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Comparative analysis of bricks manufactured in the New World (1494–1544)

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ABSTRACT: This paper makes a comparative analysis of the first bricks manufactured in the New World during the first 50 years of conquest and colonization (1494–1544). Samples of bricks and tiles were taken from the sites of the ruins of La Isabella (1494), Concepcion de la Vega (1502), Fort Santiago in Fortaleza of Santo Domingo (1540), and Royal Shipyards (1544). Petrographic analysis, X-ray fluorescence (XRF), X-ray diffraction (XRD), sclerometer and Mercury Intrusion Porosimetry were performed on these samples. In conclusion, it was demonstrated that the bricks are of very good quality, made with a good low-porosity clay. The selection of the raw material and the manufacture of the brick demonstrate the deep empirical knowledge of the craftsmen who made the first bricks in the New World.

1 INTRODUCTION

Clay bricks have been manufactured and used as a building material in many regions of the world for their excellent physical and mechanical characteristics. In the Caribbean islands the use of brick arrived with the European conquerors as the native people did not use it for construction, they only used the clay to make pots.

In the New World, the first material manufactured by Europeans was the brick in 1494 in the city of Isabela. The need to build durable structures was the motivation to manufacture kiln clay bricks, because they are resistant to compression, fire, and weathering, and provide thermal and acoustic insulation.

To know the historical brick, it is necessary to carry out a series of chemical and mineralogical composition tests of clays to define the mixtures used in the manufacture of bricks because it directly influences their mechanical and physical properties.

Many studies have been carried out on the physical, chemical, and mechanical properties of the clay bricks and their use in architecture (Arce 2004; Fernandes et al. 2010; Fernandes 2019; Kagi & Ren 1995: Yavuz & Sağıroğlu 2016;). However, there are few studies on the properties of traditional clay bricks, and it is important to overcome this deficiency in the literature, especially as urban pollution, improper use of materials and lack of maintenance in most buildings (Fernandes 2019) are causing destruction of the brick. The type of clay and the techniques used by the manufacturers of these bricks are still unknown.

For this reason, the aim of this paper is to make a comparative analysis of the chemical, mineralogical, and physical properties of the kiln clay bricks manufactured on the Hispaniola island during the first 50 years of the conquest and colonization (1494–1544).

2 BRICKS IN HISPANIOLA ISLAND

In the Second Voyage, Christopher Columbus carried the order to establish cities in the New World, for which he brought a “brigade of workers, with supplies of bricks, lime and plaster” (Palm 2002). The brigade comprised masons, stonemasons, carpenters, blacksmiths, roofers, and brick builders, who, at that time in Spain, had already distinguished themselves from the potters.

La Isabela, on the island of Hispaniola now Dominican Republic and Haiti, was the first city established by the Spaniards where the first bricks and roof tiles were made. In the surroundings of the village the Spaniards found very good raw materials to manufacture lime, bricks, and roof tiles (Cruxent & Deagan 2002). Fray Bartolomé de Las Casas said that: “there was very good stone for quarrying and for making lime, and good soil for brick and roof tiles ...” (De las Casas 1987).

The archaeologist Jose Maria Cruxent, who excavated at La Isabela, found near El Castillo a 15th century pottery kiln which also must have been used for roof tiles and bricks (Cruxent & Deagan 2002).

After La Isabela, Cristobal Colon established the village Concepción de La Vega near the gold mines in 1495, and Bartolomé Colon established the city of Santo Domingo, on the eastern side of the Ozama River, in 1498. In both cities the Spaniards manufactured kiln clay bricks. From the end of the

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Figure 1. Clay on the island Hispaniola.

15th century, some problems caused the population to leave Isabela and settle in other villas, ceasing brick production in La Isabela and building new kilns in La Vega and Santo Domingo.

Commercial growth and population increase at the beginning of 16th century caused a construction boom, requiring more material than the island produced, so the Spaniards began to import, from Spain, materials including clay brick.

In 1502 Nicolás de Ovando arrived on the island, as governor of the territories discovered to that time. During his government (1502–9) he established new cities and occupied all the island's territory. At that time the crown hired builders to carry out all the works on the island, while Ovando brought construction materials such as nails, wood, and bricks.

Between 1508 and 1509, in the shipping lists of Viceroy Diego Colon's fleet, we found several records of brick shipments from Seville. For example, in 1508, Francisco de la Fuente arrived at Santo Domingo with 3000 clay bricks (Benzo 2000) and Pedro de Umbría with 10,000 clay bricks to make "the constructions of the city of Santo Domingo" (Rodriguez Demorizi 1978). In 1509 Alvaro de Briones registered 6000 clay roof tiles; Diego Díaz 1500 clay bricks (Benzo 2000); Juan de Jerez 4000 clay bricks and two dozen axes (Benzo 2000) while Tomás Sánchez registered two quarter iron, two quarter axes (weight two quintals) and 3000 clay bricks (Benzo 2000), among others.

In 1511, the crown requested that more bricks be manufactured on the island (Marte 1981). In a letter from the King to Diego Colón and the Officers of Seville, he thought it strange that there was a lack of roof tile and brick to finish the roof of the House of Hiring because there was plenty of mud and wood to make bricks on the island (Marte 1981) (Figure 1).

Immediately, Francisco de Garay installed the first kiln and produced clay bricks and roof tiles in Santo Domingo on the shore of the Ozama River, possibly from 1512. After Garay's death the factory was sold to Garcia de Aguilar in 1528, for the sum of 500 pesos of good gold (Rodriguez Demorizi 1978).

2.1 *Handmade clay bricks*

Handmade bricks are made of clay and water. First, the paste is prepared by mixing the clay and water, kneading the mixture, usually with the use of animal force until a homogeneous paste is achieved.

A few hours later, the paste is ready to be placed uniformly in a wooden kiln of the desired shape and size, usually rectangular. Before taking the clay brick out of the mold, it was left to dry for two or three days in the open air. It then went into the kiln where it cooked for about 12 or 13 hours between 900 and 950 deg. C. after which it had to wait about five days for them to cool down before they could be taken out of the kiln, ready to use.

3 CASE STUDY

To compare the bricks, five samples were taken from various parts of three cities, namely La Isabela, Concepción de La Vega and Santo Domingo. All the cities were established between 1494 and 1544.

3.1 *Isabella. First European settlement (M1 & M2)*

Cristobal Colon, on 6 January 1494, established the villa of Isabella and immediately houses for the inhabitants were built, a church, colonial admiral's house and several public buildings like the royal warehouse, powder magazine, hospital. These buildings were made of stone, clay brick, rammed earth – tapial – and wood. The clay brick and roof tile were made on site. All these buildings were built between 1494 and 1502, because after that date the city began to be abandoned.

Among the most relevant buildings are the admiral's house and the church. For this reason, brick samples were taken from both buildings: admiral's house (M1) and a sample of a roof tile from the church (M2). The dimensions of the brick could not be determined because the sample was taken from the ruins and the bricks are not complete.

3.2 *Royal Shipyards (M3)*

The Royal Shipyards, called Atarazanas, were built in the city of Santo Domingo between 1508 and 1509, the brick roofing was completed in 1544. They were used as a dockyard and warehouse to serve the purposes of naval trade for the *Casa de Contratación*.

The building is a rectangular plan made of clay bricks and stone masonry sheltered by three barrel vaults of bricks which rest on rectangular pillars and half-point arcs, both made of bricks. Each vault had three layers of clay bricks joined with lime mortar. The sample was taken from the southern vault (M3), built in 1540. The dimensions of the clay brick are 140 mm wide, 265 mm long and 45 mm thick, and weighs 2.25kg.

3.3 *Fort of Santiago in Fortress of Santo Domingo (M4)*

The Fort of Santiago, located on the grounds of the Fortress of Santo Domingo, was built in 1540 as part of the city's defensive system, and is made of clay bricks and rammed earth. Now it is abandoned.

The sample was taken from the entrance wall of the fort (M4) and the dimensions of the brick are

141mm wide, 267mm long and 45mm thick, and weighs 2.45kg.

3.4 *Concepcion de la Vega (M5)*

Concepcion de la Vega was established in 1498 and relocated about two leagues from the original site by Governor Ovando in 1504. This was the second European settlement in the New World. The city had a fortress with two towers, gold foundry, cathedral, houses, and monastery.

In 1562 an earthquake destroyed the city and now only ruins remain with part of the fort, one tower, and some walls of the church. The sample (M5) was taken from the fort, that as built between 1505 and 1515. The dimensions of the brick are 142mm wide, 295mm long and 52mm thick, and weighs 3.371kg.

4 MATERIALS AND METHODS

4.1 *Petrographic examination*

This technique allows direct observation of the mineralogy and texture of the brick and identifies the component minerals. Standard methods of minero-petrographic analysis as well as a Carl Zeiss Jenapol optical microscope were used.

4.2 *X-ray fluorescence (XRF)*

For this analysis we used a Bruker S8 Tiger with the powder sample forming a pill. The main purpose of XRF is basic chemical analysis, both qualitative and semi-quantitative, of the elements included between fluorine and uranium.

4.3 *X-ray diffraction (XRD)*

A D8 Advance Bruker Diffractometer was used to identify the semiquantitative and qualitative mineralogical composition of the samples.

4.4 *Mercury intrusion porosimetry (MIP)*

This analysis was conducted using a Porosimetry Micromeritics, model 9320, to determine the percentage of porosity of the samples, the sizes of pores between 0.006 and 360μm, the distribution, shape, and tortuosity on pores. The results were confirmed by further testing with a Quantachrome Poremaster.

5 RESULTS

5.1 *Petrographic examination*

Sample M1. There is a reddish mass and very fine and homogeneous grain. Diffused micrograms were observed, quartz grains angular and of small size, quartz in proportion of approximately 40%, some grains of altered plagioclase and potassium feldspar stained by cobalt nitrite, also altered (Figure 2).

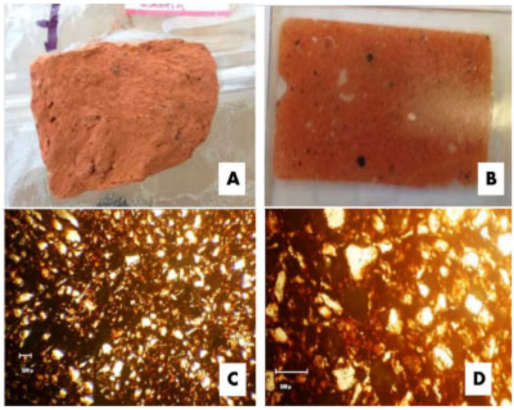

Figure 2. Sample M1: A. Initial appearance; B. Thin section; C. Microscopy X3,5; D. Microscopy X10.

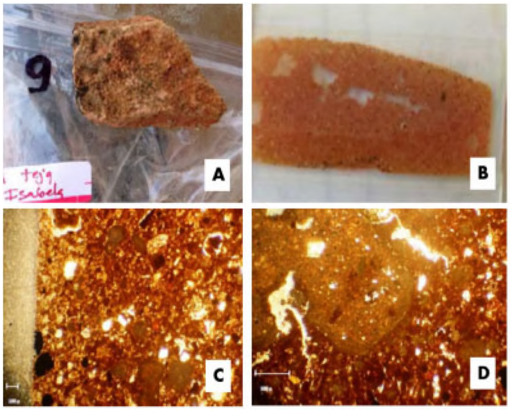

Figure 3. Sample M2: A. Initial appearance; B. Thin section; C. Microscopy X3,5; D. Microscopy X10.

Sample M2. Under the microscope, a homogeneous reddish mass and a dark isotropic mass is observed, interrupted only by sporadic grains of quartz, in a proportion of less than 2%, and some altered potassium feldspar.

With condenser the matrix appears formed by diffuse greenish and reddish grains, isotopes. Colloidal quartz and quartz are found in bigger crystalline units (Figure 3).

Sample M3. A homogeneous reddish mass is observed. Under the microscope, diffuse grains of reddish and greenish tones are observed in which grains of crystallized quartz and microcrystalline quartz both appear as degreasers. There are also small fragments of amphibole and pyroxene. Quartz grains can reach 30% of the preparation (Figure 4).

Sample M4. Under the microscope, the sample has irregular heterometric grains of angular quartz in a diffuse matrix in which reddish ochre and greenish isotropic grains and a reddish mass with whitish grains is observed. Its proportion is around 40%. Quartz

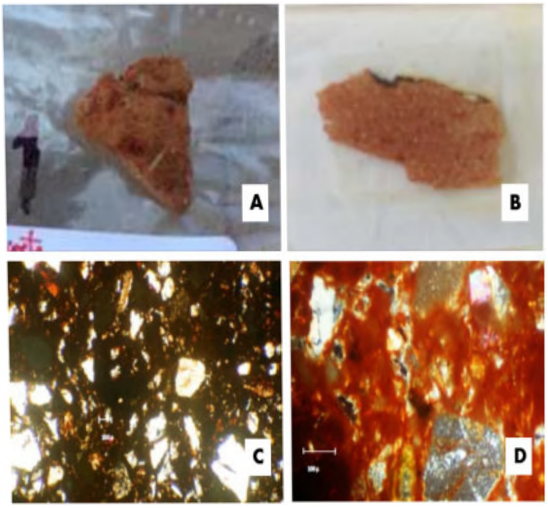

Figure 4. Sample M3: A. Initial appearance; B. Thin section; C. Microscopy X3, 5; D. Microscopy X10.

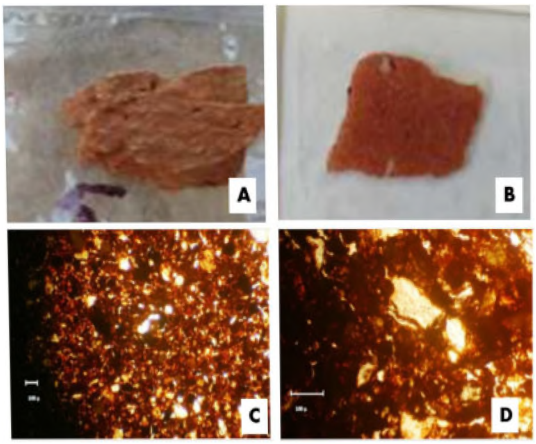

Figure 5. Sample M4: A. Initial appearance; B. Thin section; C. Microscopy X3, 5; D. Microscopy X10.

is macro and microcrystalline. It has small pyroxene grains (Figure 5).

Sample M5. A reddish colored mass with a very homogeneous aspect of fine grain and low porosity is observed. It does not present cracks or signs of alteration. There are angular fragments of approximately quartz, micritic limestone, silex, plagioclase, amphibole, pyroxene with many iron oxides (Figure 6).

5.2 *X-Ray Fluorescence (XRF)*

The major percentage of oxides of chemical composition of the five samples are the following: SiO2, Al2O3, Fe2O3, MgO and CaO, typical in a handmade brick (Table 1).

According to some authors, clays suitable for handmade brick should contain Silicon dioxide or Silica (SiO2) between 50–60%, aluminum oxide or alumina (Al2O3) between 21–28%, Iron (III) oxide or ferric oxide (Fe2O3) between 3–8%, magnesium oxide

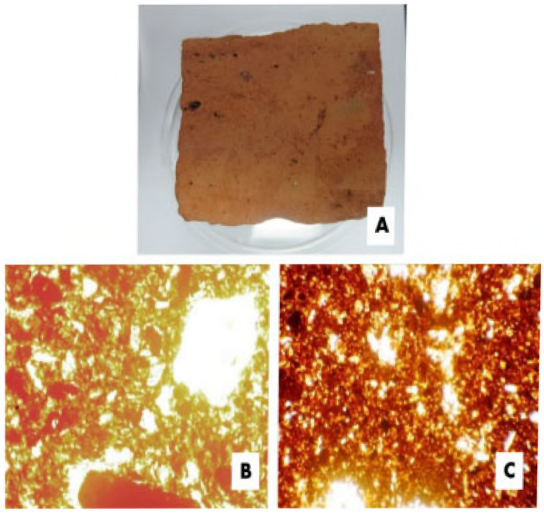

Figure 6. Sample M5: A. Initial appearance; B. Thin section; C. Microscopy X3, 5; D. Microscopy X10.

Table 1. Oxides of chemical composition.

Oxides	M1	M2	M3	M4	M5
SiO2	68.15	42.51	52.77	59.94	57.43
Al2O3	12.17	12.97	11.82	13.73	15.99
Fe2O3	6.64	12.52	13.09	12.66	10.34
MgO	1.84	2.78	2.05	–	4.79
CaO	3.70	22.00	13.39	4.64	6.41
Na2O	1.06	0.95	1.22	1.87	1.85
P2O5	1.86	1.66	1.8	1.79	0.14
SO3	0.13	0.24	0.49	1.71	0.05
Cl	0.04	0.04	0.03	0.23	0.01
K2O	3.10	2.47	1.21	1.40	0.96
TiO2	0.92	1.17	1.53	1.53	1.02
V2O5	–	0.04	0.07	0.06	–
Cr2O3	0.02	0.11	0.13	0.08	0.08
MnO	0.12	0.20	0.14	0.15	0.16
CO3O4	0.02	0.02	0.03	0.03	-
NiO	0.01	0.05	0.04	0.03	0.02
CuO	0.01	0.01	0.02	0.02	0.01
ZnO	0.01	0.02	0.03	0.03	0.02
Rb2O	0.02	0.01	0.01	–	–
SrO	0.04	0.11	0.04	0.04	0.04
ZrO2	0.08	0.05	0.03	0.03	0.01
BaO	0.04	0.08	0.07	0.04	–
PbO	0.01	–	0.01	–	–

(MgO) between 2–5%, calcium oxide or lime (CaO) between 1–10%, and other elements (Betancourt et al. 2007; Duitama et al. 2004;.

In M2 the SiO2 is low, about 42.51% and some founded as phyllosilicates, while M3, M4, and M5 are normal, varies between 52.77 and 59.94%, and in M1 is high at about 68.15%. An excess of SiO2 can be harmful because it destroys the cohesion between the clay particles in the brick and makes it fragile and weak. The percentage in M1 is high which indicates a very sandy starting material with a lot of degreasing.

The percentage of Al2O3 varies between 11.82 and 15.99%, which is very low for a typical range of old handmade brick. This variation is possibly due to the origin of the clays, which are limestone rocks with low Al2O3 content. Having a low percentage of Al2O3 implies that the brick is not very refractory; a characteristic that is not relevant to the type of building studied.

In M1 the Fe2O3 is low for a typical range, while M2, M3, M4 and M5 have normal values. The iron oxide acts as a coloring agent and an excess implies that the paste is darker. In addition, iron oxide and feldspar lower the melting temperature. In M1, M2, M3, and M5 the MgO varies between 1.84 and 4.79%, indicating that the brick is not refractory.

In M2 the CaO is a little high, indicating that lime was added. It is common for lime to be added to the clay to lower the sintering temperature of the Silica and reduce the contractions in drying and firing, because artisan kilns do not have a uniform temperature, regularly below 800° C (Guerrero 2011).

Some ferromagnesian (amphibole) grains appear as hornblende in M3, and salts are poor. In M4 the presence of ferromagnesian and salts are very poor.

5.3 *X-Ray Diffraction (XRD)*

The XRD indicates the characteristic peaks of the quartz, albite, and calcite crystalline phases in different proportions (Table 2). The results are related to their sintering level, presented in Table 1.

In M1 quartz corresponds to the high proportion of silica released by XRF. The microcline is a potassium feldspar. This mineral, along with albite, contains the aluminum present in the results. Hematite and goethite contain the iron.

The clay in M2 is marly, poor in silica and rich in calcium carbonate or lime that has been added to the paste. The presence of sanidine and anortoclase (high temperature potassium feldspars) clearly indicates a volcanic origin. The diopside indicates a higher temperature than in other bricks.

Also, in M3 hornblende was detected under the microscope, suggesting a starting clay derived from the alteration of basic igneous rocks. The epidote no doubt comes from the alteration of the calcium plagioclase (epidotization) that is albitized.

The hematite in M4 indicates the high concentration of iron and the reddish color. There are no phyllosilicates, calcium silicates or other minerals that could indicate baking temperature. The gypsum comes from environmental pollution because the place is open and abandoned. Quartz and albite are observed in M5; however, the proportions are not clear from the microscopic observation. Indeed, the proportion of alumina is very low compared to silica.

5.4 *Mercury Intrusion Porosimetry (MIP)*

The porosity is a parameter that influences other properties. In this analysis it is expressed as a percentage.

Table 2. X-ray diffraction (XRD).

Composition	M1	M2	M3	M4	M5
Quartz (free silica) %	86.4	41.8	78.0	80.9	28.75
Calcite %	1.9	32.7	9.2	–	10.91
Albite %	3.7	3.9	9.1	14.9	14.91
Hematite %	2.0	–	–	3.6	–
Goethite %	1.3	–	–	–	–
Microciline %	4.7	–	–	–	–
Anortoclase %	–	13.5	–	–	–
Diopside %	–	6.6	–	–	–
Sanidino %	–	1.4	–	–	–
Hornblende %	–	–	1.7	–	–
Epidote %	–	–	1.9	–	–
Gypsum %	–	–	–	0.6	–
Silicoaluminate %	–	–	–	–	24.21
Silicate magnesian %	–	–	–	–	11.37
Iron Oxide %	–	–	–	–	9.86

Table 3. Porosity of the bricks.

	M1	M2	M3	M4	M5
Porosity %	31.83	40.26	35.75	42.85	30.19
Absolute intergranular Porosity %	14.64	7.04	16.72	23.77	31.52
Relative intergranular Porosity %	45.99	17.48	46.78	55.40	9.52
Absolute intragranular Porosity %	17.18	33.22	19.02	19.14	68.48
Relative intragranular Porosity %	53.97	82.52	53.20	44.66	9.52
Tortuosity	1.87	1.77	1.83	1.74	–
Permeability nm2	0.05	0.01	0.00	0.06	–
Radio access to pores	0.50	–	8298.64	0.58	–
Elasticity module N/m2	0.00	5.72E −10	3.24E −10	–	–
Coordination No.	26.08	14.50	27.33	36.42	–
Breaking SI press.	0.98	1.15	1.00	1.00	–
Bulk Gr/cc density	1.76	1.57	1.42	1.83	–
True Gr/cc density	2.58	2.62	2.76	2.26	–

Historic clay bricks exhibit high porosity, ranging between 20% and 50% (Ramos Gavilán et al. 2018). The samples show a range between 30.19 and 42.85%, so all the samples were inside the normal ranges (Table 3).

The samples show a range from 7.04% to 31.52% for an absolute intergranular porosity. M2 being the lowest percentage at 7.04% and M5 the highest at

31.52%. Relative intergranular porosity shows a range from 9.52% to 55.40%.

Intragranular porosity can be absolute and relative. The absolute intragranular porosity presents a range from 17.18% to 68.48%; M1 being the lowest value and M5 the highest. The relative intragranular porosity shows a range from 9.52% to 82.52%; M5 being the lowest value and M2 the highest value.

The tortuosity is defined as the ratio of the average length of all particle path lines passing through a given cross-section during a unit time period to the width of the sample (Matyka et al. 2008). The samples show similar tortuosity from 1.74 to 1.87. It is low. so not very permeable. Permeability is very low. as befits ceramic material.

The access radius to the pores/pore radius is very low. indicating poorly communicated vug-type pores that correspond to trapped porosity. The resistance to decompression is low for a brick. so it would seem that it has undergone an alteration that has weakened its mechanical strength. The M3 range of decompression resistance is too low for a brick so it would appear that it has undergone alteration that has weakened its mechanical strength.

6 CONCLUSION

In conclusion. all bricks have a dark reddish color due to the high concentration of iron oxide. This coincides with the colors of the clays that exist in the surrounding areas where the bricks are supposed to have been made. Under the microscope. very diffuse greenish isotropic micrograms could be observed.

In all the samples it was detected that lime was intentionally added to the paste. possibly to lower the sintering temperature of the Silica and to reduce the shrinkage in drying and baking. because artisanal ovens do not have a uniform temperature. The aim was to reduce the porosity and permeability. as well as improve resistance to chemical attacks and to additionally increase its resistance to abrasion. This indicates that the manufacturers had a deep empirical knowledge of craftsmanship.

With XRF. it can be observed that their composition with regards most elements are very similar. which makes us think that they were all manufactured on the island of Hispaniola.

The high SiO_2 content of all samples allows us to estimate a low percentage of shrinkage in bricks made from this clay due to its low plasticity. as well as a high quartz content (taken from the X-ray diffraction test) indicating a high content of defatting material (sand).

The clay brick of the Royal Shipyards – Atarazanas – (M3) and the fort of Santiago (M4) present pyroxene granites which could indicate a clay-type material from the decomposition of basic rocks. Moreover. these buildings were built in the same year. The similarities affirm that both bricks were made with the same clay. maybe in the clay brick factory that was in Santo Domingo on the banks of the Ozama River.

The clay brick of Concepción de la Vega (M5) is slightly poorer in degreasing agents and richer in carbonates and ferromagnesium. compared with the other bricks. This indicates how good the brick is. and why it has endured to this day despite neglect.

In the Hispaniola island the Europeans found very good clay and lime for making bricks and roof tiles. The brick makers knew their job very well. knew how to choose good clay and produced very good bricks. which are still in good condition despite the abandonment and lack of maintenance in which many of the colonial buildings are found.

The clay bricks we have studied affirm the historical fact that the Spaniards manufactured the first building materials in Hispaniola. From that moment on. they used local raw materials to build the great Spanish empire.

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