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Initial Assessment of the Properties of Nopal Gum as a Possible Additive in the Conservation of Adobe Buildings

Ir a versión en español

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ABSTRACT

This RESEARCH ARTICLE exposes a possible application of the *nopal* gum (*Opuntia ficus*) variety as an additive to promote the durability of adobes, which may be used in the conservation of architectural heritage. This research was carried out in the Laboratory on Cubic Soil Specimens. While preparing the mixtures, different concentrations of previously dehydrated and powdered nopal gum were added. Through moisture retention, capillarity, and compressive strength analysis, the samples were evaluated, and the results found—also discussed here—show that adding nopal gum increases the compression strength of soil specimens and reduces capillarity. In fact, it was possible to maintain the cohesion of the particles in the soil samples during their exposure to humid environments. Having obtained such aptitude in the properties of said specimens makes this substance viable for its use in the conservation of adobe buildings.

KEYWORDS

nopal gum, soil, capillarity, compression strength, cohesiveness

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INTRODUCTION

Since the beginning of time, human beings have used the resources available in nature to satisfy their basic needs. First, due to hunting and gathering patterns, humans were nomadic, so they required temporary shelters, such as caves and caverns, to take refuge (Bardou & Arzoumanian, 1979, p. 23). Later, with the implantation of sedentary life, the need arose to create new construction systems, in some of which adobe has been one of the most predominant materials ever since. It is mainly made up of a mixture of soil (soil, slit, clay), water and some materials as additives; it may also contain reinforcing materials, such as vegetable fibers.

In Mexico, there are examples of very significant pre-Hispanic settlements. In the arid region, in the state of Chihuahua, the city of Paquimé stands out, whose heyday occurred between the 14th and 15th centuries. It is recognized for its constructions with thick adobe walls within a labyrinthine urban layout (UNESCO, 1998). Even though in the tropical area of Mexico the average annual rainfall is high, and the north winds hit the coast strongly, the use of adobe as a construction material is present in at least 132 archaeological sites in the center-south of Veracruz (Daneels & Guerrero, 2013, p. 35).

One of the most significant problems in buildings erected with adobe—whether due to intrinsic or extrinsic causes—is the lack of solidity of the materials. Currently, the concern to preserve or restore all the vestiges left by ancestral cultures results in a series of proposals or alternatives, such as consolidating materials that seek superficial cohesion of their particles; binding materials that allow maintaining a homogeneous union of the adobe particles or, even, a partial replacement of the adobe pieces with materials/parts very similar to the original (Figure 1).

In construction systems, additives are generally referred to as products of natural or synthetic origin that, added in small amounts before or during the mixing process, can improve the workability, compressive strength and durability of structures in extreme weather conditions. Throughout history, additives have varied and, therefore, the techniques for using them have never been static. Thus, they have been used with different properties, as stabilizers, consolidators, adhesives, binders, etc. (Veiga, 2017, p. 136; Ventola et al., 2011, p. 3315). Humans have always resorted to the use of materials in their environment, such as use of vegetable gums, tree resins, honey (Barba & Villaseñor, 2013, p. 106), rice starch (Pacheco, 2014, p. 154), extracts of mallow leaves and stems (Pinta, 2022, p. 8).

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FIGURE 1. Remnants of a wall with earth-based flattening in the La Quemada archaeological zone, Zacatecas (Picture: Josué Israel Moreno Fraga, 2020; courtesy: Centro INAH Zacatecas).

Some of the main advantages of using natural plant-based materials are their biodegradable qualities (the ability to break down biologically into natural elements without harming the environment), their non-toxicity, their low cost, their quality of renewable resources, their local availability, etc. (Jani et al., 2009, p. 309).

Currently, the restoration processes in elements of archaeological zones and colonial buildings in Mexico use additives in adobes to improve their properties. The use of these materials must comply with the general institutional guidelines for conserving cultural heritage established by the Instituto Nacional de Antropología e Historia (INAH, 2014).

Mucilage and gum are products of physiological origin from the cactus of the genus *Opuntia*, commonly called *nopal*. The first of metabolic origin, is formed inside the cell and is produced without damaging the plant, while the second is considered a pathological product, formed after the plant has suffered damage due to unfavorable conditions, such as drought or due to a rupture of the cell walls (extracellular formation; gummosis), which causes the breakdown of cellulose (Prajapati et al., 2013, p. 1686). On the other hand, the insect called *nopal borer weevil* (*Cactophagus spinolae*) is considered a pest that attacks the body of the plant and can also cause the development of gum, which in no case is reabsorbed by plant tissues (Lobos et al., 2013, p. 151).

Mucilages and gums have some similarities: they are hydrocolloid, amorphous, translucent substances and contain monosaccharides, many of which combine with uronic acids. Both also contain hydrophilic molecules, which can combine with water to form viscous solutions or gels (Jani et al., 2009, p. 309).

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Nopal mucilage is made up of high molecular weight heteropolysaccharides (D-galactose, L-arabinose, L-rhamnose and D-xylose), with colloidal properties, which swell and dissolve exclusively in hot water. Mucilage gum is insoluble in organic solvents, alcohols, and ether, and when hydrolyzed it breaks down into certain complex organic acids, as well as pentoses and hexoses (Medina-Torres et al., 2000, p. 419).

Recent research has focused on explaining the behavior of nopal mucilage in construction systems. Rodríguez-Navarro et al. (2017) and Pérez et al. (2015) studied the incorporation of this substance in the formulation of lime mortars and found an improvement in the plasticity of the pastes and good behavior against the erosion of said mortars.

Perez et al. (2021) added nopal pectin to lime mortars, improving the plasticity of the mass and reducing cracking and capillary absorption during drying, in addition to obtaining an increase in mechanical resistance. Jáidar (2006) used vegetable extracts in lime mortars and found that applying the additive after hydrating the lime is more effective, since capillary absorption and permeability to water vapor are reduced. Examples of carried out research on adobes are: Guillen et al. (2019) added nopal mucilage to soil-water-cellulose mixtures, which observed good mechanical behavior and reduced moisture absorption; Medina et al. (2015) used vegetable gums in adobe and, as a result, the permeability to water vapor was reduced and the abrasion resistance increased; before applying nopal mucilage in eroded adobes, Martínez-Camacho et al. (2008) used an alcohol/water solution that reduced surface tension and improved mucilage diffusion in adobe; and Torres et al. (2015) sprayed this substance on adobe surfaces, managing to stabilize the friable surface.

Even though there are several works found on nopal mucilage as an additive in construction systems—and, specifically, in the architectural heritage of adobe—it is important to expand knowledge based on the application of nopal gum, since it is believed to have a chemical composition very similar to nopal mucilage.

The purpose of this work is to carry out an analysis of the physicochemical properties of nopal gum and, by evaluating the mechanical resistance of its behavior as an additive at different concentrations in specimens of compressed raw earth, in order to establish a standardized and systematized methodology that serves as a reference for its possible use in processes of architectural conservation of adobe and other construction systems.

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METHODOLOGY

This section presents the materials, the preparation of compressed raw earth specimens and the analysis techniques used in this research.

Materials

Earth (soil, silt, clay)

In the elaboration of the soil specimens, soil from San Luis Potosí, Mexico was used. To know its plasticity, the Atterberg limits were determined (a measurement that defines the consistency of soil in relation to its water content) according to the ASTM D4318-05 (2005) Standard the following values were found: 29 for the liquid limit (LL), 15 for the plastic limit (LP) and 14 for the plasticity limit (IP), which indicated that it corresponds to an inorganic soil with low plasticity and is usable as a construction material (MMP-1 02 /03, 2003). The particle size of the soil was below 0.8 mm, as determined by the standards ASTM C136-01 (2017) and ASTM C117-95 (1995).

The optimum moisture content for the correct compaction of the soil was carried out using the Proctor test, in accordance with the ASTM D698-12 (2021) Standard, and an optimum moisture value of 16.6% was obtained, with a density of 1.9 g/ cm3. Based on all these results, the mix of soil samples required for the study was designed.

Nopal gum

Opuntia ficus indica nopal gum was collected in the municipality of Armadillos de los Infante, San Luis Potosí, Mexico (Figure 2).

FIGURE 2. *Opuntia ficus indica* nopal gum harvesting process (Picture: Josué Israel Moreno Fraga, 2020).

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Superficial cleaning of the gum was done, eliminating cladode residues. Subsequently, the gum was dehydrated through a drying process in a Felissa® brand oven, at a temperature of 100 °C, until reaching a constant weight. The dried gum was crushed and ground in an agate mortar until a fine homogeneous powder was obtained. Figure 3a shows the nopal gum extracted from the cladode, and Figure 3b shows its powder obtained after the drying process. The powdered gum was placed in an airtight container and then placed in a desiccator to prevent the absorption of moisture from the environment. For the identification of the functional groups present in the gum, an analysis of Fourier-Transform Infrared Spectroscopy (FTIR) was carried out in the Nicolet™ iS™ 10 equipment from Thermo Scientific, in the Laboratory of Environmental Sciences of the Faculty of Engineering of the Universidad Autónoma de San Luis Potosí (UASLP). Obtaining a completely dehydrated powdered gum allows you to accurately prepare solutions at different concentrations.

FIGURE 3a. Natural state of the gum of *Opuntia ficus indica*. 3b. Gum powder obtained after the drying process (Picture: Josué Israel Moreno Fraga, 2020).

The preparation of solutions was carried out through a process of hydrating the gum powder by dissolving it in water at a 90 °C temperature, maintaining constant stirring for six hours to ensure its complete dissolution (Figure 4), with which the nopal gum was rehydrated, guaranteeing the dissolution of the sugars in the aqueous medium and obtaining a solution with the characteristics and physicochemical properties of a fresh gum, in its natural state.

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FIGURE 4. Hydration process of *Opuntia ficus indica* nopal gum powder (Picture: Josué Israel Moreno Fraga, 2020).

Three solutions were prepared, with 6%, 9% and 12% by weight of nopal gum. The pH of each of them for the preparation of the soil specimens was determined with a Hanna® potentiometer calibrated with buffer solutions of pH 4 and 7, at a temperature of 25 °C.

Preparation of soil specimens

Cubic soil specimens—with dimensions of 5 × 5 × 5 cm—were made without and with additions of 1%, 1.5% and 2% of nopal gum, and 16.6 % of water with respect to the weight of the soil, according to the ASTM D698-12 (2021) Standard. The percentages of gum used are equivalent to 6%, 9% and 12% by weight with respect to the water content of the specimen without the addition of nopal gum, which will be taken as the reference specimen. Previously, the nopal gum was dissolved in the amount of water required for the mixture, at 90 °C, with constant stirring for six hours. After 24 hours, the specimens were demolded and went through a drying (curing) time of 28 days at room temperature.

Evaluation of physical properties of soil specimens

The weight loss during the drying process of the specimens with additions of nopal gum was evaluated by measuring differences in the weight of the specimens with respect to time until reaching a constant weight, carried out under laboratory conditions (ambient temperature of 25 °C and 50% relative humidity). The capillarity index of the soil specimens was determined in accordance with the UNE-EN-772-11 (2011) Standard; its compressive strength was

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determined after 28 days of drying (curing) in a Shimadzu UH-600 kNI (60 Tons) universal machine from the Construction Materials Laboratory of the Faculty of Engineering of the UASLP, at a speed of 1.5 kg/cm^2. The tests for the adobe specimens were carried out in triplicate, with different concentrations of gum.

The preparation and characterization of samples, as well as all the tests—except for those that have already been indicated in the text—were carried out in the Chemical Processes Laboratory of the Facultad del Hábitat of the UASLP.

RESEARCH FINDINGS

Below is a brief description of the results obtained, including a discussion of each of them.

Chemical composition of nopal gum

Figure 5 shows the FTIR spectrum of nopal gum, where the characteristic bands of the functional groups present can be seen: those located between 3 470 and 3 130 cm^{-1} correspond to the vibration of the hydroxyl groups (–OH), this vibrations are attributed to the hydrogen bond present in alcohols and carboxylic acid; the position at 2 929 cm^{-1} is attributed to stretching of –CH bonds; present in the pyranose and in the glycoside –$COCH_2$ (Gheribi et al., 2018, p. 208). The bands located at 1 730 cm^{-1} and 1 620 cm^{-1} are associated with the carbonyl group (C=O), and the band at 1 425 cm^{-1} is related to the symmetric vibration of the group (COO-), present in the gum structure, functional groups attributed to the presence of monosaccharides and acid residues. Finally, the bands between 900 and 1 200 cm^{-1} are attributed to the region known as *the polysaccharide footprint* (Razavi et al., 2014, p. 460).

The presence of these functional groups in nopal gum corroborates that its chemical composition is based mainly on sugars composed of monosaccharides—which may be very similar or equal to those reported in nopal mucilage—, such as galactose, arabinose, xylose, rhamnose of different structure (Figure 6), mentioned in the previous paragraph. It is important to mention that there is little information about the chemical composition of nopal gum. However, given its origin, it is very likely that its composition is very similar to that of nopal mucilage.

The pH of the aqueous phase of the soil specimens registered values of approximately 3.5, placing them at an acidic pH, that is, slightly more acidic than those found in previous works when using

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FIGURE 5. Infrared spectrum of *Opuntia ficus indica* nopal gum (Scheme: Juana María Miranda, 2021; courtesy of Laboratory of Environmental Sciences-Faculty of Engineering UASLP).

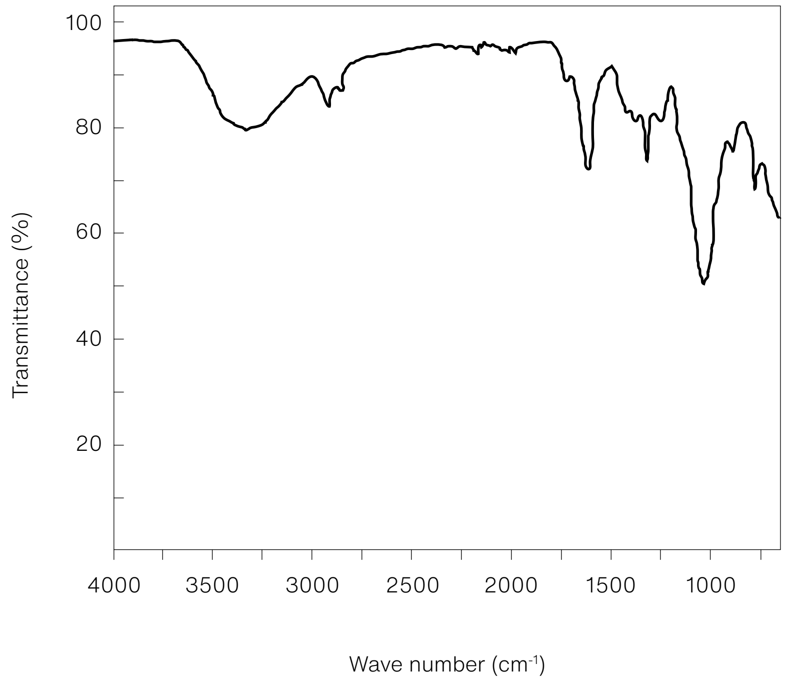
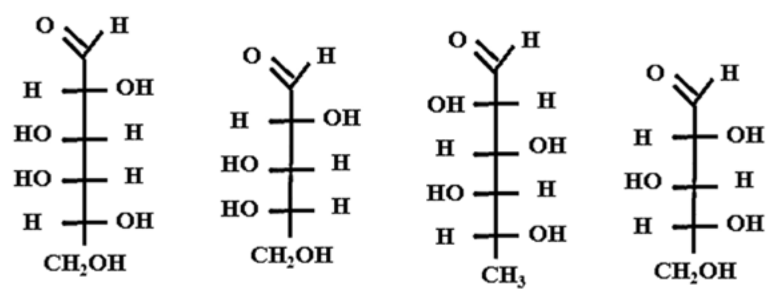


FIGURE 6. Structures of the monosaccharides present in the cactus gum Opuntia ficus indica (Scheme: Juana María Miranda, 2021; courtesy: Facultad del Hábitat UASLP).



nopal mucilage (Torres et al., 2015, p. 102). The acid character of the gums can present some small variations due to factors such as the degree of maturity of the nopal, soil conditions, the use of fertilizers, climate, humidity, etc. (Nazarene, 2013, p. 96).

Physical behavior of ground specimens

Figure 7 shows the weight loss during the drying process of the soil specimens without and with nopal gum. Note that, on the third day of drying, the moisture loss in the reference specimen is 9%, while the soil specimens with nopal gum lost approximately 6.5%. At six days, the gum soil specimens experienced a moisture loss between 8% and 10%. It is worth mentioning that the specimen

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that has a higher percentage of gum (2%) presents the lowest value of moisture loss, while the reference specimen showed a loss of 12%. After 10 days of the test, the gum specimens lose between 10% and 12% of humidity, while the reference specimen reaches a loss of 14.5%. These differences between the reference specimens and those with gum continue for up to 14 days, when the losses tend to be constant. This behavior can be attributed to the chemical composition of the gum, since, being a high molecular weight polymer, it creates internal gel networks in which water is retained and, therefore, its transport to the outside is reduced (Khachatoorian et al., 2003, p. 20). This slight moisture retention, favored by the nopal gum present in the specimens, slows down the drying process in the first few days, which could lead to less crack formation during this process. In addition, it increases the plasticity of the paste, facilitating the application in the form of layers during the processes of replacing missing parts, finishing the surface, adding fillers, etc.

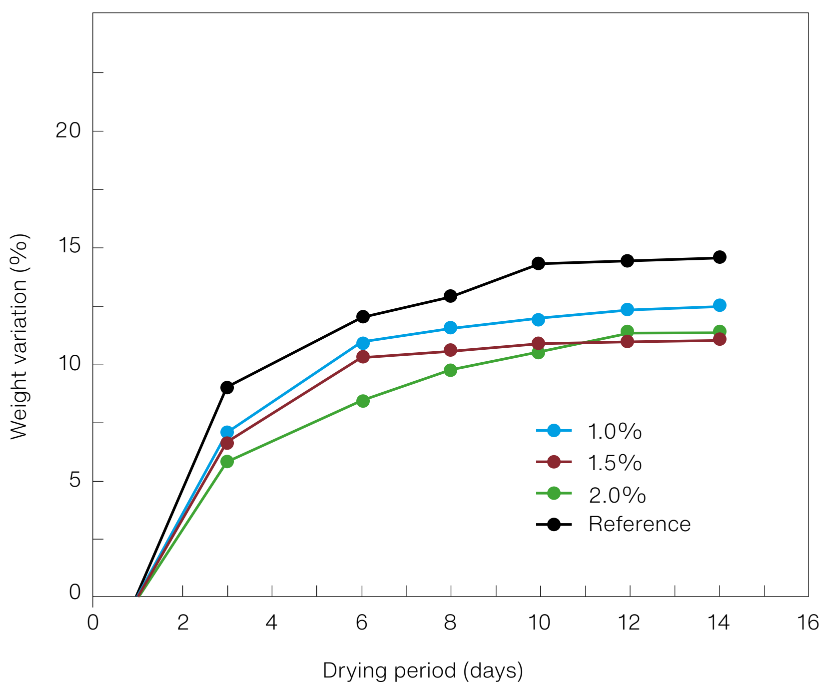

FIGURE 7. Weight variation of soil specimens with nopal gum at 1%, 1.5% and 2% by weight (Scheme: Lilia Narváez Hernández, 2021; courtesy: Facultad del Hábitat UASLP).

In Figure 8, with the capillarity indices obtained in the specimens without and with additions of gum, it is observed that the variations of these indices of the three specimens added with gum (1%, 1.5%, and 2% by weight) are less compared to the reference specimen. Although the difference is minimal, a slight decrease in the capillarity index is noticeable when gum content is higher.

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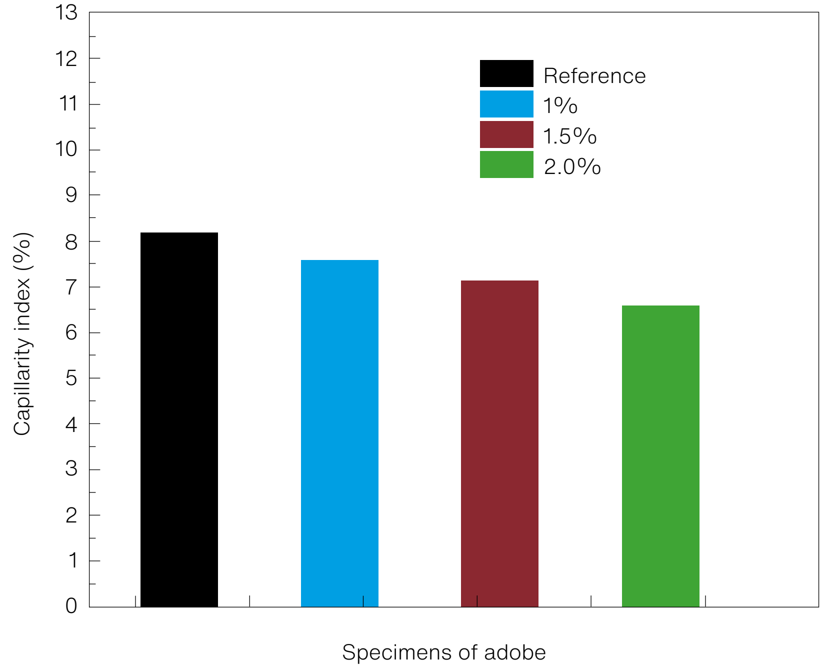

FIGURE 8. Capillarity index of soil specimens with and without nopal gum additions of 1%, 1.5% and 2% at 28 days of curing (Scheme: Lilia Narváez Hernández, 2021; courtesy: Facultad del Hábitat UASLP).

The hydrogels present in the soil specimens due to the presence of nopal gum exhibit a vitreous structure during the first seven days of drying and, therefore, provide the necessary resistance against the entry of moisture caused by capillary action, which generates a decrease in water absorption and, consequently, a reduction in the capillarity index (Muguda et al., 2017, p. 312).

Figure 9 shows the soil specimens with 2% nopal gum during the capillarity test. It can be observed that the degree of water absorption is very similar in the three specimens tested at this concentration, after being exposed to water for 10 minutes. It should be noted that the moist section of the specimen is intact and did not suffer soil losses during the test, which proves the effectiveness of nopal gum to maintain cohesion between soil particles when they are exposed to an aggressive wet environment (Lemboye et al., 2021, p. 2).

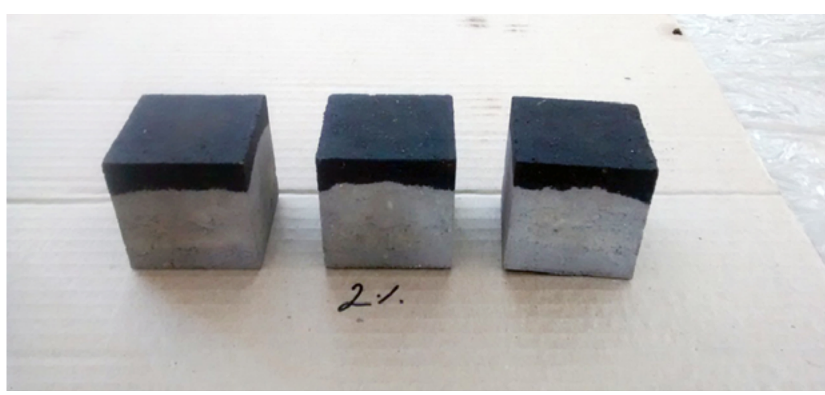

FIGURE 9. Surface appearance of soil specimens with 2% nopal gum after the capillarity test (Picture: Josué Israel Moreno Fraga, 2020).

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Figure 10 shows the results obtained from the compressive strength test of the specimens without and with additions of nopal gum after 28 days of drying (curing). An increase in compressive strength is observed as the nopal gum content increases with percentages of 12.5% with 1% gum, 20% with 1.5% gum and 25% with 2% gum, compared to the resistance of the reference specimen. As can be seen, the soil specimens added with 2% by weight of gum showed the highest compressive strength values, which indicates that the greater the amount of gum in the soil mixture, the mechanical properties are more favorable. The presence of the polysaccharides contained in the *Opuntia ficus* nopal gum in the soil mixtures induces adhesion between the soil particles, as previously mentioned in Figure 7. The slow decrease in moisture loss from soil specimens, in addition to supporting workability, causes slow drying, which prevents abrupt moisture loss and promotes adequate cohesion of the materials. Chang et al. (2016) mention that the presence of gums helps the agglomeration between the soil particles through an induced cohesion derived from the presence of the hydrogel, which varies with the humidity conditions of the mixture.

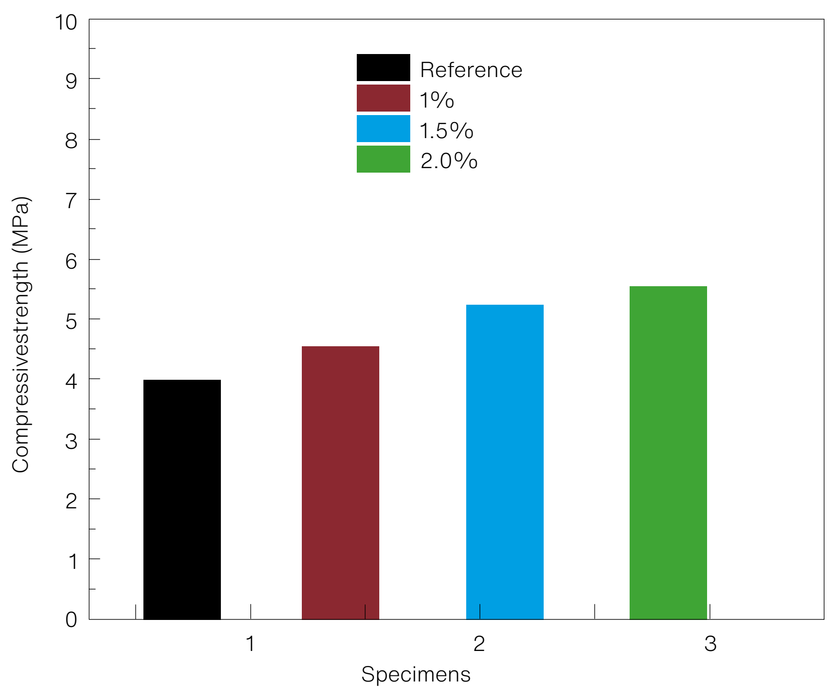

FIGURE 10. Compressive strength of soil specimens with and without nopal gum at 28 days of curing (Scheme: Lilia Narváez Hernández, 2021; courtesy: Facultad del Hábitat UASLP).

CONCLUSIONS OF THE CARRIED OUT STUDY

The process of obtaining and drying the nopal gum was efficient and adequate, since it was possible to obtain a dry powdered gum without modifying its physicochemical properties. This allowed the gum to be preserved and facilitated its use as an additive for long

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periods (six months). In addition, the powdered gum rehydration process was viable and effective for its use in the solution.

The chemical composition of the nopal gum based on the FTIR analysis allowed the establishment of the presence of functional groups belonging to the monosaccharides, which form the chains of the biopolymers present in the nopal gum, to which the physicochemical characteristics of nopal are attributed. Although the functional groups are very similar to those present in nopal mucilage, it is required to use other types of analytical techniques, such as chromatography, nuclear magnetic resonance, and mass spectrometry, which allow specifying the type of saccharides present. There are reports of chemical analyzes regarding mucilage and nopal slime, yet there is still no information on nopal gum (pathological product generated by the “borer weevil”).

The effect of nopal gum on soil specimens favored slower drying; the higher the gum content in the samples, the longer the moisture is retained. This phenomenon is favorable, since it promotes less cracking in the soil specimen, greater cohesion between the soil particles, and a better surface appearance.

The presence of nopal gum in the soil samples showed a decrease in the capillarity index; at higher gum content, the lower the capillarity index and, therefore, there is a lower moisture absorption of the samples studied. The presence of the gum led, as the percentage of gum increased, to less disintegration of the soil particles during the test.

The compressive strength tests of the soil specimens with nopal gum also showed a better performance; as the nopal gum increases in the specimen, the compressive strength is higher.

The different experimental analyzes carried out in the laboratory show that nopal gum is a material mainly based on polysaccharides, with the ability to bind and consolidate the soil present in the specimens without altering its physical appearance and pH. while also giving them firmness and solidity, which directly affects their mechanical physical behavior.

Nopal gum has the following characteristics: good penetration into soil specimens, non-toxicity, simple handling, environmental friendliness, with no formation of superficial plastic films and no crystallization. It also has good reversibility, since, if it is required to be removed or eliminated, it dissolves easily at temperatures above 90 °C. Such characteristics make this material a viable option to be used as a consolidating additive in adobe construction systems.

Future research could focus on carrying out studies on the shelf life of dehydrated and pulverized gum, as well as on evaluating

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both the influence of nopal gum on the dimensional changes of soil specimens and their mechanical behavior, using higher concentrations of nopal gum and longer curing times.

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