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PRE-COLUMBIAN EARTHEN CONSTRUCTION TECHNOLOGY AND ITS APPLICATION TO CONSERVATION

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Abstract. *There has been a significant tradition of earthen construction in tropical humid Mesoamerica, especially monumental earthen architecture, such as La Venta, Cerro de Las Mesas, El Zapotal, etc. La Joya is one of these archaeological sites, located on the coastal plain of the Gulf of Mexico, with three buildings excavated, dated from the Protoclassic period to the Classic period (200 BC - AD 1000). Only 5% of the site is preserved due to the modern extraction of earth to make brick. The remaining part of the pyramid excavated in 2008 is now being preserved. A multidisciplinary team has been working since 2009 to understand the ancient technology and to design adequate preservation strategies. The results of the analysis on construction samples show that the original inorganic materials are not favorable for general earthen construction, since they consist of high proportions of fine fractions which contain expansive clay and no obvious inorganic stabilizer of earth, such as lime. Therefore some organic additive must have been used for monumental earthen architecture to survive in the tropical humid environment. The chemical analyses of organic residues from those construction samples point to the use of bitumen, possibly diluted in vegetable oil, as the stabilizer of earthen material. Experimental walls are now being field-tested, some using plant extracts applied in modern day vernacular construction in Central America, others bitumen, in order to compare their resistance to the severe weather conditions of winter hurricanes and summer downpours prevalent in the region. Long term monitoring of these walls has confirmed the efficiency of bitumen as a stabilizer in a tropical humid environment. These studies on the ancient earthen construction techniques help us to propose alternative strategies for future preservation of the pyramid of La Joya and other earthen structures in a tropical humid area, as well as for modern construction. They also raise interesting possibilities on a technology that may have been much more widespread that hitherto known.*

1 INTRODUCTION

A little known aspect of Mexico's archaeological heritage is the monumental earthen architecture tradition that occurs along the isthmian lowlands, from the central Gulf to the Pacific coast of Central America, spanning at least 4 millennia, from the pre-Olmec levels at San Lorenzo to Postclassic sites of the Huastec civilization in Tamaulipas. It has been up to now analyzed from a purely archaeological point of view, with little attention to its building technology, remarkable in its adaptation to a humid tropical environment.

This paper presents the case of La Joya, a site built and occupied during the first millennium AD, located in the central part of Veracruz, 6 km inland from the Gulf coast, on the Jamapa River. Actually heavily damaged by modern brick-makers, it has been the object of archaeological research since 2004, focusing since 2009 on ancient building techniques and modern preservation strategies. Archeological studies produced evidence of original construction strategies to control internal pressures of fills and achieve efficient drainage, both factors crucial for earthen architecture [1, 2]. The next steps were the standard analyses of mineralogical composition and material characteristics of the building materials, showing they were of standard to low quality. This, combined with the rapid deterioration of the excavated surfaces, led to the hypothesis of the original presence of an organic consolidant that degraded through time [3]. The following steps were thus focused on the chemical identification of natural agglutinants. After extensive experimentation, a breakthrough was achieved late 2012, with the first signs that the consolidant may have been dissolved bitumen [4].

The implications of this finding are far-reaching. The use of bitumen paste in construction as mortar or waterproofing is well attested both in the Old and the New World. Though the use of dissolved bitumen in antique construction is not documented, the technique of dissolving bitumen in vegetable oil is known for other purposes. Also, when comparing the distribution of earthen architecture traditions in the world, these coincide well with the occurrences of petroleum seepages. Thus, dissolved bitumen may have been much more common in ancient construction than currently understood. From a practical point of view, reconstructing the technology offers an alternative for preservation of archaeological heritage, based on a closely similar and therefore compatible facings, and opens the opportunity to reintroduce earthen residential building in tropical regions as an economical and sustainable construction method.

2 STUDIES ON INORGANIC MATERIALS IN PRE-COLUMBIAN CONSTRUCTION

2.1 Archaeological evidence of building techniques

The archaeological project at La Joya, begun in 2004 as a salvage excavation, took a turn with the discovery that the so-called archaeological “mounds” were actually monumental architecture conforming to the common Classic period Mesoamerican standards: stepped pyramids with wide staircases, palaces, shrines and ball-courts (Figure 1). Extensive excavations of three remaining buildings, a pyramid and two palaces (The North Platform and the East Platform) showed several technical solutions to control internal pressures of an amorphous material (Figure 2). The earliest fill system consisted in horizontal strata of stamped earth (loamy sand), covered by layers of sherds (to facilitate compression); the outer casing, in which the architectural forms were modeled (tiers, staircases), consisted of a thick layer of clayey loam. The lack of internal casing made for a squat building profile with 27° slopes, the angle of natural stability. A later, more effective strategy consisted of a superposition of large blocks of clay (more than 6 x 6 x 1 m) placed in a checkerboard pattern, with the intervening squares filled by sand; the clay contained the sand, while the sand controlled the expansion and contraction of the clay blocks through the seasonal humidity cycles, and also allowed for a vertical and unimpeded drainage of pluvial penetration and evaporation of groundwater. This technique permitted a much steeper incline of the construction, with 45° slopes in the case of high buildings, like the 25 m high pyramid, or 80° slopes in the case of low platforms.

Figure 1: Pyramid of La Joya during the excavation process (Photo: Daneels, May 12, 2008).

The vertical dividing walls were made of large adobes (the earliest 80 x 40 x 10 cm, the later ones slightly narrower), made with over 30 % of finely chopped stalks, and a composition ranging from sandy to clayey. The roofs were flat, with slender beams covering 2 to 2.5 m spans, covered with rushes and a relatively thin earthen layer of clayey loam with coarsely chopped stalks. The roof contour was elevated to allow runoff only from a single point, connecting with a system of terracotta tubular drainpipes forming a well-laid drainage network for the palaces and plazas.

The permanence of this earthen architecture was ultimately due to the clay facings that covered roofs, walls, taluses and floors. These are 1.5 to 2 cm thick layers of earth, consisting of more than 60 % of fine fraction (clays and loams). In cross-sections, most buildings show 3 to 4 superposed layers, spanning several centuries, which led to estimate the life of such a facing to about 50 years, a surprising fact in view of the extremely heavy rain falls (in excess of 1500 mm per year, falling between May and September). Such facings, when recently excavated, are in pristine condition, and show neither cracking, sagging nor scouring. Yet nowadays these facings are easily damaged even by light rains. This led us to believe some sort of agglutinant was originally used that degraded through time, leaving the surfaces now unprotected.

The results of archaeological studies at La Joya, more fully published earlier [1, 2], led naturally to start a research focused on the mechanical, mineralogical and chemical properties of earthen construction that would shed light on a building tradition common to a large region of tropical lowlands in ancient Mesoamerica.

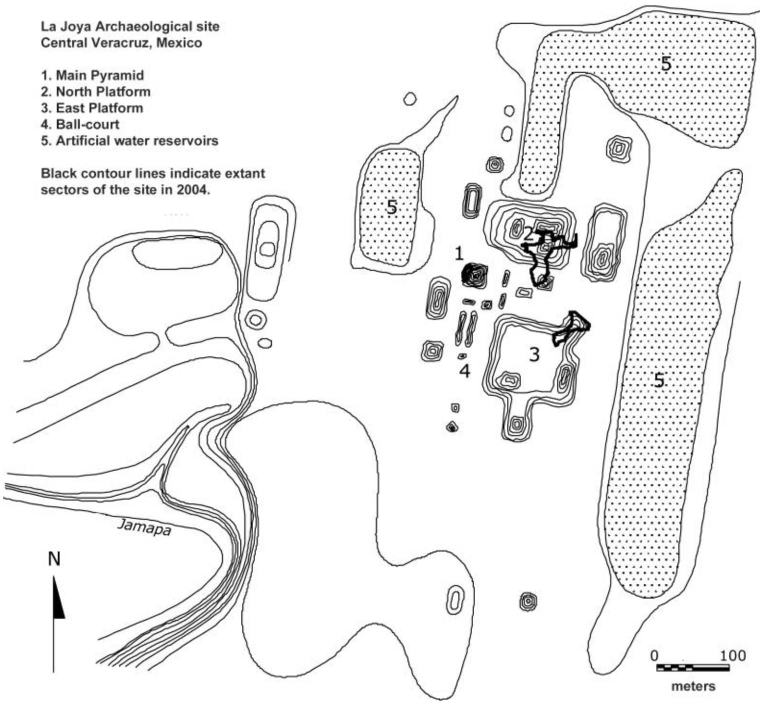

Figure 2: Map of the La Joya site [1, 2].

2.2 Mineralogical and structural analyses of pre-Columbian building materials

The first series of 20 samples consisted of fills, adobes, floors and facings, which were submitted to standard analysis of sedimentation, petrography, and mineralogy through X-ray Fluorescence and X-ray diffraction. The procedures and results have been published in 2011 [3]. To resume, the soils used for construction are all locally available sedimentary materials, ranging from paleodune sands to alluvial loams and *in situ* developed clay strata (B-horizon in paleodunes) as well as geysols, most of which are of low plasticity. Unsurprisingly in a sedimentary basin associated to detritus from the Trans-Mexican Volcanic Belt, the clay fraction resulted to consist mostly of montmorillonite, extremely expansive clay. These are obviously not good quality building materials. Also, no calcium carbonates were present, indicating the absence of lime, a natural consolidant of earthen architecture widely used in the central highlands of Mexico [5].

On the other hand, analyses of mechanical properties as resistance to compression, porosity and hardness, showed unexpectedly high performances, especially in floors and facings. Thus it is clear that the ancient builders developed specific strategies to compensate and control the adverse mineral properties of their building materials, and that the major factor must have been an intentionally added organic substance.

3 STUDIES ON ORGANIC MATERIALS IN PRE-COLUMBIAN CONSTRUCTION

3.1 Pre-Columbian construction materials

We started chemical analysis of organic compounds extracted from 16 new samples of different parts of the pre-Columbian buildings, such as adobe, floor, facing renders and fill.

Each sample was ground and 300g soaked in n-hexane (Merck), stirred with a glass rod and left for 24 hours to dissolve organic components. Then, the sample was heated up at ± 60°C for 30 minutes, stirred and filtered. The residue was concentrated by rotary evaporator. After repeating this process three times, each filtered ground sample was soaked again in methanol (J. T. Baker) and treated by the same process to obtain organic residue soluble in methanol. The hexane extract and the methanol extract of each sample were analyzed by FT-IR, NMR, and GC/MS respectively. The spectra of all samples were very similar, therefore in order to increase the quantity and identify the chemical composition of the material, the extracts were combined and then separated by column chromatography and thin-layer chromatography.

FT-IR, NMR and GC/MS analyses of the fractions identified the principal organic compounds as hydrocarbons, aliphatic methyl esters, aromatic esters, azelaic acid esters (probably produced by the oxidation of oleic acid), triglycerides, steroids and triterpenoids. These compounds may be indicative of bitumen [4] dissolved in vegetable oil.

3.2 Comparative analyses with pre-Columbian bitumen and paleosoil at the site

At the site of La Joya there are ceramic figurines decorated with bitumen and vessels painted outside or coated inside by bitumen, which are dating to the same period as the studied construction samples. The pre-Columbian bitumen on fragments of some such vessels were collected and extracted by n-hexane (Merck). The extracts were analyzed by FT-IR, NMR and GC/MS. The spectra of pre-Columbian bitumen and pre-Columbian construction materials are similar in major compounds such as hydrocarbons, aliphatic methyl esters, aromatic esters, steroids and triterpenoids, which confirm the presence of bituminous substances in the construction materials. With reference to the vegetable oil substances, interestingly, pre-Columbian raw bitumen samples on ceramics lack triglycerides, although their ^{1}H and ^{13}C NMR analyses detected signals of azelaic acid esters.

Samples of paleosoil around the site were also studied to compare with pre-Columbian earthen construction materials. These samples were treated by the same process as the pre-Columbian earthen construction materials. Their FT-IR, NMR and GC/MS analyses indicated the presence of long-chain hydrocarbons as main component. Aliphatic methyl esters, aromatic esters, steroids, triterpenoids and triglycerids were also present, but in very low quantities; however, azelaic acid esters were absent.

3.3 Discussion

The interpretation of these results indicates the presence of bituminous materials in paleosoil and also in pre-Columbian construction materials. This is not unexpected, as bitumen seepages occur naturally in the region and some environmental contamination is to be considered. Nevertheless, a “natural” presence of bitumen in the earthen building materials cannot account for the resistance of the ancient constructions, as our first preservation layers applied in 2009 using local soils (which would contain natural bitumen contamination) were not efficient. The difference in composition between the bitumen in construction sample (associated with triglycerids and azelaic acid esters) and on ceramics (with azelaic acid esters but without triglycerids) may reflect a different way of treating bitumen for different purposes or differential degradation of the oil, if we can confirm that the azelaic acid esters come from the oxidation of oleic acid. We are now studying pre-Columbian bitumen from archaeological contexts and trying to find qualitative and quantitative differences between bituminous materials in paleosoil and pre-Columbian construction materials and ceramics, to prove its intentional use as stabilizer of earthen construction.

4 FIELD TEST PHASE 1

In order to understand the pre-Columbian earthen construction technology and also to apply it to the preservation of pre-Columbian constructions, we prepared 5 walls with and without different organic additives (vegetable extracts and bituminous products):

C Control (without organic additive)
M Mallow (*Sida rhombifolia*)'s leaf-stem extract
G Guacima (*Guazuma ulmifolia*)'s bark extract
B Natural bitumen extract in boiling water / Bitumen dissolved in linseed oil
A Commercial asphalt emulsion for impermeabilization ("Impertop A", Comex)

4.1 Vegetable extracts as stabilizer of earthen construction

In humid tropical regions of Central America, they use extracts of leaves and stems of the mallow shrub (*Sida rhombifolia*) or bark of the guacima tree (*Guazuma ulmifolia*) as additives for adobe, even for earthen renders or as consolidant for earthen architecture surface layers of archaeological sites [6, 7]. As these plants that also abundant in the La Joya site, we prepared similar extracts: the leaves and stems of mallow were cut in pieces, beat with a wooden stick and soaked in water for a day; the bark of the guacima tree was peeled, split and cut in pieces and soaked in water for a day. The mallow extract is a fluid liquid with fine bubbles which indicate the presence of saponin. The guacima extract is viscous, rich in polysaccharides.

4.2 Bitumen as impermeabilizer, binder or stabilizer of earthen construction

The ancient builders of Middle East, Egypt and Indus cultures used bitumen as impermeabilizer or binder in earthen construction [8, 9, 10, 11, 12]. In the ancient cultures of coast of Gulf of Mexico such as Olmec culture, a Preclassic earthen floor painted with bitumen has been found [13, 14, 15]. All reports are on plastic bitumen, easily recognizable; dissolved bitumen on the other hand is not distinguishable at sight when mixed in earth, what may account for the fact that dissolved bitumen as a stabilizer of earthen construction has not been reported in these ancient cultures; it is only in recent times, in 1932, when Standard Oil Inc. produced an emulsified asphalt (Soil-Bitumen 1) for preservation of earthen patrimonial construction in USA [16, 17], and it continues to be recommended for modern adobe construction [18].

The technique of dissolving bitumen was known in ancient times, but historical and ethnographic data suggest its use for agricultural purposes [19] and for basket waterproofing [20].

We prepared earth mixtures using bitumen extract in boiling water, bitumen dissolved in linseed oil and commercial emulsified asphalt. In boiling water almost nothing was extracted from the bitumen block and this water was used to make "bitumen" adobes. Dissolved bitumen in linseed oil was used for renders.

4.3 Test walls

We constructed test walls making adobes of 24 cm (length) x 13 cm (width) x 5 cm (height) using a normal brick mold. Adobes were made from clayey earth (without added sand), chopped dry pangola (*Digitaria eriantha*) grass, water and organic additives, for M (mallow) and G (guacima) 5 % in volume of the mud mixture, and for B (bitumen) and A (asphalt emulsion) 1 % in volume. For C (control) we used unfired bricks with sand and a little bit of ash, without grass. Each test wall measured 80 cm (length) x 28 cm (width) x 80 cm (height from the ground) and the long side was divided in 5 sections to apply 5 renders (C, M, G, B y A). All renders consisted of 3 layers: base layer, middle layer and polished fine layer with clayey earth, chopped grass, water and the same percentage of organic additives.

Figure 3: Oxidation of M (Mallow) and G (Guacima) renders a month later (Photos: Kita, March and April, 2013).

Figure 4: Monitoring of Phase 1 test walls (Photos: Kita).

4.4 Monitoring

Test walls were completed in March, 2013 and in a month, strong sunlight oxidized the vegetable extracts and the color of renders (M and G) changed remarkably (Figure 3). The control wall (C) started to collapse with the first rains of July. The renders with vegetable extracts (M and G) were totally washed away in September. The renders and walls with bituminous products (B and A) resisted quite well to the tropic humid weather for a year (rainfall between March 2013 and March 2014: 1550 mm) (Figure 4).

5 FIELD TEST PHASE 2

The favorable results of bituminous products in the 1st phase of the field test led us to the 2nd phase of field test, which focused on various bituminous products applied in higher concentrations (6 %).

5.1 Variety of stabilizers

In the 2nd phase of field test we prepared the following 10 walls:

E	Standard (without additives)
A1	Commercial emulsified asphalt (Impertop A) 1 % in volume
A6	Commercial emulsified asphalt (Impertop A) 6 % in volume
L6	Bitumen dissolved in linseed oil (drying oil) (450 g in 1 liter) 6 % in volume
M6	Bitumen dissolved in corn oil (semidrying oil) (150 g in 1 liter) 6 % in volume
C6	Hydrated lime (Calidra) 6 % in volume
El	Standard wall + fine and polished render of L6
Em	Standard wall + fine and polished render of M6
A1g	A1 + geotextile between adobe walls and renders
T	Fired brick wall + renders of A6
Tg	T + geotextile between adobe walls and renders

Bitumen dissolves in nondrying oils (ex. olive oil and palm oil) and in semidrying oils (ex. corn oil and cottonseed oil), but much better in drying oils (for example linseed oil and chia oil). Test walls of bituminous products are A1, A6, L6 and M6. The E (standard) and A1 (asphalt 1 %) walls repeat Phase 1 composition; in this second phase they will allow to evaluate their weather resistance value in direct comparison with the new test walls. The C6 (lime) wall were planned additionally to compare them to the bitumen containing test walls. The Tg wall (brick with geotextile) is a replica of the buttress wall constructed to support the north side of the pyramid of La Joya. In order to evaluate the efficiency of geotextile, the T wall (brick) was designed to compare with the Tg wall, as the A1g wall does with the A1 wall.

In this phase, adobe brick size was designed as 40 cm (length) x 20 cm (width) x 10 cm (height), a normal size of adobe in Mexico. Fired bricks for T and Tg were 24 cm (length) x 13 cm (width) x 5 cm (height). Adobes were made from clayey earth (no sand added), chopped grass, water and organic additives, as mentioned above. Each test wall measured 40 cm (length) x 40 cm (width) x 90 cm (height from the ground) using 2 adobe blocks for each layer and placing them alternatively crosswise. T and Tg were constructed with 4 bricks in each layer, leaving a void in the center and binding with mud mixture using 2.5 % in volume of hydrated lime in the mixture. The void at the center was filled with rammed earth. Geotextile was nailed on A1g and Tg. Then 3 layers of render (base layer, middle layer and polished fine layer) were applied to each wall. The base layer contains clayey earth, chopped grass, water and the same percentage of each organic additive. The upper layers do not contain grass and contain more water. The renders for T and Tg were a mixture of clayey earth, nopal cactus (*Opuntia* spp.) cladode extract (in water), commercial emulsified asphalt 5 % in volume, commercial EVA consolidant (VINNAPAS 5044N, Wacker Chemie AG) 0.75 % in weight, and chopped fine grass only for the base render.

All the fine renders applied directly to the walls did not present deep cracks compared to the renders applied to the geotextile. The cracks on A1g and Tg were caused by the poor cohesion of geotextile to the wall, which needs additional applications of renders. (Figure 5)

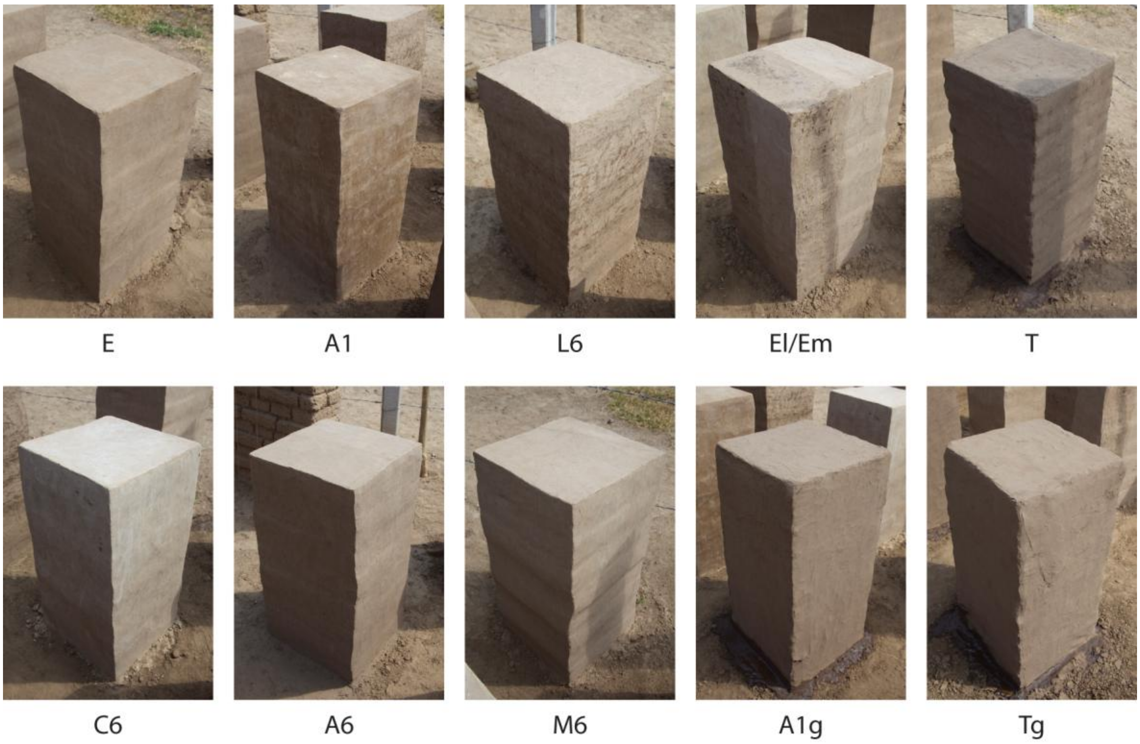

Figure 5: Phase 2 test walls (Photos Yuko Kita).

6 CONCLUSIONS

Chemical analyses on organic compounds in different samples in the site of La Joya have not yet obtained the final evidence of the intentional use of bitumen as stabilizer of pre-Columbian earthen construction, although the ongoing chemical analyses strongly point in that direction. On the other hand, the first phase of field test, monitored now for over a year, demonstrated the efficiency of low concentrations of bitumen as a stabilizer for earthen construction using mainly expansive clays. We have just started to monitor the second phase of field tests to define the most appropriate preparation of bituminous stabilizer as a preservation strategy for pre-Columbian earthen constructions.

As indicated before, the implications of finding probable evidence of dissolved bitumen in earthen construction are far-reaching. As indicated above, the use of bitumen paste in construction as mortar or waterproofing is well attested both in the Old and the New World from antiquity to the present day. Though the use of dissolved bitumen in antique construction is not documented, probably due to the fact that it is not visible to the naked eye, the technique of dissolving bitumen in vegetable oil is known for other purposes. On the other hand, it is interesting to observe that the distribution of earthen architecture traditions in the world [21] coincide well with the occurrences of natural petroleum seepages. Thus, dissolved bitumen may have been much more common in ancient construction than currently understood.

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