1647. Equation 9 form provides a numerical relation between those parameters (Fig. 13).

$$Vx = 77.089fc + 384.9 \tag{9}$$

4.5 Structural anisotropy

The structural anisotropy of the blocks was calculated relating the ultrasonic velocities measured in the three orthogonal directions using the Eq. 10 according to [30], where ΔM is the structural anisotropy and V_1, V_2 and V_3 are the UPV

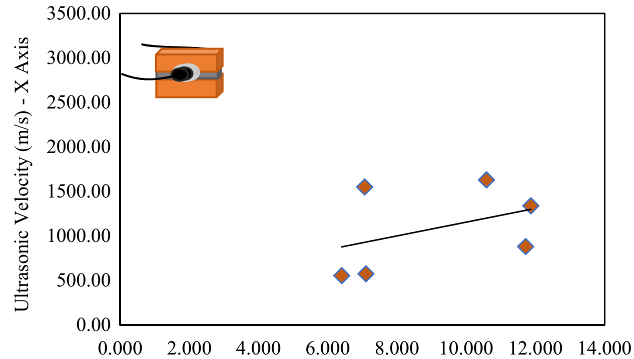

Fig. 13 Correlation between ultrasonic velocities of the X axis and compressive strength

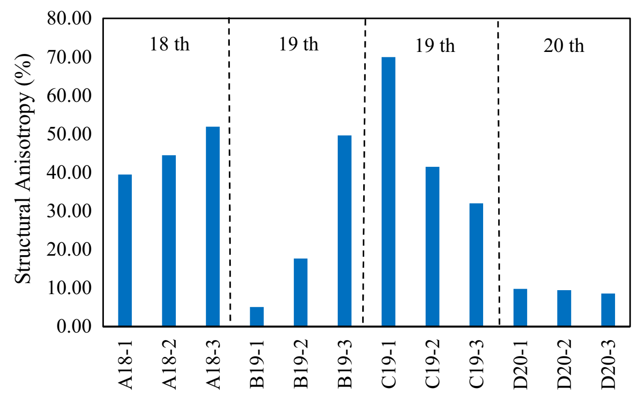

Fig. 14 Structural anisotropy of specimens

measured at the shortest, medium and longest distances between block dimensions.

$$\Delta M = 100\left[1 - \frac{2V1}{(V2 + V3)}\right] \tag{10}$$

Based on Eq. 10, adopting the three velocities measurements collected in each orthogonal axis, the results are presented in Fig. 14.

The samples from the first half of the 19th century presented variations in the structural anisotropy values. With 5.08%, the sample B19-1 obtained the lowest value among the samples under analysis, while the samples B19-2 and B19-3 presented respectively 17.65% and 49.62%. The standard deviation of the samples from the first half of the 19th century was 22.962, indicating differences in the microstructure of the blocks studied. A18-1, A18-2 and A18-3 samples from the 18th century presented respectively 39.43%, 44.47% and 51.90%, with a standard deviation of 6.2717.

The C19-1 specimen from the second half of the 19th century presented the highest value of structural anisotropy among the samples from all analyzed cities, with 66.97%, while the samples C19-2 and C19-3 presented 41.47% and 31.97% respectively, with standard deviation of 19.7758. The samples from 20th century, D20-1, D20-2 and D20-3, presented the values of 9.79%, 9.43% and 8.54% respectively, with a standard deviation of 0.6425. The lowest among the samples.

4.6 Anisotropic resitance

Anisotropic resistance was a calculated parameter relating to structural anisotropy of the samples and their respective compressive stresses [31], through the function presented by Eq. 11.

$$AR = \frac{\tau}{\Delta M} \quad (11)$$

The samples B19-1, B19-2 and B19-3 presented anisotropic resistance of 13.0971 kgf/%cm^2, 6.1154 kgf/%cm^2 and 1.4518 kgf/%cm^2 respectively, with a standard deviation of 5.8609. While the samples from the 18th century, A18-1, A18-2 and A18-3, presented values equal to 0.9782 kgf/%cm^2, 0.6558 kgf/%cm^2 and 1.2433 kgf/%cm^2 and standard deviation of 0.2941, indicating correlation between the data obtained from the blocks (Fig. 15).

The samples C19-1, C19-2 and C19-3 obtained values equal to 1.3749 kgf/% cm^2, 2.9182 kgf/%cm^2 and 3.7376 kgf/%cm^2, with a standard deviation of 1.1996. Finally, the samples from the 20th century, D20-1, D20-2 and D20-3 presented, respectively, 7.3978 kgf/%cm^2, 6.9182 kgf/%cm^2 and 12.1792 kgf%cm^2 and standard deviation of 2.9089.

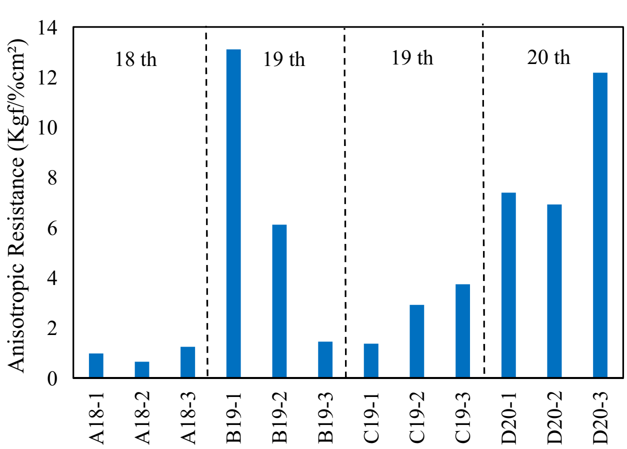

Fig. 15 Anisotropic resistance of specimens

5 Conclusions

In this paper was reported the results from historical clay bricks samples characterization from Ceará State, Brazil. The samples are dated from the 18th to the 20th century. The characterization was done through destructive and non-destructive tests, with emphasis on the study of ultrasonic velocities.

The determination of the water absorption indexes allowed to identify variations among different bricks from the analyzed periods. In this context, with an average of 6.40%, it was observed that bricks from the first half of the 19th century presented a low index compared to other cities, while the bricks from 20th century had an average of 27.34%. This indicates a higher presence of voids in the samples collected from the 20th century, a factor that may be associated with the manufacturing process of these bricks, related to its period and location.

The ultrasonic velocities were measured in the three orthogonal axes to allow the correlation with the anisotropy of the samples. Comparing the three axes measurements, the samples from the 20th century presented the lowest ultrasonic velocity values, ranging from 515.33 to 593.33 m/s. This fact allowed to states a direct relationship with the high-water absorption index of the bricks. The average of the compressive strength of the samples was 7.900 MPa.

The samples from the first half of the 19th century presented ultrasonic velocity values ranging from 769 to 1700 m/s, justifying a lower water absorption index when compared to the 20th century samples. In addition, the samples compressive strength presented an average value of 8.059 MPa, near to the result found in the 20th century samples.

Assessing the UPV from the samples of the 18th century, values from 1418.33 to 3519.67 m/s were observed. This interval was slighter to the Y and Z axes, ranging from 273.67 to 3160.67 m/s, and 1418.33 to 1736.33 m/s respectively. Nonetheless, there was a greater dispersion of results for the X axis, ranging from 2249.33 to 3519.67 m/s. The samples from the 18th century presented satisfactory water absorption index, with an average of 12.52%, while compressive strength values were the lowest between the four cities studied in this research, with an average of 4.324 MPa. This may be associated with insufficient correlation between ultrasonic velocity data and compression strength.

The samples from the second half of the 19th century presented considerably variations between ultrasonic velocities, ranging from 700.33 to 3183 m/s, with an absorption index near to the samples from the 18th century, with an average of 10.46%. While for the compression strength the samples presented highest values, with an average of 11.006 MPa, resulting in conformity with data referring to this period.

During the data processing, samples B19-1, C19-1 and D20-3 were removed from the analysis, as well as the samples from the 18th century. This allowed to assign a linear function that relates the ultrasonic velocity to the compression stress. The presented strength line grant reliability to the results.

The anisotropy study allowed to correlate the ultrasonic velocities to the microstructure, especially porosity/voids, of the samples. This provides a better understand concerning technical quality of these elements, which is associated with the concept of anisotropic resistance. Via removing dispersed values, it resulted in higher values of anisotropic resistance of samples D20-1, D20-2 and B19-2.

The physical and mechanical analysis conducted in this research allows to adequately extend the understanding about the characteristics of the historical clay bricks of Ceará State, with Luso-Brazilian influence, especially concerning to the 18th, 19th and 20th centuries.

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