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Development and Intervention Proposal with Earthen Refurbishments with Vegetal Origin Gel (VOG) for the Preservation of Traditional Adobe Buildings

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Abstract: This research focuses on the addition of an ecological, sustainable material to improve the durability of earthen constructions and for use in rehabilitation and restoration processes. Specifically, it studies the mechanical and waterproof performance of an earthen mixture with the addition of a vegetal origin gel (VOG) obtained by extracting the starch contained in rice. This solution increases the durability of the mixture and the behavior against water and improves the mechanical resistance of the system. This study is divided into two parts. First, an experimental phase was carried out in the Universitat Politècnica de Catalunya laboratory to design and develop the earthen mixtures stabilized with VOG to obtain an ecological, economical and easily replicable technology that can be transferred to any population group. The second stage consisted of the application of these mixtures and a real intervention in adobe dwellings in the community of Santa Ana Chapitiro, in the State of Michoacan, Mexico. The rehabilitation solutions and dosages were transferred to the residents of the community and applied to local adobe constructions by means of participatory design through an international development cooperation project. Good behavior of the material was found in the early stage.

Keywords: cultural heritage conservation; earthen architecture; vegetal origin gel; traditional mortars; soil stabilization; vernacular architecture

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1. Introduction

As a construction material, earth was one of the first resources humankind utilized to build structures and develop traditional and vernacular architecture, which today is considered part of our cultural heritage [1]. There are examples worldwide of earthen architecture: from the adobe structures in Neolithic period farms in Mesopotamia from around 7000 B.C. [2] to the rammed earth walls of the Nk'Mip Desert Cultural Centre, built in 2006.

Notwithstanding the availability of earth, we can find a great diversity of earthen construction techniques around the world, depending on local factors like the way of life, the culture or socioeconomic and productive aspects of the region [3] and the abundance of geomaterials. The environment and the territory are also essential factors, and they determine the uniqueness of the built heritage on land. By way of example, in the Iberian Peninsula, there is considerable earthen heritage based fundamentally on three building typologies: rammed earth, earth block and adobe [4,5]. The use of each of these construction techniques depends on access to water and the degree of soil humidity. In the case of walls, a soil of humid consistency is required with a degree of humidity of 10 to 12%. For adobes, a soil of plastic consistency is needed with a degree of humidity of 20 to 25%. In terms of the granulometry of the soil, adobes require up to twice as much clay as rammed earth and will not contain gravel in their composition. Another aspect is the availability of natural fibers from agricultural crops. When such fibers are mixed in a percentage between 25% and 75% in volume with the surrounding soil, they will improve the mechanical properties of the adobes to produce a solid, durable construction material [6]. In this way, native people learned to artificially improve the properties of the soil through the use of renewable materials and the easy handling of the land, which with the passage of time is used less and less.

Since the last decades of the nineteenth century, industrialized materials based on the scientific development of steel and concrete have replaced traditional construction materials. The old systems have been neglected and abandoned by the new generations. This, general perception was very common in our times [7–9]. Currently, in developing countries where earthen architecture is widely spread among the poorest sectors and lacks maintenance and industrialization processes, this type of architecture tends to be associated with lower socioeconomic levels and is perceived as a technology of the poor or of rural areas.

Nevertheless, traditional earth construction techniques have seen a resurgence due to their potential as a construction material with environmental qualities and hygro-thermal and acoustic benefits [10]. In recent decades, the number of studies looking at earth's potential as a contemporary construction material has increased [11]. European countries, such as Germany, France and the UK, have started to revive their earthen building tradition. For sustainability reasons, countries, such as the USA, Brazil and Australia, have followed the same path [12].

In fact, 20–25% of the world's population in what is known as the Global South live in earthen dwellings, which are mainly found in the least developed countries [13,14]. However, the knowledge of traditional building techniques and their use is being lost. Therefore, the myth must be dispelled that building with earth is a symbol of poverty and that the use of cement-based materials is better [15].

The problem that is addressed here is related to the fact that current construction is dominated by the use of materials with high environmental impact, which is why construction is one of the most polluting industries. The construction industry is responsible for at least 30% of carbon dioxide emissions and leads the list of raw material consumers globally over other economic activities, which clearly indicates its unsustainability [12]. One of the main causes of the high percentage of carbon dioxide emissions is the cement industry, which represents approximately 5% of global CO_2 production and 3.8% of greenhouse gas emissions. The demand for cement increases annually and is estimated to increase to 4.38 billion tons by 2050 [16].

This industry has a manufacturing process that requires a considerable amount of energy from the use of coal in rotary kilns and the energy needed to grind clinker [17]. In addition, most of the CO_2 emissions generated during the manufacture of cement originate from the burning of fossil fuel and the decarbonization of limestone [18]. For all these reasons, we must opt for new renewable materials that help to reduce the CO_2 emissions generated by the construction industry.

We can find extensive literature about the real development of earthen materials that not only improve the comfort of buildings [19] but constitute a sustainable construction technique due to their low environmental demand and infinite recyclability [20]. However, the biggest concerns regarding earthen materials are related to their durability against external factors, such as rain and humidity [21], and the type of treatments and solutions we can apply to increase the length of their life cycle.

This study proposes an alternative method to improve the durability of earthen constructions. The process of the loss of vernacular heritage built with earth is remarkable, so it is important to find sustainable solutions for its preservation, which is a global concern.

The main objective of the research is based on a new sustainable proposal to repair and restore existing buildings using local earthen materials with natural additives derived from the reutilization and recycling of other processes, in this case vegetal origin gels (VOGs), to increase the durability of these constructions. In addition to the experimental purpose, the project considered from the outset the socioeconomic and territorial issues of earthen construction and cooperation with local communities to adapt these new construction technologies.

Some of the secondary objectives were to guarantee the viability of the solution and to apply it to real scenarios to benefit the communities that were involved, to increase the durability of traditional buildings and help to preserve vernacular heritage, to include participatory design during the process to meet the specific needs of the case study and the local context and to foster the appropriation of this technology within the local community and promote its continuous use.

1.1. Earthen Refurbishments and Modern Solutions for Cultural Heritage Buildings

Historically, the majority of earthen structures were plastered and refurbished to protect them and guarantee their durability (see Figures 1 and 2). For these reasons, the maintenance of these buildings has always been very important and even further depends on the level of aggressiveness of the environment. The refurbishments could be based on earthen mortars, in many instances stabilized with additions [22] or mortars with conglomerating materials like lime or gypsum [23,24].

Figure 1. Pathology in contemporary cladding on a historical building in Patzcuaro, Michoacan, Mexico. Source: B. González-Sánchez.

In recent years, authors have proposed the incorporation of mass ratio additives to the earthen mixtures due to the great resistance they provide, the reduction in maintenance and the adaption to current standards [25]. Nevertheless, the addition of materials, such as cement or lime, in substantial percentages of above 4% significantly increases the carbon footprint and hampers the recycling of the mixtures [26]. Thus, they lose, the definition of sustainable, ecological constructions but gain durability. However, we can find another architecture that seeks to improve the properties of the traditional construction systems with the incorporation of renewable materials [27].

Figure 2. Pathology in traditional cladding on a historical building in Patzcuaro, Michoacan, Mexico. Source: B. González-Sánchez.

1.2. Vegetal Origin Gel (VOG) and Earthen Architecture

Recycled materials, such as clays, mixed with renewable materials like plant products can be used many times with a small energy demand, so these mortars are low energy products or have a meaningful Environmental Product Declaration. Renewable building materials must be based on plant or animal materials, either obtained by natural growth or deliberate cultivation [28]. However, their application in conventional constructions is limited by a lack of experience in their application or by limited evidence provided by scientific data to quantify their performance [29].

Materials of organic, inorganic or geological origin have been incorporated into construction mixed with aggregates to create hybrid materials since ancient times. They date back to 3000 B.C., when the Sumerians incorporated bitumen into their clay and straw mixtures [30]. The Romans used volcanic ash to improve their mortars, while in Mexico, we can find several examples and applications of opuntia ficus-indica mucilages (cactus species) for the stabilization of soils and earthen components like adobes [31,32]

In China, a paste of lime with glutinous rice was used, commonly mixed with other organic components such as tung oil, vegetable leaf juice, egg white and animal blood [33–36].

Glutinous rice was a good stabilizer due to its high content of amylopectin, which is one of the main components of starch. The addition of starch to mortars is a traditional technique in which glutinous rice was incorporated into mixtures due to its high adhesive strength, good durability and impermeability [35,37]. In addition, due to the waterproof properties of this mortar, it was used in facilities for water resources [36]. This starch mortar has also been used in modern times, for example, in the Kaiping towers in Guangdong province in China [38].

Starch is one of the most important plant products in the food industry and in other industries. It is relevant as a relatively cheap and renewable product. It has been used for centuries as an adhesive by the Romans and for medicinal purposes by the Greeks. Currently, it is used for industrial purposes, such as an additive in cement, substituting additives derived from petroleum, in the manufacture of plaster, for plasterboards, as an adhesive and in bioplastics [39–41]. Starch is a polysaccharide mixture of two polymers, amylose and amylopectin, in different proportions with a predominance of amylopectin content. It is present in plants naturally, in the form of grains. Starch in industrial processes is used in the form of an aqueous gel. This gel is formed by boiling grains in water to release polymer chains. Within biopolymers, this polysaccharide improves the mechanical strength of the earth by up to 50%. However, it must be considered that the improvement achieved will depend on the nature of the clay and its chemistry [42,43].

Research about tabia, which is a mortar of lime and glutinous rice, has shown that there is an improvement in its mechanical resistance due to the change in the structure of the mortar caused by the introduction of the starch contained in the rice. It is possible to obtain a finer porous structure, so it has a more compact texture, which leads to an improvement in its mechanical behavior [44]. Studies of the interaction between soil and starch from glutinous rice show that starch particles uniformly disperse and wrap around soil particles, filling in the porosity in the soil structure, which reduces the porosity ratio and increases cohesion. When water evaporates, soil particles are solidified and result in a compact structure [37,45]. A previous study focused on the introduction of starch from rice to the soil mixture for earth blocks. It was proved that starch in the form of gel combined with soil improved the physical and mechanical properties of the blocks [46].

1.3. Case Study of the Research: The Vernacular Adobe Houses of Santa Ana Chapitiro, Michoacan

The second stage of the research focused on the application of earthen mixtures in case studies with conservation demands. The participative methods and the involvement of local communities with their own heritage conservation were included as key factors in the project [47], to search for a more collaborative approach. This approach was achieved through the cooperation project entitled "Diagnosis of traditional constructions and intervention proposal with earthen refurbishments stabilized with vegetal origin gels (VOGs)", which was carried out by the Barcelona School of Building Construction–Universitat Politècnica de Catalunya (EPSEB–UPC) in collaboration with the Faculty of Civil Engineering–Universidad Michoacana de San Nicolás de Hidalgo (FIC–UMSNH).

The case study selected for the project was the indigenous community of Santa Ana Chapitiro, in the State of Michoacan, Mexico (see Figure 3a). Engagement with the community was enabled by the non-profit civil organization GIRA and the research group VIVE–UNAM. The locality belongs to the municipality and lacustrine region of Patzcuaro (see Figure 3b), which has great historical relevance [48] and presents unique cultural and social aspects that make the traditional architecture of the zone really interesting.

The representative houses of the region are made of volcanic stone foundations, adobe walls and wooden roofs, utilizing local resources (see Figure 4). The walls have historically been covered with lime mortars or earthen refurbishments to protect them from atmospheric agents, fauna and flora. However, with the abandonment and oblivion of traditional knowledge, most of the buildings now have unprotected adobe walls, which are very vulnerable to moisture.

(**a**) (**b**)

Figure 3. (**a**) Location of the State of Michoacan within Mexico; (**b**) location of the municipality of Patzcuaro within Michoacan.

Figure 4. Traditional adobe houses in Patzcuaro, Michoacan, Mexico. Source: A. Solís-Sánchez.

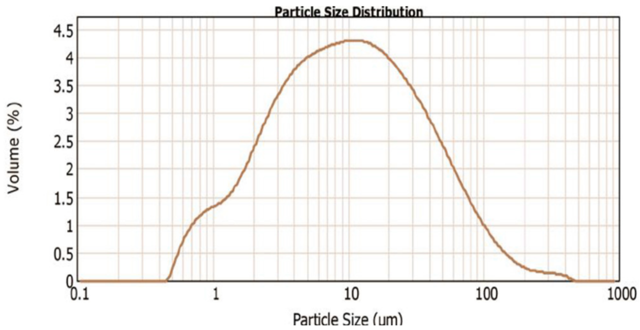
2. Materials and Methods

2.1. Materials

Earthen mixtures studied in the laboratory were made of clay, fine aggregate and the vegetal origin gel (VOG) produced from boiling rice. The clay was a Lila micronized clay from the company Argiles Colades S.A., which was used and characterized in previous research [49]. The composition was determined by means of X-ray diffraction (XRD) and fluorescence (XRF) analysis, and the granulometry was obtained from laser diffraction (ADL). The Atteberg limits of the material were also calculated. The results of these tests can be observed in Table 1.

The fine aggregate was crushed calcareous marble, with a particle size fraction between 0 mm and 0.85 mm. It is made by Aymar S.A. and its commercial name is Micromar 800. The VOG was produced by cooking rice grains in boiling water in a proportion of 1 cup per 5 cups of water until a viscous texture was acquired, with a density of 1.11 g/mL. The rice grains were then removed, leaving the gel, which was cooled to room temperature before use.

Table 1. Mineralogical and particle size characterization of clay.

FRX (%)				XRD	
SiO_2	59.87	Na_2O	0.32	Quartz (SiO_2)	***
Al_2O_3	22.87	P_2O_5	0.06	Kaolinite ($Al_2(Si_2O_5)(OH)_4$)	***
Fe_2O_3	6.33	MnO	0.02	Illite ($(K,H_3O)(Al,Mg,Fe)_2(Si,Al)_4O_{10}[(OH)_2,(H_2O)]$)	**
K_2O	1.38	LOI	6.87	Chlorite ($(Mg,Fe)_3(Si,Al)_4O_{10}(OH)_2{\cdot}(Mg,Fe)_3(OH)_6$)	*
TiO_2	1.04			Calcite ($CaCO_3$)	*
CaO	0.73			Hematite (Fe_2O_3)	*
MgO	0.61			Orthoclase ($KAlSi_3O_8$)	*
Atterberg limits				**ADL**	
LL: 40.80 PL: 25.40 IP: 15.40 MH: Mud, medium plasticity					

*** Predominant, ** abundant, * present.

2.2. Samples Preparation

The samples that ware made were classified into two groups. The first ones were made only with water, as a binding activator for the clays. The second set of samples was made by completely substituting the water for the VOG. In addition, the two groups of samples were made with two dosages of aggregates. The optimum dosage of water required to make the mortar was found to be 25% with respect to the clay. This conclusion was reached through a previous phase of observation of the shrinkage and cracking of different dosages of water, clay and aggregates. Table 2 shows the final dosage of the mixtures. Each mortar was mechanically mixed for one minute, with a mortar mixer model E93 of the MASTEST brand, with a working speed in rotation of 140 $\pm$ 5 rpm and in planetary movement of 62 $\pm$ 5 rpm, according to the UNE-EN 196-1:2018 standard [50]. Samples of dimensions 4 cm $\times$ 4 cm $\times$ 16 cm were made for the two groups of mortars according to standard UNE-EN 1015-11:2020 [51], although this regulation is not specifically for testing soil mortars. The samples were made by compacting layers as thick as 1 cm manually in molds until completely filled. After 24 h, the samples were removed from the molds and left to dry at room temperature for 2 weeks, until they reached stable weight in the temperature and relative humidity of the laboratory (23 °C and 50% HR).

Table 2. Matrix composition of the samples.

Sample	Dosage (Volume)			
	Water	VOG	Clay	Sand
W 2:1	0.50	-	2	1
W 3:1	0.75	-	3	1
VOG 2:1	-	0.50	2	1
VOG 3:1	-	0.75	3	1

2.3. Characterization of the Materials in the Laboratory

The consistency of the fresh mortar was tested, following the test described according to standard UNE-EN 1015-3 [52]. To determine the mechanical characteristics and the porosity accessible to water the following were determined. The dynamic Young's Modulus was calculated following the procedure of standard UNE-EN 14579:2005 [53], using equipment for ultrasound PROCEQ Pundit Lab and an Ultrasonic Instrument ultrasound device, which emits at 55 kHz. The maximum flexural and compressive strength were determined following the procedure of standard UNE 41410:2008 [54] (for both tests, the Wykeham Farrance press of 5000 kg, and a load application speed of 1000 mm/min were used; for the flexural strength test, the same press was used with an element that allows the application of the load at three points of the specimen). The bulk density and percentage of porosity available to water were defined according to standard UNE-EN 1015-10:1999 [55] but using white spirit as the liquid.

To study the behavior of the mortar against the action of water, the capillary suction, the permeability to water vapor and the erosion generated by the continuous fall of water on its surface were determined. The water absorption by capillarity effect of the samples that were studied was determined, according to standard UNE-EN 772-11:2011 [56]. The permeability to water vapor was determined according to the standard UNE-EN ISO 12572:2018 [57]. Additionally, the erosion of the samples was determined according to the standard UNE 41410:2008 [54]. All tests were performed with the number of samples required in the specified standards.

Finally, the moisture-drying accelerated artificial aging test was carried out, according to standard UNE 41410:2008 [54], with a total of 12 cycles of immersion and subsequent drying under ambient conditions. Afterwards, it was checked whether the weathered mortars had experienced modifications in their percentage porosity, bulk density, mechanical characteristics and Young's modulus.

2.4. Empirical Application of the Earthen Mixtures in Adobe Buildings

With the experimental part completed in the laboratory, the purpose of the research was to apply the designed earthen mixtures to real traditional buildings to observe the performance and protect these structures from the surrounding environment. As discussed before, the case study that was selected was the community of Santa Ana Chapitiro in Michoacan, Mexico, and the vision of the project included the participative design of the houses' inhabitants and users [47]. Even though most of the houses had mixed systems and poor construction solutions, most of the walls were built with adobe masonry. Some of the walls had cracks and light structural damage (see Figure 5). They were repaired with earthen mortars before the earthen refurbishments were applied.

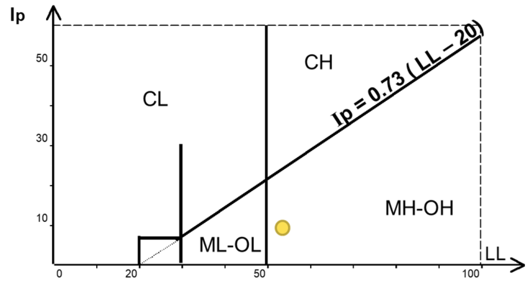
Figure 5. Adobe walls of Santa Anna Chapitiro before the intervention. Source: A. Navarro-Ezquerra.

The materials (clays and sand) used for the intervention proposal in the community were characterized according to Mexican and international standards (ONNCCE and

ASTM, respectively) in the soil mechanics laboratory of the Universidad Michoacana de San Nicolás de Hidalgo. The results are shown in Table 3.

Table 3. Characterization of soil mixtures designed for traditional community buildings.

Mesh Size (mm)	Retained (g)	Pass (%)
2.00	3.2	98.4
0.84	4.2	96.3
0.42	4.4	94.1
0.25	3.2	92.5
0.13	4.8	90.1
0.074	7.2	86.5
<0.074	1.73	
Atterberg limits	LL: 52.8; PL: 44.7; IP: 8.1; MH: Mud, medium plasticity	



The representative samples of the fine material were submitted to a sieve analysis, and the Atterberg limits were calculated. The sieve analysis was carried out following the Mexican standard NMX-C-496-ONNCCE-2014 [58], which is based on the international standard ASTM D6913/D6913M-17 [59]. The Atterberg test was performed following the Mexican standard NMX-C-493-ONNCCE-2018 [60] (see Table 3). The sand that was utilized was found at the same workplace (maximum size 0.5 mm), and the rice starch gel was prepared and brought from the laboratory. As this was an empirical application of the experimental research, only a basic analysis was carried out to characterize the fine material.

Before the intervention of the houses in Santa Ana Chapitiro, three dosages of sand, clay and gels were tested on the adobe walls of a kitchen unit in the facilities of the non-profit organization GIRA (see Figure 6) to monitor the behavior of the mixtures in a real environment and to select the ones that presented less shrinkage (see Table 4).

Table 4. Composition of soil mixtures designed for traditional community buildings.

Mixture	Dosage (Volume)				No. Test
	Water	VOG	Clay	Sand	
W A	1/2	-	1	1	2
W B	1/2	-	1	2	2
VOG A	-	1/2	2	2	2
VOG B	-	1/2	3	2	2
VOG C	-	2/3	3	4	2

The refurbishment was applied in two layers (see Figure 7). First, the adobe wall was thoroughly dampened to guarantee the mechanical adherence of the mixture, and a first layer, approximately 3–4 cm thick, was applied, composed of clay and sand mixed with water at a 1:1 volume dosage. After letting the layer dry for approximately 24 h, the surface was moistened again to apply the second and last layer that was approximately 2 cm thick. It consisted of a mixture of clay and sand with VOG at a 3:4 volume dosage.

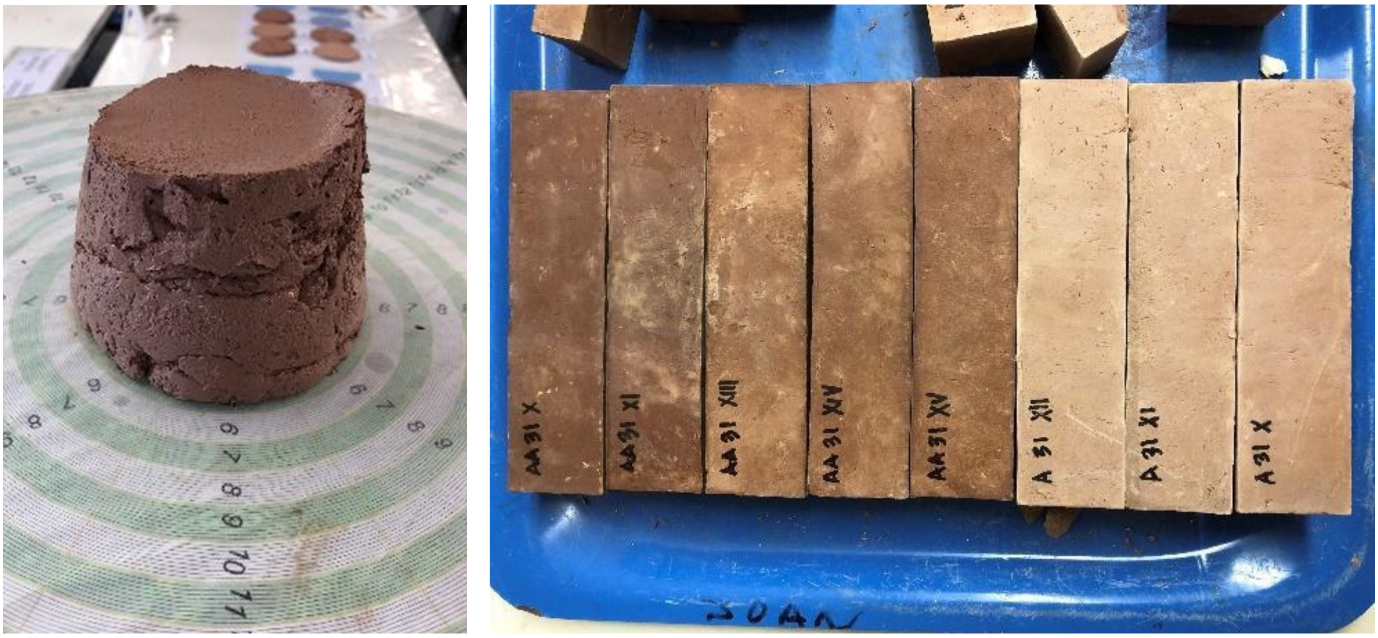
Figure 6. Testing mixtures by application on an adobe wall. Source: A. Solís-Sánchez and A. Navarro-Ezquerra.

Figure 7. Preparation and application of the earthen refurbishments. Source: A. Solís-Sánchez.

3. Results

3.1. Comparative Laboratory Test

The consistency of the mortars made with water and VOG for the two dosages studied was dry and without slump, as shown in Figure 8a The only difference observed is that the mortars made with water dried before those made with the addition of VOG (see Figure 8b).



(**a**) (**b**)

Figure 8. (**a**) Consistency test and (**b**) specimens with water (the lighter ones) and with VOG (the darker ones) of the 3:1 dosage. Source: K. Sandoval-Castro.

Table 5 shows the values of the parameters studied for the two types of mortar and their dosages.

As can be seen, VOG produced earth mortars with lower porosity, which hampers the access of water and provides a higher modulus of elasticity with a consequent increase in mechanical strength. The higher the clay content, the better the mechanical performance. The two dosages without VOG had very similar mechanical performance, water-accessible porosity and bulk density. Regarding the coefficients that condition the mobility of water through the porous network of the mortars, Table 6 shows the values of capillary suction and permeability to water vapor.

Table 5. Porosity and mechanical properties of mortar.

Sample	**Mechanical Properties and Porosity**				
	n_0 (%)	**Da (g/cm^3)**	**MOE (GPa)**	**Cs (N/mm^2)**	**Fs (N/mm^2)**
W 2:1	21.5	2.04	5.30 ± 0.38	3.29 ± 0.77	2.11 ± 0.45
W 3:1	21.9	2.07	5.38 ± 0.50	4.06 ± 0.29	2.31 ± 0.09
VOG 2:1	18.8	2.08	10.58 ± 0.78	7.64 ± 0.39	5.51 ± 0.56
VOG 3:1	17.3	2.13	7.82 ± 0.47	8.01 ± 2.14	6.45 ± 0.35

n_0 (%): porosity accessible to water; Da: bulk density; MOE: dynamic Young's modulus; Cs: compressive strength; Fs: flexural strength.

Table 6. Capillary suction and permeability to water vapor of mortar.

Sample	**Mobility of Water**		
	C.S.c (Kg/(m^2 min)	**μ Dry Glass**	**μ Wet Glass**
W 2:1	2.88 ± 0.09	39.38 ± 8.16	14.84 ± 1.34
W 3:1	3.27 ± 0.35	26.20 ± 5.26	14.35 ± 0.41
VOG 2:1	1.29 ± 0.31	123.76 ± 64.48	17.73 ± 0.90
VOG 3:1	1.29 ± 0.17	119.21 ± 30.75	16.20 ± 0.85

C.S.s: capillary suction coefficient; μ: water vapor resistance factor (dimensionless).

The use of VOG in mortars modifies the behavior towards water. It considerably reduces capillary suction and prevents the mobility of water vapor through the porosity. When the dry cup test is carried out, that is, when the humidity has to pass from the outside to the inside of the permeameter, the VOG mortars are very impermeable. In contrast, when the humidity has to pass from the inside to the outside of the permeameter, the permeability of the VOG mortars has similar behavior to those made with water.

The Swinburne (SAET) test, normalized by the UNE 41410:2008 standard [54], provides criteria to determine whether a sample of mortar is suitable to resist the erosive effects of the direct, constant action of water. The test was carried out on samples of mortar made with water or VOG. All the specimens tested are "suitable" according to this test because the cavity generated does not exceed 10 mm in depth. However, the samples made with VOG did not suffer any marks, while those made with water had marks of 1.5 mm on average. Figure 9 shows the images of the test specimens before and after testing.

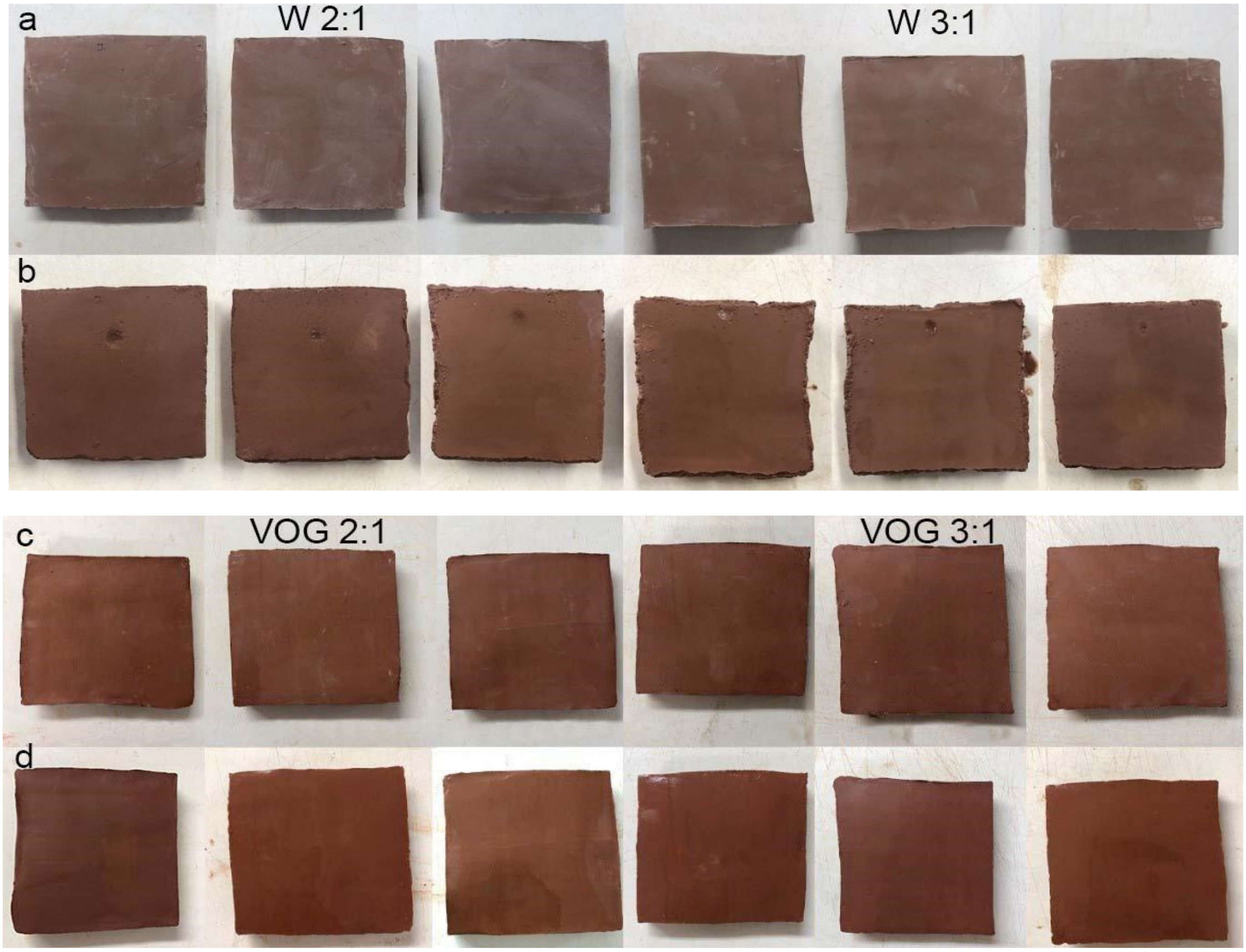


Figure 9. Images of the test specimens before and after testing SAET. Samples: (**a**,**c**) before erosion test and (**b**,**d**) after erosion test. Source: K. Sandoval-Castro.

After the 12 moisture-drying cycles, the samples made with water showed a general loss of the outer layers and local pitting. In contrast, the samples made with VOG did not suffer significant impact from the action of water. The state of the samples after the 12 cycles is shown in Figure 10.

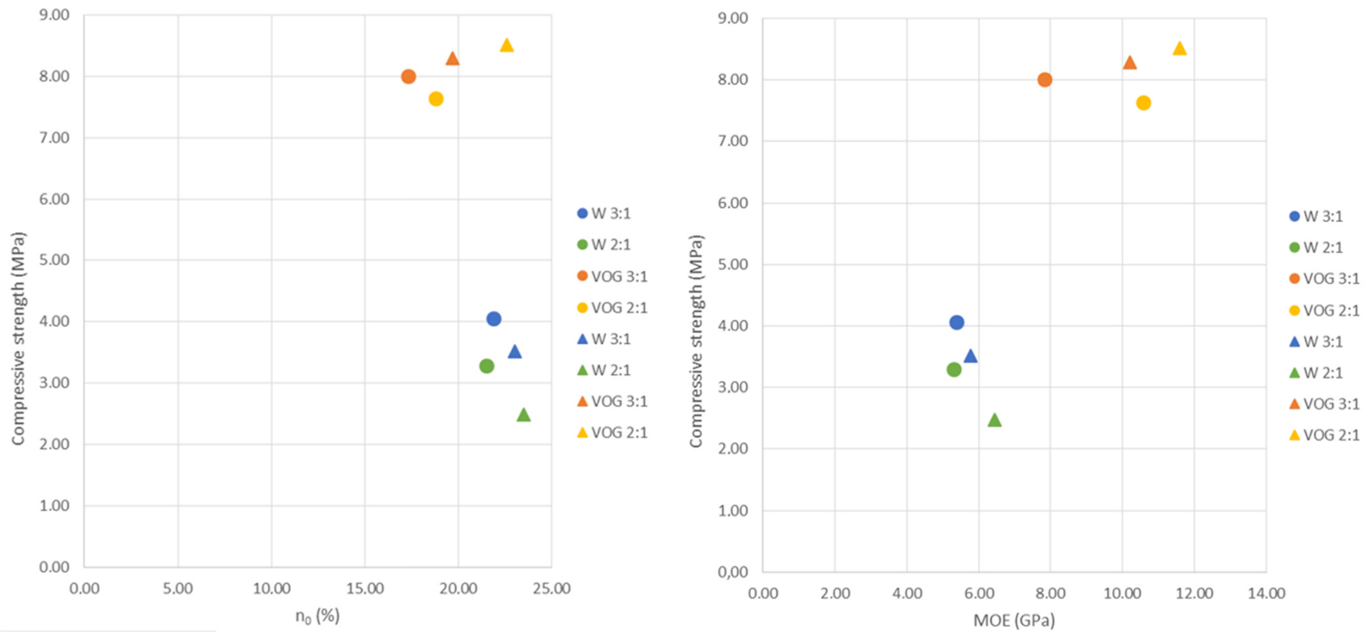
Figure 10. Specimen images after the 12 moisture-drying cycles. Source: K. Sandoval-Castro.

The final percentage variation of the mass of the aged samples is shown in Table 7.

Table 7. Percentage variation of the mass of the aged samples.

	Sample			
	W 2:1	**W 3:1**	**VOG 2:1**	**VOG 3:1**
% percentage variation mass	−1.30	−0.81	−0.38	−0.59

The accelerated artificial aging by moisture-drying affected the structure of the specimens and, consequently, their water-accessible porosity and mechanical properties. Notably, the modifications experienced by specimens manufactured with VOG resulted in a reduction of their porosity and a significant increase in their Young's modulus and compressive strength, as shown in Figure 11.



(**a**) (**b**)

Figure 11. Correlation graph of porosity with respect to simple compression (**a**) and MOE with respect to simple compression (**b**) before and after moisture-dry aging.

The circles correspond to values before aging, and the triangles correspond to values after aging. The blue and green colors correspond to values of the samples made with water, and the orange and yellow colors correspond to values of the samples made with water and VOG.

3.2. Application of the Earthen Refurbishments

Regarding the application of the stabilized mixtures in the community of Santa Ana Chapitiro, the refurbishments proved to be functional and had a homogeneous appearance after the rainy season during the summer. The users of the dwellings were very pleased with the intervention and the behavior of the system, and it improved the appearance of the walls. After the rainy season, approximately six months after the intervention, the mixtures still had a homogeneous aspect and texture with almost no cracks or deterioration (see Figure 12).

Figure 12. Final result of the earthen refurbishment after the rainy season. Source: A. Sanchez-Calvillo.

After this first intervention, the refurbishments will be monitored for a long period of time, to determine and compare the behavior of the system in a real environment with rainy seasons. This will help to corroborate the experimental analysis of accelerated artificial aging developed in the laboratory to predict the performance of the mixtures. Additionally, we can observe the impact on the walls depending on the orientation and construction aspects of the building.

4. Conclusions

As earthen architecture is at risk, the incorporation of renewable, sustainable materials, such as rice starch, to improve the properties of traditional systems is a sustainable path to protect and preserve our cultural heritage. The main vulnerability of adobe constructions is against water and moisture. Therefore, solutions that increase their durability and resistance to erosion are the most suitable and efficient for these buildings.

As shown with the correlation of the testing methods, the replacement of mixing water with VOG considerably improves the properties of earthen mixtures. The samples show better resistance to erosion; no alteration of the samples was visible, which is very important for earthen architecture to resist inclemency and mitigate the effect of rainwater. The compression strength also increased, doubling its value compared to samples made with water alone. These results are encouraging since they show that traditional buildings with earthen refurbishments can be well-protected against atmospheric elements. Additionally, the VOG uses an available resource that is economically viable and does not have detrimental residues or effects on the environment. Furthermore, the use of VOG by mass ratio increases the durability of the refurbishment and the entire system, which increases the life cycle of adobe constructions and decreases the maintenance costs and times.

The mortar in the Santa Ana community buildings is at present six months old, and the plasters show no major cracks, fissures or delamination. They withstood the rainy season. It is important to keep monitoring the intervention as the long-term behavior of the refurbishments will assess the real durability of the solution. Follow-up is needed to determine whether the full-scale alteration resembles the results obtained in the laboratory since it is well-known that laboratory-accelerated weathering tests do not include all the variables that occur in reality.

Cooperation activities in the region are expected to be continued, and the initiative will be extended to other communities and case studies. Furthermore, other locally available resources that could be used to optimize earthen mortars and refurbishments should be examined and explored. Thus, another future research area would be experimentation combining VOGs with other additions and dosages to consolidate better solutions for durability purposes.

Apart from empirical testing of the material designed in the laboratory, the social and human learning from this experience was even more important. The community of Santa Ana Chapitiro accepted and embraced this new technology. In recent decades, the interventions to protect and maintain the adobe walls of vernacular buildings have usually used cement mortars although the traditional solutions involved earthen, lime or mixed mortars. In addition to the bad compatibility of these systems, the communities are losing their traditions and, consequently, their cultural heritage.

It is important for the rural communities to bring back the local materials and in the process incorporate renewable resources, all without losing sight of their construction techniques, their traditions and their territorial identity. We should stress the involvement of local communities in the cultural heritage projects as historically the institutions and elite have made the decision themselves. The incorporation of participatory design is essential since everyone can contribute and the final result is more satisfactory.

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