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Effects of the use of plant mucilage on the physico-mechanical properties of raw earth structures

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Abstract
Raw earth constructions, by their very nature, are particularly sensitive to variations in the surrounding climatic conditions. Consequently, the use of this material implies the incorporation of substances of various kinds that have a stabilising function and help to prolong the life of these structures. For this reason, the use of plant substances from succulent plants is proposed, which is also a sustainable and safe option, both for the environment and for cultural assets. In this sense, the aim of the present research is to study the effect of the incorporation of these substances in the chocototype of raw earth used from pre-Inca times to the present day in the Archaeological Park of Cochasquí, Ecuador. For this purpose, plant substances of the cactaceae family of the genus Opuntia; Austrocylindropuntia Subulata (MUHLPFRDT. Backbg) and Opuntia huajuapensis (Bravo), which can be found in the natural environment, have been evaluated. In this experimental investigation, the characteristics of these substances and the influence they can have on the stabilisation of this raw soil have been evaluated through a series of physical-mechanical tests, including: the comparison of the kinematic viscosity of the different plant substances used, as well as the evaluation of the water behaviour in soil samples stabilised with different concentrations of mucilage.

Keywords: *opuntia; raw earth; conservation-restoration.*

1. Introduction

In the area of heritage conservation and restoration, research has been carried out on the possibilities of integrating traditional construction methods as a sustainable alternative (Kita, 2015). For this reason, this research evaluates the efficiency of plant extracts from succulent plants on the soil called chocoto for use in the conservation-restoration of archaeological structures in the Archaeological Park of Cochasquí, Ecuador.

The historical data that have been preserved, as well as the archaeological evidence that has been collected over the years, together with folklore, point to the importance of the Cactaceae family and its influence on social, religious and economic life since ancient times in the Americas, where they originated (Alanís and Velazco, 2008). Specifically, in Andean countries such as Ecuador and Peru, their use dates back more than 11,000 years (Novoa, 2006 and De la Torre et al., 2008) and among their various uses in the construction sector, the remains belonging to pre-Inca cultures such as the Chavín (1200 BC - 400 BC) or Churajón (800 BC - 1450 AD), which left archaeological evidence of their use in the preparation of mortar for their walls, as thorns belonging to various opuntias were found (Álvarez and

Cáceres, 2003 and Zeballos, 2020), and their use in the sealing of pavements and the preparation of adobes for the construction of their temples (Benítez, 2017). However, due to their biodegradable nature, it is not always possible to detect these substances in ancient constructions. In these cases, some authors choose to rely on the traditions that vernacular architecture carries with it (Kita et al, 2013), since the latter acts as a means of transmitting the knowledge of the past.

In recent decades, experimentation with these substances has followed an upward trend, especially due to the guarantees of viability and compatibility that have been demonstrated over time. Most of the research published on plant gums from the Cactaceae family has been carried out especially in Mexico, and their application in Portland cement or cement-based materials stands out (Torres et al., 2010; Ramírez et al., 2012). They have also been incorporated in other materials such as gypsum, lime or concrete, obtaining slight physical and mechanical improvements (Martínez et al., 2008; Pérez, 2009; Durán et al., 2012; Ochoa et al., 2013). In raw soils, there are several laboratory studies and field applications with more or less promising results, including improvements in compressive strength, abrasion resistance, as well as a decrease in porosity (Martínez et al., 2008; Kita, 2013; Aranda and Suárez, 2013; Torres et al., 2015).

2. Objective

The main objective of this research is to evaluate the effects of the incorporation of plant extracts on the stability and resistance to deterioration of raw earth structures. For this purpose, and following previous studies carried out at the University Institute of Heritage Restoration of the Universitat Politècnica de València (Medina et al., 2015), two types of plants from the cactaceae family that are naturalised both in the archaeological area and in the Mediterranean Levant have been selected. These plants belong to the genus Opuntia spp.: Austrocylindropuntiasubulata (MUHLPFRDT. Backbg) and Opuntia huajuapensis (Bravo).

The results presented in this paper are part of a broader research project belonging to a doctoral thesis in progress, related in this case to the comparison of the kinematic viscosity of the plant substances under study, as well as the evaluation of the water behaviour in soil samples stabilised with different concentrations of mucilage.

3. Methodology

3.1. Extraction of the gums and preparation of the test tubes.

The fragments and adult cladodes of the plants were collected early in the morning, as recommended by some studies (Torres et al., 2015). After cleaning in running water and peeling, the fragments were cut into small portions. For each of the species, 3 subgroups were differentiated by temperature and maceration time, using the bain-marie technique for the hot macerations (Table 1).

Maceration methods evaluated		
Species	**Temperature**	**Time**
Opuntiahuajuapensis (Bravo)	18-22°C approx. 40ºC 80ºC	72 h. 5 min. 5 min.
Austrocylindropuntiasubulata MUHLPFRDT. Backbg	18-22°C approx. 40ºC 80ºC	72 h. 5 min. 5 min.

Table 1. Temperatures and times used to evaluate kinematic viscosity (η).

Once the maceration time had elapsed, the samples were filtered using a tulle cloth to prevent the smallest fragments from straining out. After stabilisation of the temperature, the kinematic viscosity evaluation test was started (Fig. 1).

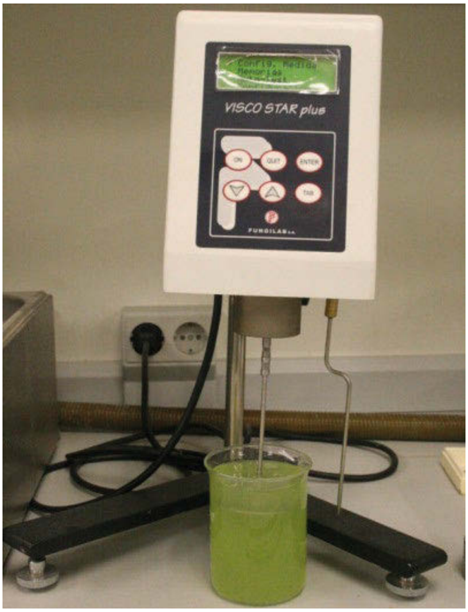

Fig. 1. Evaluation process of kinematic viscosity (η). (Source: Medina Lorente, 2022).

Subsequently, for the elaboration of the soil samples, the fragments and cladodes were collected and prepared with the same methodological approach as described above. In this case, the extraction method selected for the production of the soil samples was maceration at room temperature (approx. 18-22ºC). For this process, distilled water was also used in a mass ratio of 1:1 during 72 hours.

Once the indicated time had elapsed, the solid plant remains were strained and pressed to obtain a viscous substance. Three concentrations by weight were then established: 100% (substance obtained directly after maceration), 75% and 50%, the latter diluted in water. The solutions obtained are incorporated during the kneading of the raw materials in the manufacture of the raw soil samples. At the same time, reference samples are manufactured with the addition of water to evaluate the effect produced by the incorporation of the plant extracts.

The Chocoto soil was characterised by infrared spectroscopy (FT-IR). It is a clayey composition, with an absence of calcareous matter (data not shown in this publication). For this reason, clays of a similar siliceous nature were used as support for its reproduction, and an attempt was made to achieve a similar grain size to the soil by sieving.The specimens are divided into 3 groups: raw soil without gums (reference specimens, group 1) and stabilised with vegetable gum: Opuntia huajuapensis (Bravo) (HUA, group 2) and Austrocylindropuntiasubulata MUHLPFRDT. Backbg (AUS, group 3). Groups 2 and 3 are subdivided according to gum concentration: 50, 75 and 100% (Table 2).

Groups	Subgroups	Abbreviations
Group 1: REFERENCE	Raw earth mixed with water	REF-0
Group 2: HUA	Raw earth mixed with gum from Opuntia huajuapensis (Bravo) diluted 50% in water	HUA-50
	Raw earth mixed with gum from Opuntia huajuapensis (Bravo) diluted 75% in water	HUA-75
	Raw soil mixed with gum from Opuntia huajuapensis (Bravo) obtained directly from the 1:1 (water-plant) maceration.	HUA-100
Group 3: AUS	Raw soil mixed with gum from Austrocylindropuntias ubulata MUHLPFRDT. Backbg. Diluted 50% in water	AUS-50
	Raw soil mixed with	AUS-75

	gum from Austrocylindropuntias ubulata MUHLPFRDT. Backbg. Diluted 75% in water	
	Raw earth mixed with gum from Austrocylindropuntias ubulata MUHLPFRDT. Backbg. obtained directly from 1:1 maceration (water-plant).	AUS-100

Table 2. Groups comprising the specimens under study.

For the water vapour permeability tests, semi-plastic specimens of different sizes were manufactured, using manual compression, with the aid of a compression tester. Following the indications given in the regulations (Table 3). For the studies to determine the water vapour permeability and water vapour resistance, the following tests were performed.

Test	Size	Nº
Digital rotational viscometer: Visco Star Plus	500 ml	6
Determination of water vapour permeability. UNE-EN 15803-2010 (CEN©)	3Ø x1,5 cm	21
Determination of water absorption by capillary action. UNE-EN 15801: 2010 (CEN©)	3Ø x1,5 cm	21

Table 3. List of tests together with the characteristics of the specimens.

Rigid acetate and stainless aluminium moulds were used for the tests. The drying was carried out in an open air area but protected by a roof, periodically changing both the orientation and the faces of the blocks for a homogeneous drying. The drying time was 30 days.

3.2. Instrumentation and testing

3.2.1. Evaluation of kinematic viscosity (η)

The methodology consisted of using the Visco Star Plus digital rotational viscometer. Viscosities were recorded by SP: R3 at a speed of v=60 rpm. The data were recorded after 15 seconds of shaking. In this test, mucilages of the species of the genus Opuntia: *Opuntia huajuapensis* (Bravo) y *Austrocylindropuntia subulata*MUHLP-FRDT. Backbg, obtained by three types of macerations (see Table 1) where temperature and time were varied.

3.2.2. Determination of water vapor flow density

- Test procedure:

The objective is to measure the water vapour flow through the test tubes. For this purpose, the wet cuvette method was used, which consisted of placing the test specimens on a cylindrical plastic container filled with Parafilm®, with a saturated solution of potassium nitrate ($KNO3$) inside, which provides a relative humidity in the container of 93%, leaving an air space between the specimens and the solution of 1.5cm in height. The water vapour flux is determined by varying the mass of the specimens. The weight of the specimens is recorded every 24 hours for 10 days. The specimens were kept in an extraction chamber during the whole process, without drastic changes in temperature and humidity

After the collection of the data obtained, a series of formulas were calculated until the water vapour permeability values were reached, according to the standards used:

The cumulative mass variation (Δmi):

$$|\Delta m_i| = m_i - m_0$$

Where m_i and m_0 are the mass at times t_i and t_0 in kg.
After obtaining these data, the flow density was calculated:

$$g = \frac{G}{A}$$

where G= Δm/Δt, in kg/s.

3.2.3. Determination of water absorption by capillarity

For this test, the procedure indicated in the Spanish standard: UNE-EN 15801: 2010 (CEN©) was followed. The purpose of the test was to determine the capillary water absorption of the test specimens, assessing the influence that these plant substances can have on the porosity of the raw soil specimens. The quantity of water absorbed by the specimen per unit area Qi (gr/ cm^2) in time ti (s) is calculated using the following formula:

$$Qi = \frac{mi - mo}{A}$$

Where Qi is the quantity of water absorbed per unit area in gr/cm^2, mi is the mass of the specimen at time t_i, in gr., mo is the mass of the specimen dry in gr. and A is the surface area of the specimen in contact with the water, in cm^2. The capillary water absorption coefficient (AC) is the slope of the linear part of the curve obtained, representing the variation of mass per unit area (Qi) as a function of the square root of time in seconds (ti ½) (Fig. 2).

Fig. 2. Sample of the capillary water absorption test (Source: Medina Lorente, 2020).

4. Results

4.1. Evaluation of kinematic viscosity (η)

The data obtained show that the viscosity of the extracts remains constant for most of the mucilages during the first 72 hours, irrespective of temperature and time in the three types of macerations. In contrast, the AUS-20 and AUS-80 extracts exhibited a more heterogeneous behaviour, showing large variations in viscosity depending on the type of maceration, however, viscosity did not undergo relevant changes for the extract with maceration at 40oC (AUS-40). It should also be noted that the extracts with the greatest changes in viscosity (AUS-20 and AUS-80) are also those with the highest viscosities (Fig. 3).

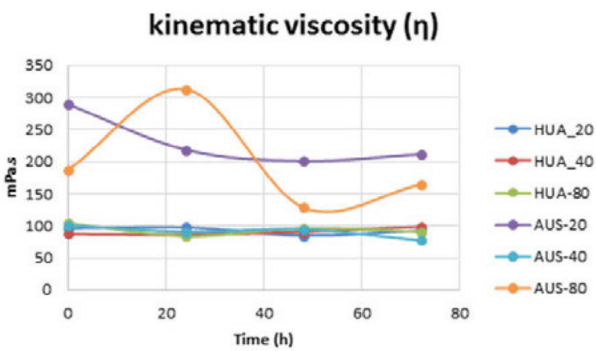

Fig. 3. Comparison of viscosities obtained at different maceration temperatures. Data obtained at v=60 r.p.m.

4.2. Determination of water water vapor flow density

TEST TUBE	WATER VAPOUR FLOW RATE (kg/(m^2.s)
REF	0,2579
HUA-50	0,2191
HUA-75	0,1941
HUA-100	0,1941
AUS-50	0,2285
AUS-75	0,2191
AUS-100	0,2191

Table 4. Results obtained.

As can be deduced from the previous results (Fig. 4), the addition of mucilage in the material produces in all cases a decrease in the flow rate of water vapour transmitted, with the lowest flow rates being recorded for specimens HUA-75 and HUA-100. On the other hand, the AUS-50 specimen is the one with the highest flow rate values, although lower than those of the reference specimen.

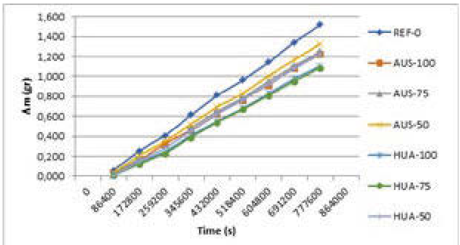

Fig. 4. The slope of each of the data series represented in the graph corresponds to the water vapour flow rate for each of the test specimens, which are shown in the following table (Table 4).

4.3. Determination of water absorption by capillarity

The results obtained show that the reference specimens (REF) disintegrate in shorter times compared to the specimens with mucilage, which seem to provide greater consistency to the material, which does not disintegrate so easily in contact with water. With respect to the HUA (Opuntia huajuapensis (Bravo)) specimens, a certain decrease in water absorption can be observed, with those made with a 100% mucilage concentration (HUA-100) standing out, followed by HUA-50 and HUA-75, respectively (Fig. 5).

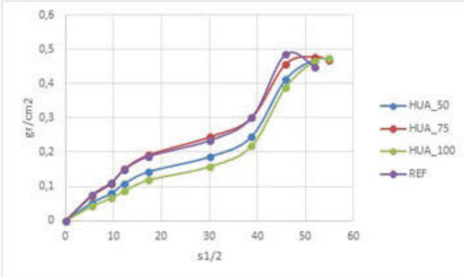

Fig. 5. Comparison of the results obtained in the test to determine the water absorption by capillarity of specimens made with *Opuntia huajuapensis* (Bravo) and reference specimens. Average curves obtained from three independent tests.

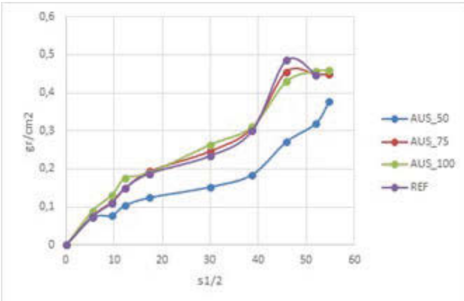

Fig. 6. Comparison of the results obtained in the test to determine the capillary water absorption of specimens made with *Austrocylindropuntia subulata* MUHLPFRDT and reference specimens.

In relation to the specimens made with Austrocylindropuntiasubulata MUHLPFRDT (AUS), the absorption results between the specimens with mucilage differ with respect to the specimens made with Opuntia huajuapensis (Bravo). In this case, there is a greater difference between the specimens made with 50% mucilage (AUS-50), being this group the one with the lowest water absorption compared to both species and the REF group. The remaining concentrations

(AUS-75 and AUS-100) show slightly lower absorption values compared to the reference samples (Fig. 6).

Among the species tested, Opuntia huajuapensis (Bravo) seems to slightly reduce the water absorption of the specimens when added undiluted (HUA-100). On the other hand, in the case of the species AustrocylindropuntiasubulataMUHLPFRDT, the 50% addition results in the greatest reduction of water in the material (Fig. 7).

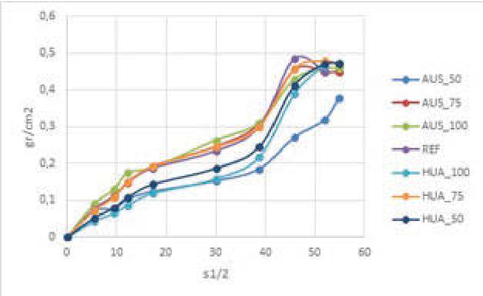

Fig. 7. Results obtained in the test to determine the water absorption by capillary action of the tested groups.

5. Conclusions

Overall, the results seem to show that different temperatures and maceration times do not significantly influence the viscosity values. This seems to be fully applicable to *Opuntia huajuapensis* (Bravo), however, for *Austrocylindropuntia subulata* MUHLPFRDT exceptions are recorded.

On the other hand, it should be noted that the values obtained (water vapour flow rate) allow all the materials to be classified as materials with high water vapour transmission according to the UNE EN 1062-1:1996 standard.

With regard to the capillary water absorption tests, in general, the incorporation of mucilage seems to produce a reduction in water absorption, as well as an increase in consistency compared to specimens without mucilage. However, there seem to be differences in behaviour between the species studied, as the addition of the 50% extract of the *Austrocylindropuntia subulata* MUHLPFRDT species is more effective in reducing capillary absorption, which may be related to its rheological characteristics (greater viscosity of the mucilage), compared to that obtained from *Opuntia huajuapensis* (Bravo), which gives the best results when incorporated undiluted. As for the different behaviour of test tubes with extracts of the same species, these differences may also be related to the heterogeneity and granulometry of the soil itself.

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