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CEMENTITIOUS MATERIALS AND CONCRETE OF ANCIENT CULTURES IN AMERICA AND YAXCHILAN BRIDGE

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Abstract. *Outstanding results of research projects on the development of cementitious materials in ancient cultures of America are presented. This is done to spread the important developments achieved by these cultures in the art of construction, as well as a tribute in the memory of Professor Raymundo Rivera Villarreal, pioneer in Mexico on this field, as well as Heriberto Díaz Coutiño, very fond of Maya culture. With this base, results from recent research projects, done in the institution of the authors, on the development and use of cementitious material in the Maya culture are presented and compared with other references. Laboratory results are presented for: a) chemical properties of mortars samples from the archaeological sites of Comalcalco, Toniná, Palenque and Yaxchilán, including diffraction analysis and spectrograph study, b) mechanical properties of mortar and concrete samples from the archaeological sites of Palenque and Yaxchilán. With the data of chemical properties if was possible to: a) suggest a possible manufacture method, b) the possible existence of empirical rules for the preparation and use of mortars and stucco in all the Maya culture, and c) calculate a pozzolanic ratio with an average of 0.107 and a rank of 0.021 which means an intentional pozzolanic activity. In other references it is assumed that Mayas achieve the construction of a pendant bridge of 180 m in length at the ancient city of Yaxchilán, in this paper, taking into account the results of laboratory tests, as other goal, arguments on the feasibility of the construction of such a bridge are presented. With this is assumed that the deck of the bridge was made of chico zapote tree stringers united with henequen fibers, pairs of vertical cables 50 mm in diameter spaced at 3.50 m made of henequen to support the deck and the two main henequen cables of 150 mm in diameter as the principal structural elements. Two masonry piles with a core of cyclopean concrete 25 m high at a distance of approximately 60 m serve as towers of the pendant bridge and two end abutments of the same material to anchorage the cables. Of interest is to mention that the existing remains of the piles and abutments are the main arguments to support the existence of the bridge. It is concluded that a) the bridge in effect may be constructed with the materials and techniques available and developed by Mayas of the classic period, and b) its reconstruction is feasible at a reasonable cost which for sure may be a touristic attraction with an aggregate value to the archaeological sites of Bonampak and Yaxchilán.*

1 INTRODUCTION

It is cause of admiration the constructive heritage left by several cultures of America before the arrival of Europeans. Many books and papers have been written on historical, archeological and anthropological aspects but only a few on technological and constructive characteristics of the ancient constructions and even less on the development and use of ancient cementitious materials.

The objective of this paper is paper is to analyze results of several research projects related to the development of cementitious material and concretes from different archeological sites with the purpose of pointing out the improvements attained by antique cultures in the art of building. As part of this paper work done by Raymundo Rivera is mentioned, as pioneer of this subject and as a modest but care tribute in memory of this Emeritus Professor, fellow member of ACI and recognized researcher in the subject of cement and concrete technology. As well as also in the memory of Heriberto Díaz Coutiño, very fond of Maya culture.

2 FINDINGS BY RAYMUNDO RIVERA

At the ancient city of Comalcalco in the actual State of Tabasco, the builders, facing the lack of stone quarries, developed the construction of pyramids, palaces, walls and other components with clay bricks jointed with lime mortar added with pozzolan materials. The author [1] found that stuccos and mortars contained a special addition to get strength and hardness. Based on data reported by Littman [2] who detect the crystal grow during curing of mortars, which diminished considerably porosity, concluded that the crystal were particles of nefeline and diopside, which are complex alkaline silicates responsible of the pozzolanic reaction. In this investigation he found that in the process to elaborate nixtamal, dough to make tortillas (corn bred), a byproduct is the nejayote a material rich in calcium hydroxide used by ancient cultures as an addition to cement materials as a pozzolan, for instance at Comalcalco and El Tajín. Average compressive strength of 4.4MPa was reported on test of mortars from El Tajín. He concluded that the discovery of pozzolan mortars let to similar material used ayt preset times made with hydraulic cements.

The author [3] analyze a flat slab at El Tajín made of light concrete, he found that the concrete was formed with pyroclastic fragmented rocks, micrites, calcareous and tuffaceous rocks embedded in a paste composed by clay and micrite. Some similitude was found with cement type material used in the construction of roads in ancient Greek.

By means of the application of mineralogical studies the author [4] developed the pozzolanic index applied to ancient cementitious materials, defined as the sum of silica (SiO), alumina (Al2O3) and ferric oxide (Fe2O3) divided by the sum of lime (CaO) and magnesium (MgO). This index is used to know when a pozzolanic reaction is fortuity or intentional, if the index of a given material is equal or higher than 0.08 the pozzolanic reaction was intentional.

Definitively the work of Raymundo Rivera is very extensive; the results presented are only a small sample in some way related with the next parts of this paper related to studies made by the authors of this paper.

3 CEMENTS AND CONCRETE IN THE MAYA CULTURE

3.1 Chemical properties

With the permission of INAH (National Institute of Anthropology and History), samples of mortar from four archeological sites were obtained: Comalcalco, Toniná, Palenque and Yaxchilán. The microstructure characterization, the chemical analysis and the diffraction spectrometry were performed. Main results are [5]: average of silica content of 4.56% with rank of 3.83%; average alumina content 3.04% with rank of 2.64%; average calcium content of 31.34% with rank of 18.95%; average of ferric content 2.82% with rank of 1.22%. The observed variability is an indication that the elaboration of the ancient cement was not standardized, however some common patrons are identified which suggest the existence of empirical rules based on density, hardness and color of the row materials. Significant contents of silica and alumina were observed so it is probable the use of additions, particular for each zone, as volcanic ashes, burned clay and other types. The evident intention was to get increasing hardness with time. This is clearer when the oxide contents are taking into account, from which can be used to calculate the pozzolanic ratio, as was defined later, the result is an average of 0.107 with rank of 0.021. According with the criteria stated by Raymundo Rivera the pozzolan activity was intentional.

3.2 Mechanical properties

Samples of the size required for physical test were possible to obtain only from Palenque and Yaxchilán. It was possible to form eight concrete cubic specimens with side of 61mm approximately. With comparative purposes a cubic specimen of same dimensions was elaborated with natural aggregates of Yaxchilán and modern Portland cement. Average pulse velocity was 4.16X105 cm/s. Average compressive strength was 9.2MPa which is 53% of comparative specimen. Modulus of elasticity was measured only in one specimen; the result was 3690MPa which represents 18% of the comparative specimen [6]. In Figure 1 photograph of a sample of concrete from Yaxchilán is shown.

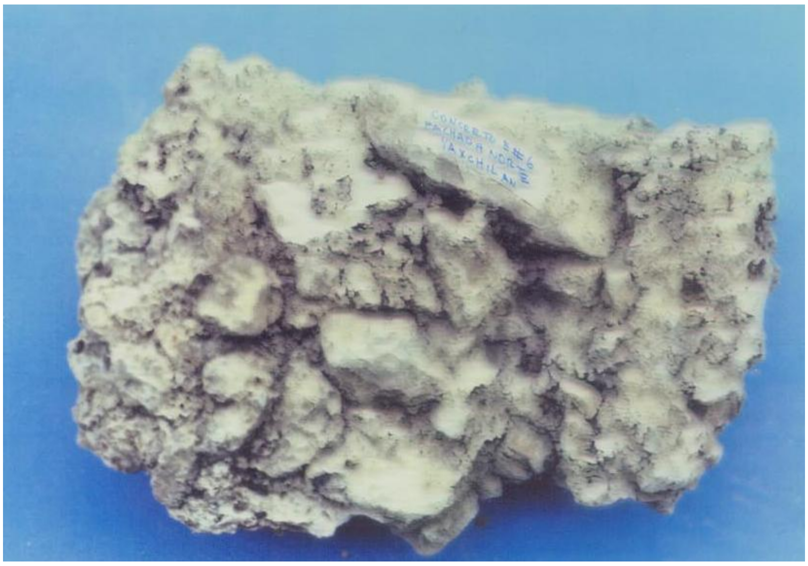

Figure 1 photograph of a sample of concrete from Yaxchilán is shown.

Five specimens of mortar and concrete were utilized to obtain the tension strength according with standardized flexure test. For this propose the antique specimens were embedded in prismatic elements made of new concrete, in all cases the section of failure include the antique material. The average tension strength for mortar was 0.66MPa and for concrete 1.82MPa [7].

The main observations of this part are: a) the artificial materials developed by the Mayas have a exceptional durability because for more than 1500 years under severe atmospheric conditions maintain its integrity and with even significant strength, b) strength values for specimens of the Maya zone are significant higher than those of El Tajín, c) The mechanical properties found are compatible with the original use.

4 YAXCHILÁN BRIDGE

O'Kon reclaimed that the Mayas achieved the construction, at Yaxchilán during VII Century, a pendant bridge with a length of 180m to cross Usumacinta River [8]. The bridge was supported in two extreme abutments and two intermediate piles made of masonry with a concrete core. This researcher based his deductions in aerial photographic studies that show the perfect alignment of the components, mainly the remainders of the abutments and one pile that stick out from the river surface only at low water season. However there is not consensus about the existence of the bridge because some archeologist explains the remainders in different way, as a kind of control for the fluvial transit of commercial activity and war ships, or a lighthouse because in that part the river has a wide curve. So it was decided to investigate the feasibility to build the bridge with the materials and techniques available at that time. To study the structural behavior for permanent, live and accidental loads an analytical model was developed. The properties of the masonry and concrete were based on the results of the test already discussed, the properties for other materials as sisal and timber were assumed to be similar to that reported in actual studies. In this way it was possible to estimate the general dimensions of the components, as is summarized next [6,9]:

4.1 Deck

With the observation of some pendant bridges constructed in the zone with ancient techniques, the construction of the Yaxchilán Bridge probably consist of standard modulus 2.0 to 3.5m length and 6.0m wide. The transversal ties made of timber of chicozapote (local tree) with a diameter of 150mm approximately, arranged at a distance of 1.50m to sustain a platform of sticks of small diameter, 15 to 20mm, jointed together with sisal fibers. The unitary self weight for this system is approximately 1.8kN/m, which is a relative low.

4.2 Secondary cables

Taking into account the arrangement of the deck assumed, 16 pairs of secondary cables were used in the central span and 20 pairs in each of the extreme spans. The observation of artisanal elaboration of sisal cords, each one is made with plaiting fibers to get a cord with a diameter of about 5.0mm. The test of 10 of these cords gave a resisting force of 1.4MPa, the factored load per cable was estimated as 61.5kN, so it is concluded that about 44 cords were used to form the secondary cables with a total diameter of 50mm approximately.

4.3 Main cables

No data is available on the sag of the main cable, so calculations were made to different sag values from 7.0 to 11.0m, using the same approach as before the result for the worst case was a cable formed by 155 individual cords with a total diameter approximately of 150mm.

4.4 Piles

With the examination of the remainders it is supposed that the base of the piles was a rectangle of 18m in the direction of the water flow and 13m in the transversal direction. The high from the river bed to the deck was estimated as 25m. Section of the pile is reduced with height, at the level of the deck the probable dimension was 10 by 5m. The upper part, as was suggested by O`Kon consist of a false arch to form the pass for the pedestrians and to sustain at the pick the main cables. The maximum stress considering the critical condition of dead load, maximum live load and the maximum seismic intensity is 1.01MPa which is less than the resistant stress from test of 9.2MPa.

4.5 Abutments

The remainders of the north abutment are well preserved but the south abutment is completely collapsed. The one that was observed consist of a square platform of about 20m side and 6 m height with stairs and ramps and a long inclined mat to the edge of the river. As in the previous case the stress is relative low (0.8MPa) respect the strength of the concrete.

The analysis of the model indicates level of stresses and deformations reasonably low, so is concluded that the Yaxchilán Bridge should have approximately the dimensions proposed in this study and are represented in Figure 2. Definitively the possibility of the construction of the bridge with the materials and techniques available in the classic period of Maya culture is affirmative. It is possible to reconstruct the bridge at a cost of about six million dollars, amount that may be easy to recover because the bridge will by a touristic attraction with an aggregate value to the archeological zones of Yaxchilán and Bonampak which have height index of visitors.

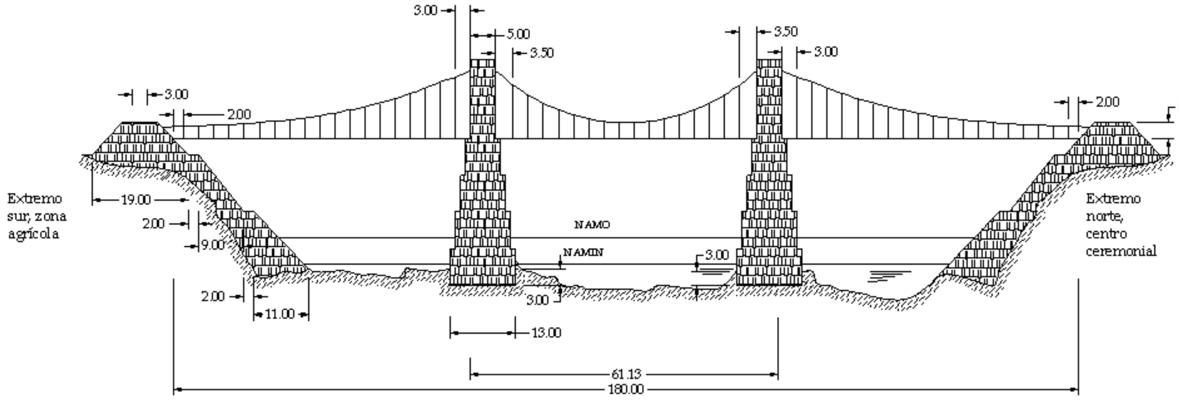

Figure 2. Representation of Yaxchilán bridge

5 CONCLUSIONS

There are few technical studies on construction materials used by ancient cultures of America. This paper intent to divulgate some of the result of work done in this subject.

Raymundo Rivera was a pioneer with important contributions in this line of knowledge. In this paper some of his findings were mentioned as a tribute in his memory, as well as Heriberto Díaz Coutiño, very fond of Maya culture.

With the data of chemical properties if was possible to: a) suggest a possible manufacture method, b) the possible existence of empirical rules for the preparation and use of mortars and stucco in all the Maya culture, and c) calculate a pozzolanic ratio with an average of 0.107 and a rank of 0.021 which represents an intentional pozzolanic activity.

In relation to mechanical properties the main conclusions are: a) the artificial materials developed by the Mayas have a exceptional durability because for more than 1500 years under severe atmospheric conditions maintain its integrity and with relative high strength remain, b) strength values for specimens of the Maya zone are significant higher than those of El Tajín, c) the mechanical properties found are compatible with the original use.

In relation to the Yaxchilá Bridge it is concluded that: a) the bridge in effect may be constructed with the materials and techniques available and developed by Mayas of the classic period, and b) its reconstruction is feasible at a reasonable cost which for sure may be a touristic attraction with an aggregate value to the archaeological sites of Bonampak and Yaxchilán.

The study of ancient materials has an enormous potential because only a few sites has been studied, there are many other sites with potential, for instance: a) Malinalco, mortars and stuccos to build slabs on grade and ornaments, b) Pyramid of Fuego Nuevo, concrete to build mats and slabs, c) Complex of Templo Mayor, concrete to build slabs to support columns and walls, d) Tlatmanalco, concrete and mortars to construct a very large wall, probably with defensive purposes, e) Zempoala, mortar of exceptional strength to form masonry made with rounded rocks, boulders; as well as slabs on grade, f) Several Maya sites as Palenque, Toniná, Yaxchilán, Comalcalco, Uxmal, Kabah and many others were is evident the use of stuccos, mortars and concrete that they used as a base to its monumental architecture as well as engineering works as bridges, roads (sacbé), ports and docks, cisterns (chultunes) and dams.

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