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Evaluation of the physical and mechanical properties of artisanal clay brick manufactured in the metropolitan area of Tuxtla Gutiérrez

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— Abstract—

The objective of this work was to evaluate the geometric characteristics and strength of handmade clay bricks manufactured in the metropolitan region of Tuxtla Gutiérrez, Chiapas, in accordance with current standards. Forty bricks from six different suppliers were selected to analyze geometric variation, water absorption percentage, volumetric weight, and compression strength. The tests were conducted following the NTCM-20 and NMX–C–ONNCCE regulations. The results show that while the length and width dimensions of the bricks meet the recommended minimum values, the height does not. 50% of the analyzed samples exceeded the maximum water absorption limit of 23%. All samples surpassed the minimum volumetric weight of 1300 kg/m^3. Compression tests indicated an average strength of 23.41 kg/cm^2, representing only 33.44% of the minimum compression strength of 70 kg/cm^2 set by the standards. These results highlight the need to regulate the production of fired clay bricks in the region, to ensure compliance with normative standards and to design masonry walls that are compatible with local materials.

Keywords:

Mud brick; water absorption; compression strength; masonry.

Annealed Mud Brick (AMB) is a basic masonry material in the construction of homes in Mexico. It has been used since the time of the colony, although its massive use for construction in popular housing emerged at the beginning of the 20th century. Currently, the AMB in the national environment is one of the most used in the construction of masonry walls; in Tuxtla Gutiérrez, it is the second most used material for the construction of walls in popular housing (Argüello Méndez et al, 2022).

However, the AMB pieces manufactured in the metropolitan area of Tuxtla Gutiérrez have been used without reliable knowledge of their physical and mechanical properties, since they are not standardized or evaluated in a laboratory, and these properties are of interest for the calculation of masonry structures. Knowing the real characteristics of this material makes it possible to properly design the dimensions of masonry walls and improve their performance. Guaranteeing a building with a better structural response to different types of stresses, especially in regions of great seismic activity.

The manufacturing procedures of the AMB in the region are mainly artisanal, cooked in wood-fired ovens, and industrialized, cooked in industrial ovens. The pieces have a prismatic shape with different proportions in their dimensions. Commonly, the dimensions of the most used pieces are 5 cm high, 10 cm wide, and 19 cm long, not counting the masonry joint.

The use of AMB has certain advantages: it is a material that can be used in load-bearing walls and partition walls, adapting to many architectural styles. It can contribute to energy savings in buildings due to the thermal insulation properties it can possess. Depending on its quality and the minimum protection provided during its useful life, it can reach approximately 100 years. Brick parts are more economical (less than $10.00/piece and require little maintenance) than other similar masonry materials. It can be considered a "sustainable" and "friendly to the environment and living beings" material, since it does not contain pollutants and allergens. These characteristics make AMB a timeless material, since in Mexico and Chiapas its use represents an identity and part of the local culture.

AMB could be considered a material of natural origin and environmentally friendly manufacturing. Its manufacture requires minimal industrial treatments, reducing and being more efficient in the polluting intermediate processes, since the ecological and carbon footprint could be reduced. In this sense, the AMB becomes a suitable option for the construction of low-income housing.

Most of the experimental studies on masonry worldwide have focused on the study of the physical and mechanical properties of this material. In Mexico, Professor Meli (1975) investigated the seismic behavior of masonry walls, analyzing the variability of the component materials, the determination of basic properties of masonry in small specimen tests, and the study of behavior under lateral loads in one direction and under alternating loads.

Their results contributed significantly to the development of recommendations for the design of masonry structures in Mexico. Since then, controlled tests have been carried out in different parts of the world to determine the physical and mechanical properties of this material.

Piscal Arévalo et al. (2012) evaluated the mechanical properties of solid ceramic bricks manufactured by hand in the municipality of Ocaña (Colombia). First, the physical characterization of the clay used as raw material was carried out, then different brick producers were selected, and non-destructive and destructive tests were carried out for quality control. For this purpose, they used the Colombian Technical Standard NTC-4017, "Methods for sampling and testing of masonry units and other clay products". They were able to determine the modulus of elasticity and compressive strength of the tested material.

In El Salvador, Berríos Alvarado and Gómez Bonilla (2015) studied the compressive strength of mud brick piles using two types of mortar. In addition, they evaluated the characteristics of the stress-strain relationship in these masonry piles. They concluded that the use of different mortars does not produce significant changes in masonry quality. They also determined that the values of the modulus of elasticity of this material are lower than those indicated by the Salvadoran standard “Technical standard for the design and structural construction of masonry".

Soto and Sanchez (2017) investigated the main physical and mechanical properties of handmade mud brick produced in northwestern Honduras. They analyzed the geometric dimensions, absorption percentage, and compressive strength of individual pieces. They compared their results with ASTM C 62 standards, concluding that the material meets the minimum required strength. In addition, depending on the moisture absorption capacity of the tested bricks, they may be suitable for use in high-humidity environments. Evaluation of the geometric dimensions revealed that the material has a uniform geometry.

In 2016, Aguilera Morán carried out an extensive study on the characterization of the physical and mechanical properties of the annealed mud brick of the city of Aguascalientes and its conurbation area. He gathered material from 38 different brick kilns with batches of 7 pieces. He tested 71.5 % of the total number of pieces and left 28.5 % as a reserve. He mentions that the geometric characterization and compressive strength tests on brick pieces were carried out per the standards of the National Organization for Standardization and Certification of Construction and Building (ONNCCE). The analysis of the results shows that 61% of the lots tested do not meet the minimum compressive strength criteria indicated in the NMX-C-404-ONNCCE-2012 standard. In addition, none of the 190 pieces studied complies with the geometric dimensions established by the NMX-C-038-ONNCCE-2013 and NMX-C-404-ONNCCE-2012 standards.

On the other hand, Arbildo Huamani and Rojas Paco (2017) studied the resistance to axial and diagonal compression in masonry specimens of mud bricks, manufactured in Tacna, Peru. In their work, they considered a mortar joint thickness of 1 cm and a cement-sand dosage of 1:4. They carried out controlled compression tests on 5 piles and 5 walls, according to the protocol indicated in the NTE 070 regulations of Peru. They concluded that the material analyzed has medium strength and durability, suitable for general-purpose masonry constructions. However, the type of brick studied should not be used for buildings in particularly rigorous service conditions. In addition, they suggest carrying out strict quality control and inspection of this material during the construction process of the building.

Other studies have focused on determining the shear strength of mud brick masonry. Among these studies, the one carried out by Valdivia Espinoza (2020) stands out, who determined the resistance to compression and shear in the masonry of industrially manufactured mud bricks in Huánuco, Peru. The tests were carried out following the protocols of the N.T.P. 399.605 and E.070 regulations of Peru. Based on his results, he concluded that it is not advisable to use this brick in the construction of load-bearing walls because its compressive strength values are lower than those indicated by the regulations, tending to shear the walls under the action of diagonal tension.

In Chiapas, despite the wide and attractive use of this material, there is a lack of sufficient studies on the geometric and mechanical characterization of locally manufactured LBR. This prevents making sensible calculations for the design of structures with this type of masonry and obtaining adequate levels of structural safety. On the other hand, there are also no regional construction regulations for the design of structures with this construction system. The current construction regulations for Tuxtla Gutiérrez do not include a section in which the design of masonry buildings is addressed or the quality of the used masonry elements is recommended.

Due to the absence of specific regulations in Chiapas, in the metropolitan region of Tuxtla Gutiérrez, there is no regulation of the LBR quality produced by manufacturers. As a consequence, there is no uniformity in the manufacture of this material, with the parts being of dubious and poor quality. This puts structures and their occupants at risk in cases of seismic stress.

MATERIALS AND EXPERIMENTAL PROGRAM

6 AMB suppliers were chosen, and from each, a batch of 40 pieces was purchased, using a total of 30 pieces for tests such as geometric characterization, initial water absorption, and simple compressive strength. The surplus

was left as a spare for unforeseen situations during the handling of the tests. The number of parts used in each batch for the controlled tests was as follows:

Geometric characterization: 10 pieces
Initial water absorption: 10 pieces
Simple compressive strength: 10 pieces

To carry out these tests, the recommendations of NTCM-23 (Complementary Technical Standards for the Design and Construction of Masonry Structures) and the standards of the National Organization for Standardization and Certification of Construction and Building (ONNCCE) (NMX-C-404-2012-ONNCCE) were met.

In addition, the compressive strength of the glue mortar was examined, for which 9 cubic specimens were manufactured and tested according to the specifications of NMX-C-486-2014-ONNCCE (Structural Use Mortar-Specifications and Test Methods).

The tests of the brick pieces and the mortar were carried out in the Laboratory of Soil Mechanics, Strength of Materials and Concrete Technology, of the Faculty of Engineering of the Universidad Autónoma de Chiapas (UNACH).

Procedure for Compressive Strength Test

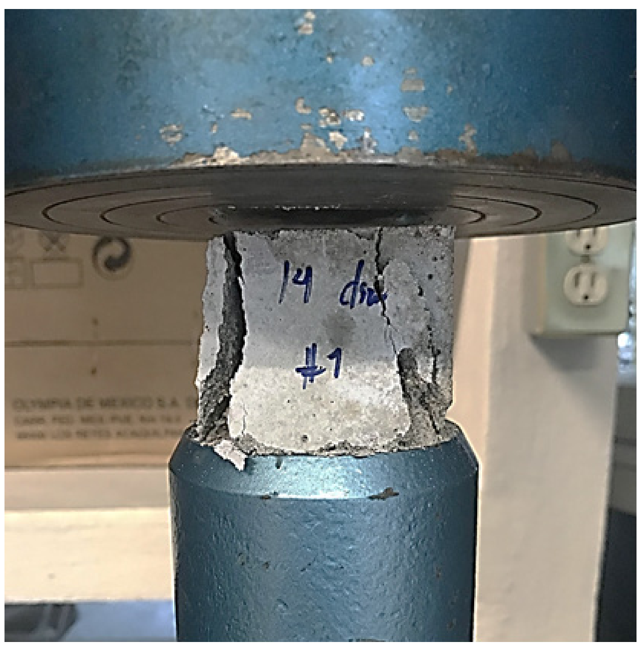
The mortar mixture was manufactured with cement (CPC type) whose characteristics comply with the recommendations of NMX-C-021-ONNCCE-2015 and NMX-C-414-ONNCCE-2017. Local river sand was also used. The volumetric proportion of the mix was 1:0:3 (cement-lime-sand), commonly used in local practice and classified as type I mortar following NTCM-23.

The controlled tests were carried out by NMX-C-061-ONNCCE-2010. Steel molds with dimensions of 5×5×5 cm^3 were used to prepare the mortar specimens (Figure 1). The molds were filled in two layers of mortar and compacted with 32 blows. The mortar was left to set for 24 hours, after which it was demolded and immersed in water for 27 days, and compressive strength tests were performed at 28 days of age.

Note: Own elaboration.

Figure 1. Mortar test tubes

Compression tests were performed using a universal press, as shown in Figure 2. The load was applied to the face of the test tube that was in contact with the vertical walls of the mold and maintained until the point of rupture.



Note: Own elaboration.

Figure 2. Compression test on a mortar specimen

Procedure for geometric characterization of the AMB

To perform the geometric characterization, we proceeded according to the protocol of NMX-C-038-ONNCCE-2013, and 10 pieces of ABM were chosen for each supplier. The dimensions (length, height, and width) of each piece of brick were measured with a Vernier (caliper) and a graduated ruler (Figure 3). Three measurements were made on each side, and the average and standard deviation of the dimensions recorded for each lot were calculated.

Note: Own elaboration.

Figure 3. ABM geometric characterization

Procedure for 24-hour water absorption

In order to determine the water absorption after 24 hours, we proceeded as described in NMX-C-037-ONNCCE-2013. Three brick samples were chosen for each supplier and marked with a number and a letter of the alphabet for proper identification (Figure 4).

Note: Own elaboration.

Figure 4. Specimens with identification

The samples were oven dried for 24 h at a temperature of 100 ± 10 °C (Figure 5). Subsequently, the dry mass value (*Ms*) of each sample was obtained. These were submerged in water at a temperature between 17°C and 23°C for a period of 24 hours. After this time, they were removed from the container, and the excess water on the surface of the samples was eliminated with a flannel, thus obtaining the value of the saturated mass and dry surface (*Msss*).

Note: Own elaboration.

Figure 5. Specimen drying process

With the recorded *Ms* and *Msss* data, the volumetric absorption (A) in percentage after 24 hours was calculated with equation 2:

$$A = \frac{Msss - Ms}{Ms} \times 100 \tag{1}$$

Procedure for volumetric weight

From each supplier, 10 pieces of LBR were selected, the dimensions of which were measured, and the dry mass of each brick was recorded. The volumetric weight was calculated by dividing the mass of the brick by its volume. These values were compared with those specified in NTCM-23, which establishes a standard volumetric weight of 1300 kg/m³ for solid artisanal clay partitions.

Compressive strength test on brick parts

Compressive strength tests were performed in accordance with NMX-C-036-ONNCCE-2013. In the 10 brick pieces chosen for this test, a pitching process was applied on both sides with a gypsum-based paste, as shown in

Figure 6. This procedure aims to achieve a uniform contact surface between the brick and the universal press, which allows for improving the distribution of the load on the brick piece.

The load was applied in a gradual and controlled manner on the major surface of the brick pieces. The last recorded load was the one that was reached at the time of the rupture of the material.

Note: Own elaboration.

Figure 6. Pitching of the brick pieces

In NTCM-23, it is indicated that the design compressive strength of individual parts must be calculated with equation 3:

$$f'_p = \frac{\overline{f_p}}{1 + 2.5C_p} \quad (3)$$

Where, $\overline{f_p}$, is the average of the compression strength of the pieces, referred to the gross area, and C_p is the coefficient of variation of the compression strength of the pieces, which in the case of handmade production pieces should not be less than 0.35.

RESULTS AND DISCUSSION

This section presents the results obtained from the different tests carried out on LBR parts, manufactured in the metropolitan region of Tuxtla Gutiérrez, Chiapas. The tests included evaluations of the geometric dimensions, water absorption percent, volumetric weight, and compressive strength of the parts. Each controlled test was conducted to determine how these properties affect the quality and applicability of brick in the construction of masonry walls.

Compressive strength of the glue mortar

Table 1 shows the results of the final load recorded and the values of the compressive strength at the age of 28 days for each test tube of mortar specimen.

Table 1
28-day mortar specimen compression test results

Test tube number	Breaking load (kg)	Compressive strength $\overline{f_j}$ (kg/cm²)
1	6000.00	240.00
2	6100.00	244.00
3	7100.00	284.00
4	5800.00	232.00
5	6000.00	240.00
6	5800.00	232.00
7	6800.00	272.00
8	6200.00	248.00
9	5800.00	232.00

The average value of the final load applied (Table 1) was 6177.78 kg, with a standard deviation (σ) of 465.78 kg. The average compressive strength determined was 247.11 kg/cm², with a standard deviation (σ) of 18.63 kg/cm².

According to NTCM-23, the design compressive strength (f_j') of the mortar test tubes was calculated with equation 1.

$$f_j' = \frac{\overline{f_j}}{1 + 2.5C_j} \quad (1)$$

Where C_j is the coefficient of variation of the compressive strength of the mortar, which in no case will be taken less than 0.20, and $\overline{f_j}$ is the average compressive strength of each mortar specimen.

The results obtained for f_j' ' are shown in Table 2 using the values in Table 1. According to the data in Table 2, the average value of the compressive design strength is 164.74 kg/cm², and its standard deviation is 12.42 kg/cm².

From these results, it was observed that the mortar performs well in compression tests. According to NTCM-23, the minimum design compressive strength, f_j', for glue mortar must be 125 kg/cm². According to the results of Table 2, it can be seen that all the specimens satisfactorily complied with the regulations. Therefore, the material can be considered of appropriate quality, and the dosage of cement:lime:sand of 1:0:3 commonly used in local construction practice is adequate.

Table 2

28-day mortar specimen design compression strength

Test tube number	Design compressive strength f_j' (kg(cm²)
1	160.00
2	162.67
3	189.33
4	154.67
5	160.00
6	154.67
7	181.33
8	165.33
9	154.67

AMB Geometric variation

The average values of the ABM dimensions: length, width, and height of each supplier, are shown in Table 3, as well as the respective values of the standard deviation (σ).

Table 3

ABM mean value and standard deviation of geometric dimensions

Provider	Length (cm)	σ_{legth} (cm)	Width (cm)	σ_{width} (cm)	Height (cm)	σ_{height} (cm)
1	25.9133	0.0805	12.8866	0.1097	4.5400	0.1114
2	26.2533	0.2098	12.8800	0.1360	4.9433	0.1764
3	25.7700	0.2057	12.5800	0.3490	4.6266	0.4133
4	26.2300	0.2523	13.0166	0.1424	5.5200	0.1661
5	25.6966	0.3042	12.7233	0.1563	4.6466	0.2765
6	25.2866	0.1727	12.6200	0.1194	4.6733	0.0904
Total	25.8583	0.2042	12.7844	0.1688	4.8250	0.2057

The NMX-C-404-ONNCCE-2012 standard establishes that the manufacturing dimensions of clay partitions must comply with the following minimum requirements: 190 mm long, 100 mm wide, and 50 mm high, and that the actual dimensions must not differ by more than ± 3 mm from the other manufactured pieces.

Comparison of the data in Table 3 with the minimum requirements of NMX-C-404 indicates that, in general, the length and width dimensions of the pieces do comply; however, they do not meet the minimum height requirements. Specifically, Table 4 shows the suppliers that meet the minimum dimensions for length and width. In terms of height, only one of the six suppliers was able to meet the minimum dimension established.

Table 4

Revision of minimum dimensions on individual parts

Provider	Length	Width	Height
1	Complies	Complies	does not comply
2	Complies	Complies	does not comply
3	Complies	Complies	does not comply
4	Complies	Complies	Complies
5	Complies	Complies	does not comply
6	Complies	Complies	does not comply

Regarding the tolerance of ± 3 mm in individual parts, Table 5 shows that only supplier 3 does not comply with this tolerance for the width and height dimensions.

Table 5

Revisión de la tolerancia de ± 3 mm en piezas individuales

Provider	Length	Width	Height
1	Complies	Complies	Complies
2	Complies	Complies	Complies
3	Complies	does not comply	does not comply
4	Complies	Complies	Complies
5	Complies	Complies	Complies
6	Complies	Complies	Complies

Water absorption

The results of the 24-hour water absorption test are presented in Table 6. This table includes the average absorption values for each supplier and the standard deviation, as well as those corresponding to all the brick pieces analyzed.

According to NMX-C-404-ONNCCE-2012, the maximum water absorption level for clay pieces in a 24-hour period is 23%. The results shown in Table 6 indicate that three suppliers (3, 4, and 5) comply with this requirement, while the remaining three (1, 2, and 6) have absorption levels above the maximum level of the NMX-C-404 standard. Despite these variations, the average water absorption for the total number of pieces analyzed complies with the recommended level.

Table 6

Mean value and standard deviation of water absorption

Provider	*Ms* average (g)	σ_{dry} (g)	*Msss* average (g)	$\sigma_{saturated}$ (g)	% average absorption	$\sigma_{humidity}$ (%)
1	189.67	12.12	257.78	11.95	36.06	2.46
2	130.67	32.31	165.93	39.24	27.30	1.35
3	167.33	23.54	199.81	28.26	19.40	0.57
4	168.03	5.57	196.26	11.85	16.81	5.99
5	129.08	2.62	152.57	4.44	18.18	1.54
6	160.57	42.30	202.33	53.92	25.92	0.37
Total	157.56	19.74	195.78	24.94	23.95	2.05

Volumetric weight

Table 7 shows the average volumetric weights and standard deviations for each supplier. It also contains their respective values for the total population analyzed.

Table 7

Mean value and standard deviation of the volumetric weight

Provider	Volumetric Weight (kg/m³)	$\sigma_{Volumetric\ Weight}$ (kg/m³)
1	1500.00	100.00
2	1400.00	85.74
3	1600.00	68.74
4	1700.00	55.43
5	1600.00	58.39
6	1500.00	38.61
Total	1550.00	72.94

NTCM-23 establishes that the minimum net volumetric weight for handmade clay pieces in the dry state must be 1300 kg/m³. From the results in Table 7, it can be seen that all suppliers comply with this requirement.

Even when considering the higher value of the standard deviation (100 kg/m³ for supplier 1), the parts still meet this requirement.

Compressive strength in brick pieces

Table 8 shows the average values of ultimate load and compressive strength for each supplier, together with their standard deviations.

Table 8

Mean value and standard deviation of ultimate load and compressive strength of individual parts

Provider	Breaking load (kg)	σ_{carga} (kg)	Compressive strength $\overline{f_p}$ (kg/cm²)	$\sigma_{estress}$ (kg/cm²)
1	11916.70	5822.6961	31.8159	15.3714
2	22816.80	7476.5686	61.3298	19.8244
3	10227.70	5595.1417	24.2665	16.3864
4	24677.50	7379.7185	66.7251	20.1791
5	21305.50	5951.8540	56.9133	15.8609
6	8481.30	3274.103	22.8689	8.9726
Total	16570.90	5916.6803	43.9866	16.0991

According to NMX-C-441-ONNCCE-2013, it establishes that handmade partition pieces, for non-structural use, must have an average resistance of 30 kg/cm² and a minimum individual resistance of 24 kg/cm². The values in Table 8 show that the ABM pieces tested are suitable for non-structural use, except for those of supplier 6.

Using the values of the compressive stress $\overline{f_p}$ and the standard deviation of the stress (σ_{stress}) (Table 8), the coefficient of variation (C_p) was determined to calculate the design compressive strength.

The average values of the design compressive strength (f_p') calculated with Equation 3, and for each supplier, are shown in Table 9. The values of the standard deviations and their coefficients of variation (C_p) are also shown. It is worth mentioning that for suppliers 2, 4, and 5, the value for C_p of 0.35 was used as indicated in NTCM-23.

The results of the design compressive strength, presented in Table 9, show that no supplier meets the minimum strength of 60 kg/cm² established by the NTCM-23 ABM standard, which is insufficient for this parameter. The resistance deficit varies between suppliers, reaching 84.95% in the case of supplier 3 and 36.67% in the case of supplier 4.

Table 9
Mean value, standard deviation, and coefficient of variation of the individual pieces' design compressive strength

Provider	f'_p (kg/cm²)	σ f'_p (kg/cm²)	Coefficient of variation C_p
1	14.4104	6.9617	0.4831
2	33.9193	10.9627	0.3232
3	9.0272	6.0952	0.6752
4	37.9972	11.4904	0.3024
5	33.5433	9.3485	0.2787
6	11.5449	4.5291	0.3923
Total	23.4070	8.2313	0.4092

The low design compressive strength observed in the brick pieces indicates that a good-quality masonry cannot be considered. It should be noted that mud bricks require sufficient mechanical strength to ensure adequate load transmission; in addition to ensuring durability, it significantly contributes to the stability and strength of the walls.

CONCLUSIONS

The design compressive strength of the glue mortar complied with what was indicated in NTCM-23 for type I mortar, being that the cubic specimens showed resistance capacities higher than the minimum value of 125 kg/cm², which indicates that the mortar used in the usual local practice was considered adequate and of good quality.

The masonry units analyzed met the minimum dimensions of length and width specified in NMX-C-404-ONNCCE-2012, although in most cases the minimum required height was not reached. It was found that the pieces of almost all suppliers remain within the tolerance of ± 3 mm in relation to the established manufacturing dimensions.

Regarding the percentage of water absorption, it is observed that only the bricks of three of the six suppliers were below the maximum limit of 23%, which suggests adequate permeability. However, the masonry units of the remaining three suppliers showed absorption levels higher than 23%, which indicates a higher porosity than recommended.

All the volumetric weight values of the pieces evaluated met the minimum of 1300 kg/m³ for artisanal clay partitions, as recommended by NTCM-23. However, as not all parts reached an adequate level of water absorption, it is necessary to improve the compaction and vibrating processes of the clay paste to optimize the correlation between porosity and volumetric weight.

Regarding the design compressive strength, the pieces tested were very poor, since none met the minimum value of 60 kg/cm^2 for solid artisanal clay partitions established by NTCM-23. Therefore, these pieces are not suitable for use in load-bearing walls, although they can be used in non-structural applications.

According to the results presented, it is necessary to improve the pieces' geometrical uniformity. Although they exceed the minimum length and width dimensions recommended by NMX-C-404-ONNCCE-2012, there is significant variability between different suppliers. In addition, it is crucial to optimize the pieces' porosity so that they do not exceed 23% water absorption, as stipulated by the same regulations. By achieving this, it is considered that the adhesion between the brick and the mortar can be improved, thus increasing the durability of the pieces.

Finally, it is considered very necessary to regulate and control more effectively the local handmade mud brick manufacturing process in order to improve the quality of the material. This will ensure that the masonry walls built in Tuxtla Gutierrez have adequate strength and meet the required safety and quality standards.

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