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Application of Natural Organic Additives in Cement-Based Mixtures: State of the Art

Aplicación de Aditivos Orgánicos Naturales en Mezclas Base Cemento: Estado del Arte

Diaz-Flota, O.S.[a], Yeladaqui-Tello, A.[a], Jiménez, L.F.[a], Vega-Azamar, R.E.[a], Cruz, J.C.[a]. Gurrola, M.P.[b*]
[a] Tecnológico Nacional de México/ Instituto Tecnológico de Chetumal, Chetumal 77013, México.
[b] CONACYT-Tecnológico Nacional de México/ Instituto Tecnológico de Chetumal, Chetumal 77013, México.
m19390726@chetumal.tecnm.mx; alberto.yt@chetumal.tecnm.mx; luis.jt@chetumal.tecnm.mx, ricardo.va@chetumal.tecnm.mx; * mayra.pg@chetumal.tecnm.mx

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Resumen

En la industria de la construcción, y particularmente en las mezclas a base de cemento como el concreto, se han implementado un sinfín de materiales alternativos con el propósito de mejorar las propiedades físicas, mecánicas y químicas. Los materiales conocidos como biopolímeros, como la celulosa, se implementan en las mezclas de concreto. Asimismo, se utilizan materiales orgánicos (MOs) derivados de residuos naturales como aserrín, fibras de celulosa, plantas de cactus, aceites, mucílagos, semillas, etc., debido a su estructura y a la disposición de sus componentes. Específicamente, el uso de MOs, así como las especies de cactáceas, se han ganado su lugar en el área de la construcción, siendo el nopal la especie más estudiada, el cual ha mostrado resultados favorables en términos de propiedades físicas, mecánicas y de durabilidad cuando se aplica a las mezclas de morteros y concretos. En cuanto a las cactáceas, esta revisión proporciona una descripción de la variedad de especies en cuanto a su uso en mezclas a base de cemento, así como de las estrategias de evaluación en función de las propiedades físicas, mecánicas y de durabilidad. Para ello, en primer lugar, se explican las ventajas y desventajas que presentan las diferentes especies de cactáceas implementadas en las mezclas a base de cemento. Luego, se presentan estudios recientes acerca de los métodos de extracción de las cactáceas para su correcta implementación dentro de dichas mezclas. También, se analizan sus propiedades físico-químicas y la forma en las que éstas influyen dentro de la matriz cementante. Los resultados de los trabajos de investigación revisados han demostrado que la aplicación de las cactáceas favorece a la mejora de la permeabilidad de la mezcla, aumenta la resistencia a la compresión y mejora la capacidad frente a la presencia de agentes externos como los iones cloruros y la carbonatación.

Palabras clave: Mezclas de concreto base cemento, Cactáceas, Concretos, Aditivo Orgánico.

Abstract

In the construction industry, and particularly in cement-based mixtures such as concrete, an endless number of alternative materials have been implemented with the purpose of improving the physical, mechanical and chemical properties. Materials known as biopolymers, such as cellulose, are implemented in concrete mixtures. Likewise, organic materials (OMs) derived from natural waste such as sawdust, cellulose fibers, cactus plants, oils, mucilage, seeds, etc. are used, due to their structure and the arrangement of their components. Specifically, the use of OMs, as well as cactus species, have earned their place in the construction field, with nopal being the most studied species, which has shown favorable results in terms of physical, mechanical, and durability properties, when applied to mixtures of mortars and concretes. Regarding cacti, this review provides a description of the variety of species in terms of their use in cement-based mixtures, as well as evaluation strategies based on physical, mechanical, and durability properties. In order to do this, firstly, the advantages and disadvantages of the different cacti species implemented in cement-based mixtures are explained. Then, recent studies are presented about the extraction methods of cacti for their correct implementation in cement-based mixtures. Also, their physical-chemical properties and the way in which they influence the cementitious matrix are analyzed. The results of the reviewed research works have shown that the application of cacti favors the improvement of the mixture permeability, increases compressive strength and improves the capacity against the presence of external agents such as chloride ions and carbonation.

Keywords: Cement-based concrete mixtures, Cacti, Concretes, Mortars, Organic Additive.

1. Introduction

Since the beginning of the 20th century, the use of cement has increased to the point of becoming one of the most important sectors for the economy of all countries in the world. Cement production has existed since Roman times and Portland cement was patented in 1824 (1). Over the years it has evolved, with the implementation of new technologies to meet the demands of the concrete industry, driving and developing special concretes in which mineral admixtures are used (2). Most of the infrastructure of the countries is made of this material, so it is of great importance to know its manufacturing process. Poor construction practices often lead to poor concrete properties, and when problems occur in concrete structures, most of them function improperly, limiting their useful life (3). In the construction industry, and more specifically in the case of concrete mixtures, a number of alternative materials are used to improve physical, mechanical and chemical properties. Materials known as biopolymers, such as cellulose, are used in concrete mixtures. In the same way, organic materials (OMs) derived from natural waste such as sawdust, cellulose fibers, cacti plants, oils, mucilage, seeds and others, are also applied due to their structure and component arrangements (4). Most of these materials contain proteins (2), such as keratin, casein and proteins from animal blood, milk and eggs, which act as additives and hydrophobic agents, or sometimes as air entraining agents, presenting small bubbles, which act as a lubricant within the cementitious matrix and, mainly, improving physical properties, such as permeability, consistency and workability of the mixtures (5–7).

In the past, several studies have been conducted on the use of OMs in concrete mixtures. Authors such as Chandra *et al*. (8) used different types of proteins (flour gluten, milk protein and purine protein E) with ratios of 0.45 to 0.46, evaluating properties such as flexural and compressive strength and water absorption. The mixes showed an improvement in the adhesion between the paste and the aggregate, but compressive strength was affected, due to the entrainment of air from the proteins in the mixture, affecting the pore structure. Contrary to compressive strength, the mixture presented a lower water absorption capacity, thus improving its hydrophobic properties. Boltryk *et al.* (9) modified the cement mixture with an organic filler, made up of sawdust and cane, reducing water absorption by approximately 60%. Similarly, the addition of a superplasticizer and a waterproof material improved physical and mechanical properties. Along with the microstructural development, the adhesion between the organic filler and the paste was improved, due to the organic material occupied the spaces left by the hydration process, which also brought better results in the density of the mixture, serving as an insulating (environmentally friendly) material. In the same way, Udoeyo *et al.* (10) conducted experiments to study flexural and compressive strength of concretes when adding sawdust and wood chip ash in percentages of 5, 10, 15, 20, 25 and 30% by weight of cement; they also analyzed the chemical composition and found compounds that classify it as a pozzolanic material. Properties such as water absorption were affected as the percentage of ash increased, although none exceeded the standard limit (10%). In general, compressive strength increases along with curing time, but decreases with the increase of ash content, because ash acts more as a filler in the cementitious matrix than as a binder. Likewise, Abdulrahman *et al*. (11) studied corrosion on a reinforced concrete element, by adding Indian bamboo extract (*Bambusa arundinacea*) and evaluated its performance against corrosion using electrochemical techniques such as EIS (electromechanical impedance spectroscopy) and LPR (linear polarization resistance). Results showed that the addition of Indian bamboo acted as a corrosion inhibitor in the presence of chlorides, due to the high potassium content of bamboo, which maintains the passivity of the steel in the concrete mixture. On the other hand, Hernández-Carrillo *et al.* (12) evaluated the hydration and microstructural characteristics of nopal mucilage for addition to concrete mixes, using TGA (thermogravimetric analysis), SEM (scanning electron microscopy) and EDS (energy dispersive X-ray spectrometry). This research work showed that, in the event of a water loss higher than 95% by weight, nopal has the capacity to retain 5% of it in microstructural deposits, related to the presence of polysaccharides, proteins and some minerals, which is important in the hydration phase of concrete mixtures. Based on the above, it has been shown that the use of OMs as additives, mainly known as natural organic additives (NOAs), which are locally available in many places and at affordable prices, in concrete mixtures improve their properties (13).

The use of these OMs, such as cacti (of which there are more than 2000 species), have gained ground in the construction field and, as it has already been mentioned, the most studied one is nopal, which has presented favorable results in terms of physical, mechanical and durability properties when applied to mortar and concrete mixtures, since the implementation of some mineral additions based on materials such as fly ash, blast furnace slag and others, may be unfeasible due to transport costs. In this way, cacti species have been implemented in the construction industry, resulting in a wide variety of species under study (14).

2. Cacti plants in the construction industry

2.1. Origin and classification

The cacti family, belonging to the American continent, are considered young species in the field of plant evolution (15). They are called American plants, since it is difficult to find them anywhere other than the American continent in a wild or natural way except for some species that are found in Africa, Madagascar and elsewhere (16). Taxonomies of this family are often collected with commercial purposes, for distribution to European collectors, the United States or Japan, and are found under different names, causing confusion when identifying them. This is important, as an object of study, because in order to interpret the taxonomy (17), there is no exact number of genera included in this family (more than 2000 species have been found and one more group has not yet been included) (18).

The cacti group is considered a plant group, since it shares common characteristics of organisms with a taxonomic and nomenclatural complexity, process of vegetative reproduction and hybridization, they also present characteristics of succulence, spiny leaves and the appearance of areolas, but there are obstacles to determine the geographical distribution due to lack of information from the countries (19). Mexico is a country with abundant richness of this genus with 913 taxa, 80 percent of which are endemic, most of them are found in arid regions, for instance, the Mixtec Mountains and the deserts in Sonora and Chihuahua, but also the rainforests help Mexico to be the country with the greatest variety and richness in the world, making it a place with potential for the use and application of this genus of cacti (20,21). In general, the classification of these plants is affected by factors such as geographic location, topography, and climate. Likewise, this classification underwent changes, due to the diversity of anatomical characteristics selected by cactus specialists, giving rise to the scientific and philosophical concepts prevailing at the time, motivated by the need to introduce the species that were discovered into these systems. These classifications were initially Linnaean, later phylogenetic, and now biological. The complexity for the correct classification of the cacti family is due to each family is a taxon and each species is also a taxon so that the same species will have different names according to the criteria of each researcher (22). For example, Bravo-Hollis (23) annexes a taxonomic summary of the genera of cacti, according to Franz Buxbaum, recognizing a total of 3 subfamilies of cacti: *Pereskioideae*, *Opuntioideae* and *Cactoideae.* Similarly, Anderson (16,24), in collaboration with the International Cactaceae Systematics Group, recognized 4 subfamilies: *Pereskioideae*, *Maihuenioideae*, *Opuntioideae*, and *Cactoideae* divided into 9 tribes.

The diversity of subfamilies included in the cactaceae family is remarkable, so their implementation in different areas, such as construction, medicine, as a source of human food or as raw material, have been of great importance, as shown in Fig. 1. Also, in other circumstances, these species often have a divine meaning, and are used in religious rites and ceremonies of some ethnic groups

(23,25). Plants and their component parts are used in different ways: ornamentally and as protective barriers (Fig. 1a-c), some of them are even industrialized. Another important application field is the construction industry due to their characteristics and properties, as mentioned below.

Figure 1. a) Flower of cactus, Pelecyphora aselliformis, b) Cylindropuntia, and c) Fruits and pieces of tender stems, nopals, prickly pears and garambullo in a Mexican market (based on 26,27).

2.2. Use in construction

The application of cacti in the field of construction is due to their chemical composition (moisture, mineral salts, carbohydrates, starch, cellulose, pectic acid and mucilage) and their great capacity to store water for long periods of time in the stems, mainly known as succulence (23). These characteristics are found in the genus *Opuntioideae*, which is why it has been widely used in the construction industry. Their use comes from colonial times, when they built with lime mortars, adding different local OMs (28), probably, they were also used to improve adobe walls in the past (13,29). The choice of this genre of research interest in the application of nopal in paints and lime plaster improved hydrophobicity due to binding and anticorrosive properties. The application of this type of NOAs in cement-based mixtures improves mechanical resistance, reduces water absorption and porosity and increases the durability of the structure (30–32).

In accordance to these characteristics, Cárdenas *et al.* (33) used the *Opuntia ficus indica* species, specifically, the one known as nopal; they extracted the mucilage and added it as an organic adhesive in the mortar mixture, improving its hydration capacity, which protects the building from a cold and humid environment, water and insects, generating the formation of a gel network. The extract of this organic OM was added to cementitious mixtures, preventing them from accelerating their hydration process, conserving part of the moisture that the mixture needs to set correctly (34). The improvement of properties in cementitious mixtures is due to the composition of nopal mucilage, made up of polysaccharides (35) and composed of: L-arabinose, D-galactose, L-rhamnose, D-Xylose and galacturonic acid (36); when these components come into contact with water and cement, they react favorably, showing improvements in the curing stages, causing the particles to store large amounts of water, connecting the network of interlocked pores and acting as an additive for the good hydration of the mixture.

Likewise, Torres-Acosta *et al.* (14) evaluated the effect of nopal and aloe vera additions, in dehydrated form, in cement and mortar mixtures, in percentages of 1, 2 and 4%. Regarding nopal, the authors explain that the addition showed a good behavior for water absorption, apparently the pores were occupied by a gel that obstructed the filtration of water to deeper spaces, as shown in Fig. 2. Electrical resistivity of the mixture was greater (it became a little denser, so that it showed less conductivity spaces) and compressive strength increased. The authors state that these effects occur at late ages, and with addition percentages no greater than 2%, due to the constant hydration that occurs in the mixture. Contrary to nopal, aloe vera showed poorer results for the studied properties. Table 2, shows the way the authors assessed the mixtures, as well as the quality control criteria, according to the DURAR Network Manual (37).

Table 1. Behavior of specimens in the tests (30).

Test/specimen	Resistivity	VPU	Compressive strength	Porosity
C0	Excelent	Good	Good	Good
CN1	Excelent	Excelent	Excelent	Good
CN2	Excelent	Excelent	Excelent	Good
CN4	Regular	Good	Good	Regular
CS1	Regular	Bad	Regular	Bad
CS2	Regular	Bad	Bad	Bad
CS4	Regular	Bad	Bad	Bad

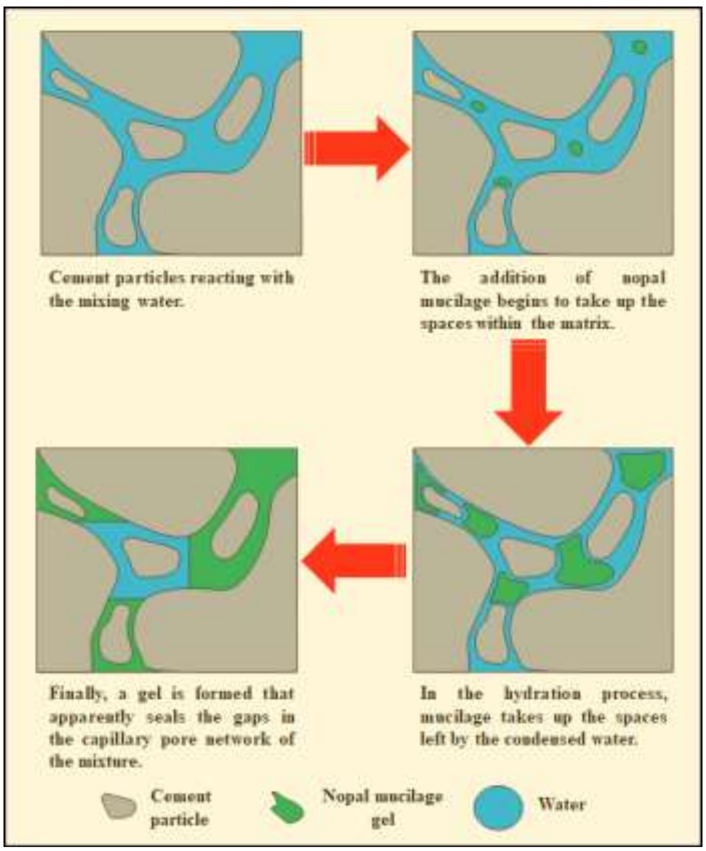

Figure 2. Gel formation in the cementitious matrix (14).

On the other hand, Caballero (38), studied the properties of capillary water absorption, moisture loss by drying, and the diffusion coefficient of the chloride ion when replacing water by a nopal mucilage solution, in order to know the impact of chlorides on the mixture. Three W/C ratios were used: 0.30, 0.45 and 0.60; the nopal mucilage was treated by flaking, maceration and filtration. The mixtures were tested at 28, 56 and 120 days to obtain the response variable, in this case, chlorides and water absorption. Results showed a beneficial effect of nopal mucilage in reducing moisture loss, which is reflected in a higher hydration, a denser mix and, therefore, a reduction in permeability, capillary absorption, porosity and chloride diffusion. Similarly, Azizi *et al.* (39) studied the effect of OFI (*Opuntia ficus-indica*) leaves on the mechanical and durability properties of mortar mixtures, with substitution percentages (in powder) of 1, 2.5 and 4% by weight of cement, with a W/C of 0.5 and a 1:3 ratio for the mortar. Through XRD (X-ray diffraction) analysis, they observed the presence of polysaccharides (40), usually pectin and lignocellulosic material. Results of these experiments showed an improvement in compressive strength for 1 and 2.5% substitution, when compared to the control sample. However, this was negatively affected for percentages greater than 4% of cement substitution. Overall, this improvement could be attributed to the formation of a denser matrix, keeping the mixture in prolonged hydration, due to the encapsulation of water within it, and interacting with the organic matter components, improving as time progressed. In terms of durability, they evaluated the resistance to acid attack (acetic and hydrochloric) and, as for compressive strength, the mixtures with the addition of OFI showed better resistance to acid attack, attributing this to the presence of calcium (Ca) of the organic material, forming a seal in the porous network of the mortar, preventing the movement of water particles and improving permeability.

As it can be appreciated, research on these OMs in cement-based mixtures, is based on the possibility of producing materials that provide similar or better characteristics to those of a regular mixture, without losing essential properties and helping to optimize construction processes. Most of these research works have implemented the OFI genre (Figure 3), as it is found and used as a medicinal element and as a food crop in more than 30 countries, with these species having a great social impact, by providing greater profitability and added value, implementing those that are not used for consumption in an industrialized way (41,42).

Figure 3. Opuntia ficus-indica with details of the flower.

3. Cement-based mixtures with cactus (CMC)

The collection of this organic material can take three forms: from the wild, home gardens and commercially: mostly, from stables or cactus forage gardens, as it is one of the main sources of feed for livestock, and sometimes the source of organic material comes from local ranches.

3.1. Cactus extraction

The way to extract this OM, for its application in the field of construction, influences its chemical and physical characteristics, so the extraction procedure will invariably affect the properties of the mixtures (43). In the literature, two ways can be found for the extraction and use of cactus. The first one is water-based, from the stems or leaves of the nopal, which produces a viscous material with properties compatible with cement, known as mucilage, using basic techniques, such as maceration and filtering of the cactus (Fig. 4), sometimes taken to the point of cooking (Fig. 4d) to obtain the extract. The second one, in the form of powder or fibers, either commercially or manually, the latter, following a process of washing, dehydration and grinding (44).

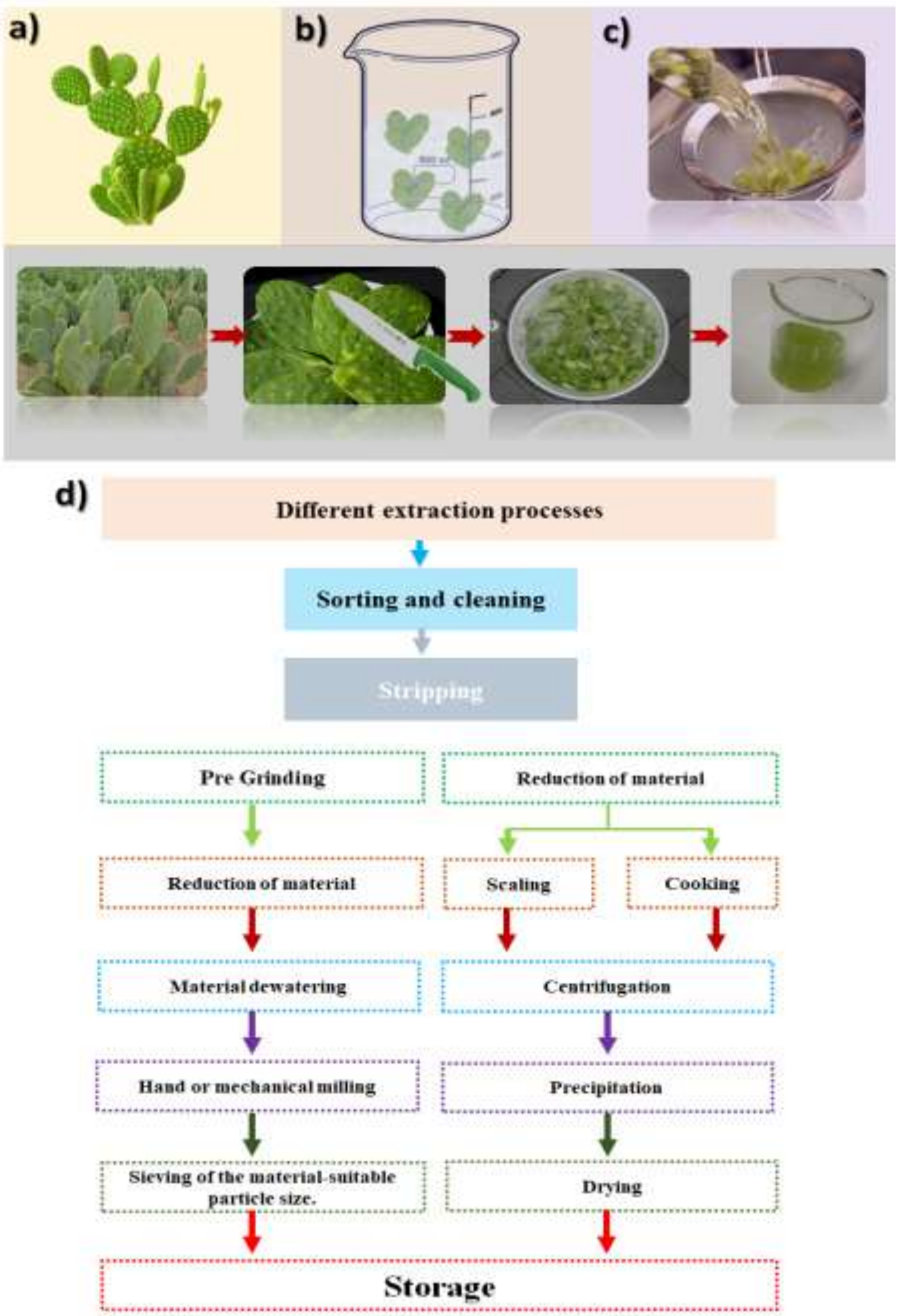

Figure 4. a) Fresh cactus leaves, b) Nopal mixed with water, c) Nopal mucilage filtration process, d) Nopal mucilage extraction process and d) Diagram of the different types of extraction process (44).

The extraction methods presented above are carried out according to the type of material and the way it was collected. Fig. 4d, summarizes the different extraction processes. The aqueous and dehydrated form were studied according to the improvement capacity of the addition in the mortar or concrete mixtures. The application of these methods is influenced by the scope of each research work, since, for the case of mucilage extraction methods, the process is simple, making them the easiest methods to apply. In the case of dehydrated form, the process can be more time consuming and variables such as temperature, particle size and storage can influence the properties of the mixtures such as the curing process, hydration and strength. These properties are discussed below.

3.2. Effects of cacti on the curing of CMC

It is well known that, that the moisture must be present inside the mixes while the curing phenomenon takes place, which contributes to improve the properties of the mixes. Therefore, curing affects the quality of the mix, whether it is modified with some kind of additive or supplementary material.

The inclusion of nopal in mortar mixtures acts as a setting retardant. Also, the addition of nopal improves the workability of the mixture in mortars, improving this property for percentages of 50 and 100% replacement of the mixing water by mucilage in aqueous form, due to the polysaccharides provided by the leaves, the storage of water and the slowing of the curing process (13), as shown in Fig. 5b, which helps to reduce cracks, and improve compressive strength and durability. The addition of mucilage, at low water/mucilage ratios, acts as a setting accelerator in concrete mixtures, but at proportions above 0.45, it acts as a retardant, increasing the curing time. In this sense, it is possible to note that the addition of nopal, in aqueous form, increases the setting time of the mixtures when the amount of the extract is greater, possibly due to the content of proteins that help retain moisture within the cementing matrix, which could act as a blocker of water evaporation, which in turn keeps the mixture hydrated (42,45,46). On the other hand, in the dehydrated form, it is possible to note that, due to the partial replacement of cement, the extract acts as an accelerator in the setting time (Fig. 5a), as a result of the presence of pectin, forming a gel network, which reacts with calcium ions (Ca^{2+}) (18,31,46). This is linked to the workability of the mixture, depending on the increase of consistency or fluidity. In research works in which dehydrated nopal powder is substituted by 1, 2 and 4% by weight of cement, the setting time accelerates when compared to the reference specimens, which affects the performance of the final properties of the mixtures. As the percentage of the cactus extract increases, so do the setting times (47).

The interaction of the cactus with the mixture components generates microstructural changes, due to the way it is stored within the mixture, promoting, as already mentioned, fast or slow curing processes. Therefore, the study of the processes that occur at the microstructural level is useful to fully understand the role of the implementation of NOAs within the mixture, a topic that will be addressed in the next section.

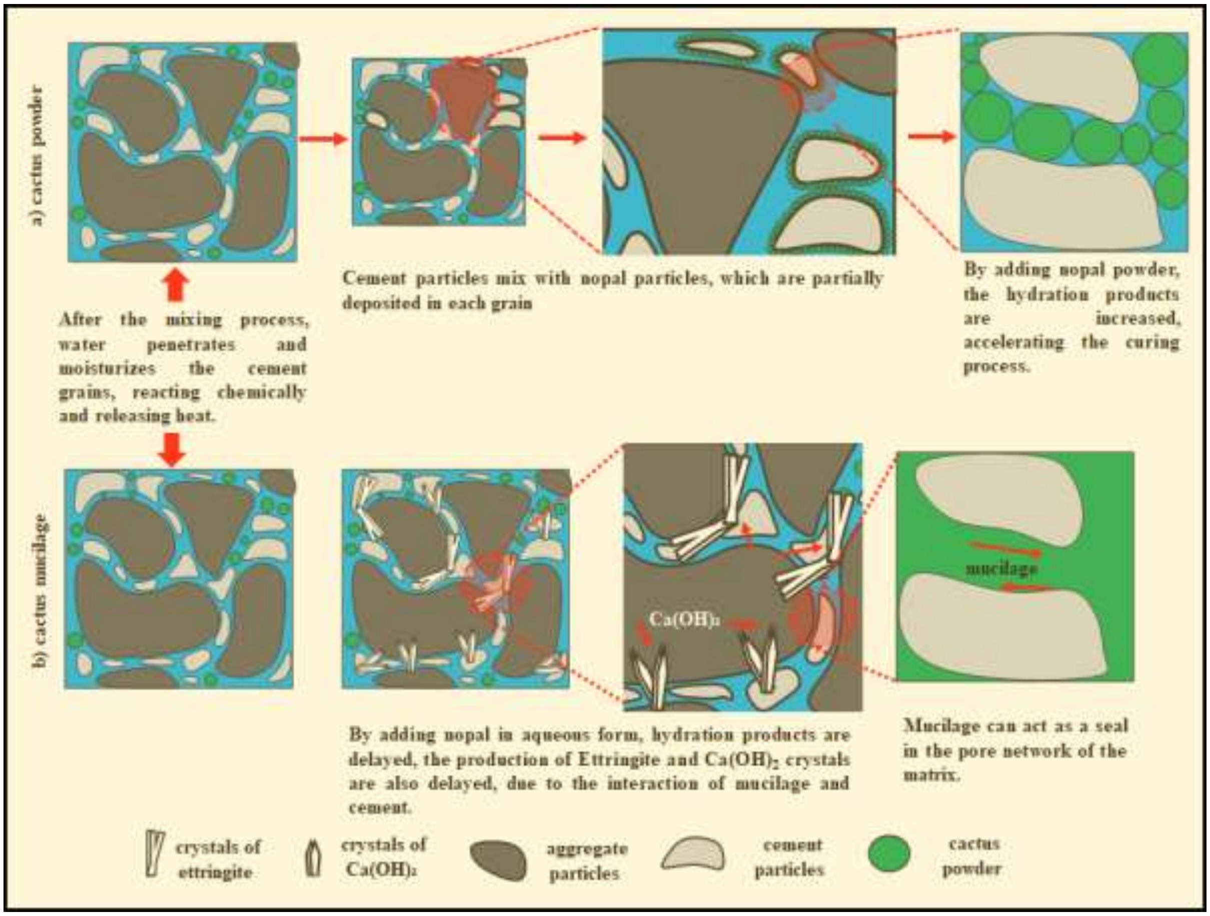

Figure 5. Hydration process of the mixture with a) addition of nopal powder and b) nopal mucilage.

3.3 Microstructure of the CMC

Testing techniques are important complements for the correct interpretation of the results of the different properties in cement-based mixtures. Techniques such as Infrared Spectroscopy (IRS), allow to know the fingerprints through the spectra they show (presented in an intensified way), which reveals the crystallinity of the hydration elements, the reactions and the phases within it (48). Likewise, the SEM technique is of great importance to analyze changes and morphology in the surface of the materials and XRD allows to identify the structure of the materials.

Considering this, compressive strength, and other important properties of cement-based mixtures, is originated mainly in the processes that take place in the matrix, during the hydration process (49). Therefore, the knowledge of the mechanisms that take place in the CMC are of great importance. Based on this, studies have been carried out to understand, in the first instance, the chemical characteristics of the cactus and the way in which it interacts with cement. Specifically, an important reason for the use of cactus is the hydrophobic characteristic, caused by the presence of polysaccharides that, possibly, prevent water evaporation, retaining it longer, storing 80% more water, carbohydrates and protein (50). This is evident in IRS studies, where the presence of amide and amine peaks related to polysaccharides can be observed for this species; they are responsible for the fact that this species can remain for long periods without presenting changes, even in alkaline environments. Similarly, there are components such as oxygen and carbon, which constitute 85% of the total, and other elements such as iron, potassium, calcium and sulfur, in low amounts, which help the water retention process in the nopal plant (12,51,52).

Several authors have studied the microstructure of mixtures with this type of organic material using SEM, one of the main methods that helps to understand the interaction of organic materials with the cement paste. These studies have shown that the incorporation of nopal in aqueous form reduces the production of calcium hydroxide crystals, which increases the hydration time and decreases the appearance of cracks in the mixtures, since it is denser, being described as an "open cell" morphology that allows water storage at the cellular level (12,14,43). This agrees with the results of studies that applied the XRD technique, which analyzed mixtures at different ages, showing the hydration process in diffractograms for different phases, with the presence of dicalcium (C_2S) and tricalcium (C_3S) silicate; it was observed that, the higher the W/C ratio, the higher tobermorite gel products (CHS) are formed, contrary to the mucilage/cement (M/C) ratio, the CHS formation occurs slowly at ages prior to 28 days, therefore, the development of the properties is affected at later ages and during curing, from which it can be inferred that the mucilage has effects on the cement hydration and consequently on the mechanical properties (34,49).

3.4. Mechanical properties

One of the main issues when evaluating mortar and concrete mixtures is the physical and mechanical properties in the hardened state. Compressive and flexural strength allow the quality of the mix to be assessed when exposed to a series of loads or mechanical stress and are related to the ability to undergo elastic changes.

3.4.1. Compressive strength

This property depends on the adhesion of the paste and aggregates, the aggregates strength and, to some extent, on the way they interact with the cement paste. In Figure 6, different results collected from the published literature are shown, in which, compressive strength is presented as a function of different substitution percentages of nopal mucilage. It is possible to observe that, at early stages, the samples with nopal mucilage do not improve the compressive strength value when compared to the standard sample at 0 days (16.8 MPa for the reference mixture, and 15.7 and 14.9 MPa for the samples with 50 and 100% of mucilage, respectively). On the contrary, at day 90 of curing, when the samples of mucilage presented values of 54.3 and 57.4 MPa, they exceed the reference sample (51.2 MPa), as shown in Fig.6a (12,33). On the other hand, the addition of nopal mucilage presented favorable changes only for the M/C ratio of 0.30 at all ages (Fig. 6b); while, for the M/C ratios of 0.45 and 0.60, compressive strength was higher, due to the high porosity (Fig. 6c), since this OM has the ability to store water at the cellular level (49,53).

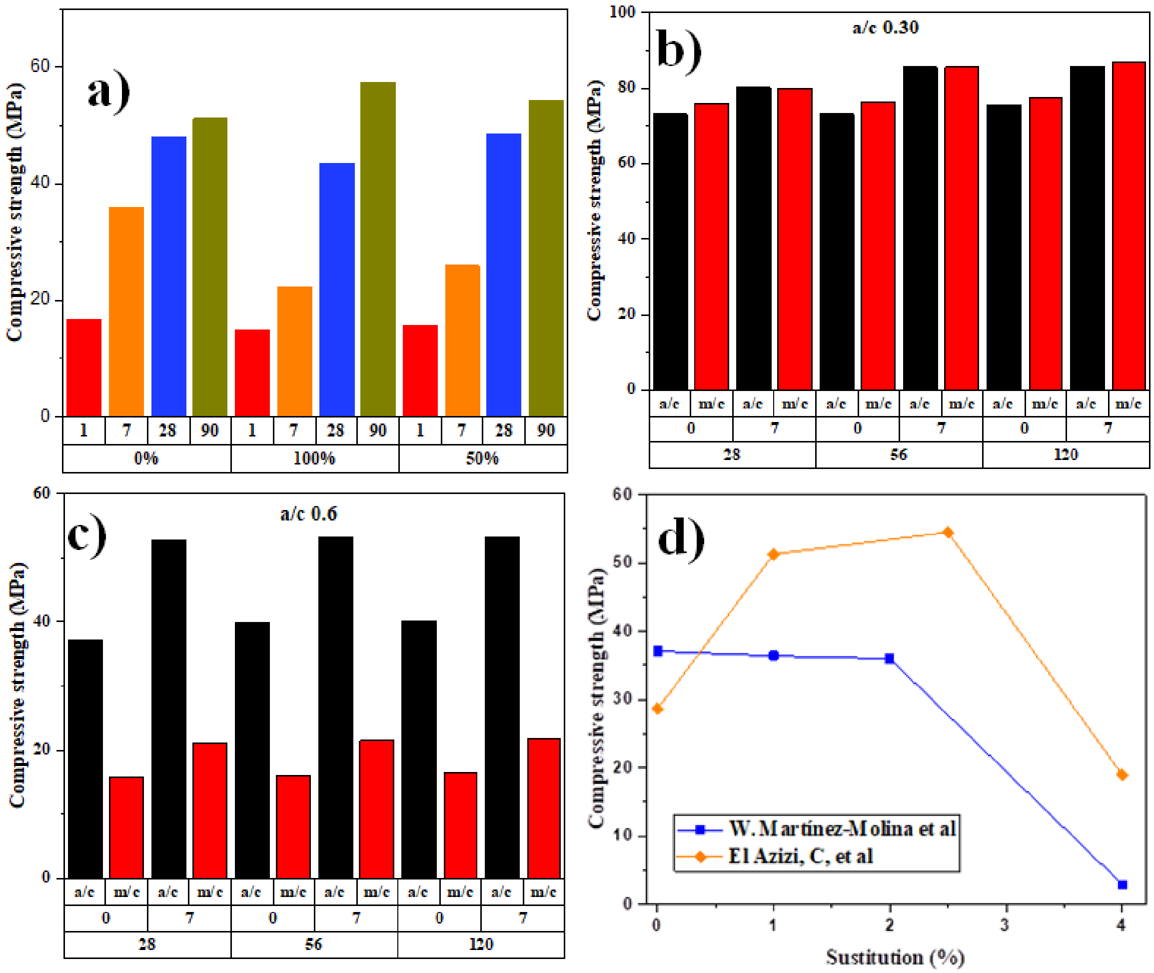

Figure 6. Compressive strength of mixtures a) with 50% and 100% substitution of mixing water, b) with W/C of 0.3 at 0 and 7 days of curing, c) with W/C of 0.6 at 0 and 7 days of curing (12,49), and d) compressive strength with different percentages of substitution (41,46).

In the dehydrated form, replacement percentages of 0.5, 1 and 2%, by weight of cement, have also been implemented with a varied W/C ratio, due to the consistency of the mixture, in periods of 30, 90, 180 and 900 days, as it has been inferred that this material remains in constant hydration over time (46). From this perspective, the effect that the addition of nopal powder has on the mixtures is different. Since workability of the mixtures decreases, a greater water volume is required to reach the necessary consistency, increasing the W/C ratio, so the mechanical properties are also affected by increasing the percentage of substitution, as represented in Fig. 6d, since a larger volume of nopal absorbs a larger amount of water, causing the mixtures to hydrate faster due to the presence of pectin, a soluble polymer that interacts with C_3S products and decreases the Ca volume, accelerating their hydration. The effect of aloe vera powder has also been evaluated, but has not shown remarkable improvements, due to its high absorption (41,45).

Other authors have also applied nopal mucilage in exudate, cooked and powdered form, with substitution percentages of 4, 8, 15 and 30 for exudate and cooked extracts and 1, 2 and 4% for the powdered addition, in periods of 30, 90, 180 and 900 days. The authors reported that all the mixtures exceeded the control samples, except for the dehydrated samples in percentages of 2 and 4%, which did not reach the design value, even after 400 days of study. In the case of the exudate mucilage, the values were similar to the control mixture. Results show that the addition of this material significantly improves compressive strength if the nopal ratio is not greater than 2% for the powder, while for the aqueous form, the values are similar to those of control specimens. Other mechanical properties were also studied, so, given the results presented in this section, it is expected that flexural and tensile strength will present values related to this significant improvement in compressive strength (13).

3.4.2. Bending strength, tensile strength and modulus of elasticity

There is little research on these properties; however, it is possible to state that flexural strength is affected by NOAs. Research works have explored the use of nopal fibers in specific weights of 5, 10 and 15 kg/m^3 replacing the same volume of aggregates to evaluate mechanical properties. For the case of flexural strength, it was tested at 28 days, showing improvements of 135% and 156%, when compared to the reference value (approximately 1.5 MPa). This value was influenced by fiber length (3 cm and 5 cm); this helped to improve the adhesion of the mixture, when testing, it was observed that they remained anchored due to the inclusion of the fiber, as exemplified in Fig. 7 (51). For the cases in which flexural strength was studied with the addition of mucilage in aqueous form, this property increased as the percentage of mucilage was higher, which is also reflected in tensile strength, after 90 days (45).

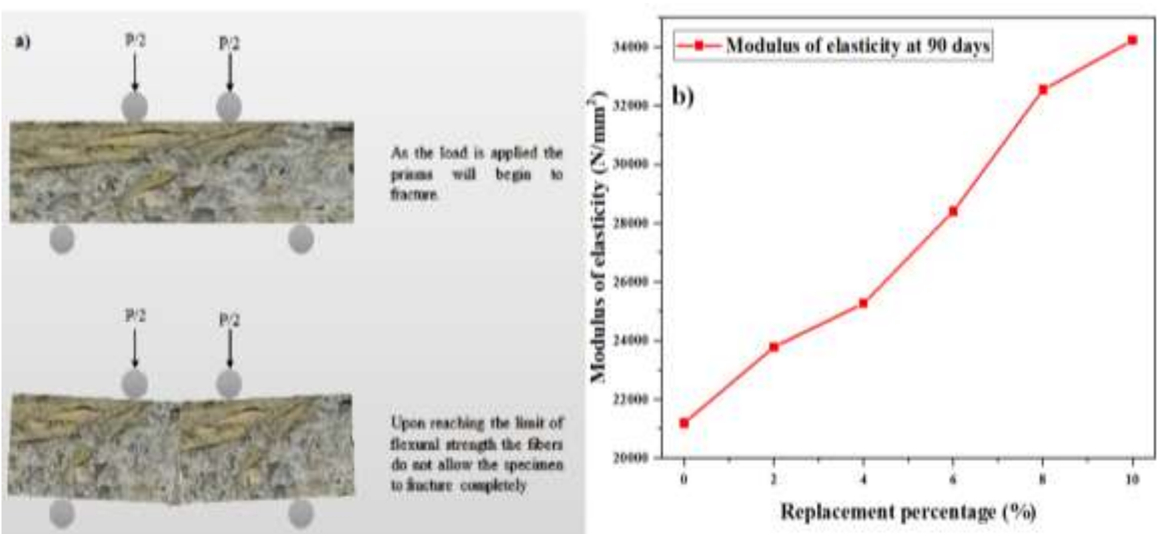

Figure 7. a) Specimen after the breakup (51) and b) Concrete elasticity module at 90 days with different percentages of mixing water replacement (45).

Specific studies were found on the behavior of the modulus of elasticity in cement-based mixtures. This property is linked to compressive strength and the way the organic addition interacts with the mixture. In Fig. 7b, the modulus of elasticity of concrete at 90 days with percentages of substitution of mixing water, according to the published literature, is shown. In the graph of the figure, it is possible to observe that, in the aqueous form, when the percentage of substitution of the mixing water for nopal mucilage increases by 2, 4, 6, 8 and 10%, the modulus of elasticity improves because it works as an adhesive and provides better hydration due to the presence of polysaccharides, which act as retardants, preventing contraction and the appearance of microcracks, which, in turn, continues to improve when the specimens are subjected to the curing process, where mixtures with nopal mucilage improve their modulus of elasticity after 7 days when cured at low w/c and m/c compared to the reference mixtures (42,45). These results agree with those found for flexural strength, where the modulus of elasticity of the specimen was also improved due to the length of the organic fibers (51).

3.5 Physical properties

3.5.1 Electrical resistivity and Ultrasonic pulse velocity (UPV)

Resistivity can be understood as a parameter to measure the quality of the mixture in terms of its compressive strength and the interconnection of the pores, it is a useful variable to know the resistance capacity of the mixture to external agents and substances (46,54). The process consists of subjecting the lateral faces of the specimen under study to an established current to determine the current regulation capacity.

Several authors have studied this property in cement-based mixtures using mortar cubes at 900 days of curing, going through a drying process in an oven at 50ºC, until reaching a constant weight, and finally being placed in a plastic container with high humidity, measuring resistivity until reaching a constant value. Results showed greater resistance for the control mixtures, while the specimens with 1 and 2% of organic material presented a decrease of 22% with respect to the reference, which can be attributed to the addition of nopal powder, a material capable of storing water in its pores, decreasing resistance to water penetration (46). On the other hand, recent research has evaluated the saturated electrical resistivity index. This was measured using ASTM C-1876 procedure (ρs) at ages of 30, 90, 180 and 400 days, noting that this parameter increases at late ages when the mucilage is cooked for its application and percentages were larger (8%, 15% and 30%). From the above, it can be inferred that the nopal mucilage improved the resistance of the mixture to the passage of water ions, preventing the pore network in the matrix from interconnecting, acting as a plug (14).

UPV is a non-destructive test, which allows the obtention of quality parameters of the mortar, verifying the activity of the matrix before the appearance of cracks and fissures that influence its properties, by means of vibratory waves propagated through the cement matrix that are related to the quality of the material (30,54). The influence of nopal, both in powder and in aqueous form, has recently been studied and it has been found, after 3, 7, 28 and 90 days, with substitutions of 10, 20, 40 and 60% for mucilage and of 0.5, 1, 1.5 and 2% for powder, a decrease of UPV at early ages, specifically at 3 days, for the replacement by mucilage, but this improved at 28 and 90 days, obtaining the best results for the 60% substitution. Similar results of those for mucilage were obtained for powder, showing the same improvement tendency after 28 days with respect to control specimens, but decreasing as the percentage of substitution increased (49). On the other hand, there are studies that present similar results, when evaluating mortar cubes with substitution percentages of nopal powder of 1, 2 and 4%, significantly increasing the UPV values by 1% with respect to the control samples, which decreased substantially in percentages of 2 and 4% (46). This can be understood probably because aqueous and dehydrated NOAs decreased the presence of voids within the matrix, generating a denser mixture, less prone to the appearance of cracks that decrease durability, an important property, which is used to determine the quality and useful lifespan of concrete structures (30) that is presented in the next section.

3.6 CMC Durability

3.6.1 Water permeability

For the evaluation of the absorption capacity of mixtures, research work has focused on the assessment of the capillary phenomenon in specimens, measuring the increase in mass and weight in certain time intervals to verify the capacity of the specimens in the presence of water. This property was investigated in 2016 by measuring the water absorption capacity for two mixing design methods, HPC (High Performance Concrete) and ACI (American Concrete Institute), containing nopal mucilage at 50% of the mixing water with W/C ratios of 0.30 and 0.60 at 120 days. Results show that HPC samples, containing nopal mucilage, presented lower absorption capacity than the reference mixture, which improved when they were cured at 28 days. ACI mixtures with a W/C of 0.60 presented increases in the absorption capacity with respect to the reference and the HPC mixture, the latter may be attributed to the mixture type, the treatment and a very high W/C ratio, which makes the mixture more permeable.

On the other hand, mixtures with W/C and M/C of 0.45 and 0.60, respectively, have also been analyzed by the ACI method and of 0.30 according to the method proposed by Aitcin and Mehta for HPC concretes with 0 and 7 days of curing at ages of 28, 56 and 120 days (42). The mucilage addition, for a W/C of 0.30, improved the absorption capacity of the mixture with respect to that of the control one after 56 days with both curing parameters. In the case of the tests at 28 days, no improvements were observed, probably due to the ability of this material to store water and present prolonged hydration, therefore, the values at early ages did not show any improvement, similar to that of compressive strength. For W/C and M/C of 0.45 and 0.60, the water absorption capacity showed a comparable improvement, making the mixture less permeable, preventing the passage of water in it, which is indicative of a denser matrix and agrees with that described by Chandra *et al.* (13), where the concrete mixtures, cured at 5 days with a W/C of 0.50, improved the permeability of the concrete mixture, when it was impregnated with CEX, due to the formation of a protein barrier and polysaccharides, during the interaction of CEX and calcium ions, which increases water resistance. Other results are shown in Fig. 8, from tests in mortar cubes at ages of approximately 900 days, with additions of dehydrated cactus and aloe of 1, 2 and 4%, which were conditioned, dried at a temperature of 50ºC and kept inside a container to avoid water loss by evaporation, measuring their weights until reaching a constant mass and verifying the capacity of the mixtures before the passage of water with different percentages of NAOs. Results show a small improvement when compared to the control mixture for nopal mixtures with 1 and 2%. This, compared to other results mentioned above, may be attributed to the addition method, which can influence the matrix of the mixture differently, showing an optimal percentage of substitution no greater than 2% (46). As already mentioned in the physical properties section, this OM may have decreased the spaces within the matrix, making it denser because this OM has acted as a sealer between the capillary pores of the mixture without allowing the transport of water molecules, or some other material, which is reflected in the mechanical properties, significantly improving them. In the case of aloe vera, the percentages below 1% showed some improvements, but not more than the control mixture presented in Fig. 8.

In other research works, the same property was evaluated for a mortar mixture with substitution percentages of 1, 2, 4 and 8% of dehydrated cactus and aloe. It was reported that, for the mixtures with both additions of 4 and 8%, rapid absorption of water occurred, affecting fluidity and presenting solidification, so they were eliminated. Results revealed that the control sample presented a mean absorption of 15.2 kg/m^2, compared to the mixtures with 1% (10 kg/m^2) and 2% (12 kg/m^2), which showed a small improvement in absorption capacity. In the case of mixtures with aloe vera, only the 1% substitution presented values similar to those of the control mixture. The mixtures with both additions, and substitutions greater than 2%, did not improve permeability. Similarly, in these mixtures the W/C increased, as a percentage of cement was replaced, which could have modified the durability properties. Given the mixtures behavior, the best results were observed for those a substitution percentage lower than 2% due to the fact that nopal can act as a plug between the pores in the cementitious matrix, avoiding the free transport of the water in it (55).

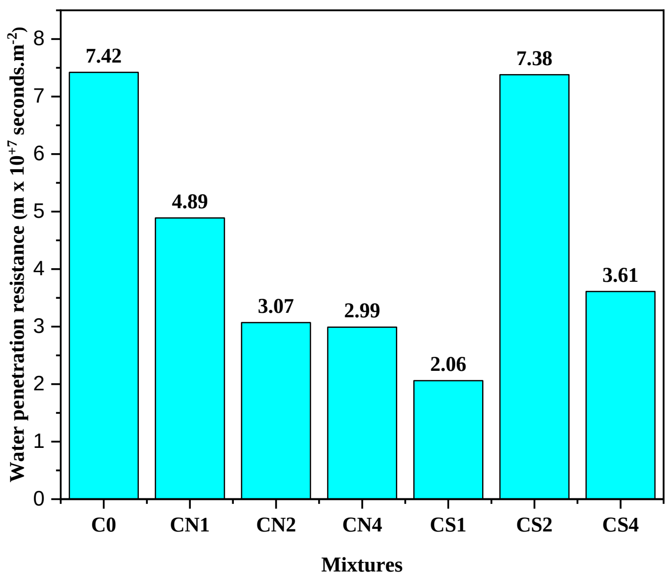

Figure 8. water penetration resistance with different percentages of nopal and aloe (46).

Other researches evaluated the effective porosity before the penetration of aggressive agents, the authors mention that the results of this tests are also known as capillary absorption, since they are based on the Swedish standard under the Fagerlund test. They used concrete cylinders with proportions of 4, 8, 15 and 30% for the exudated nopal mucilage (eNm) and cooked (cNm) and of 1, 2 and 4% for the mixtures with dehydrated nopal (dNp). Results, with respect to the control mixture, improved for the eNm and cNm mixtures (15 and 30%) and a better performance was presented at the age of 400 days for the eNm and cNm mixtures. The dNp mixture presented a greater pore volume than the control mixture and only improved with 1 and 2% at ages of 180 days and 400 days. For the case of effective porosity, only the dNp mixtures improved with 1 and 2% (14). This could be due to the organic material, which could clog the pores in the cementitious matrix, absorbing water and preventing it from migrating into the concrete (12,30). In the same way, it is necessary to note the different forms of application of nopal in the mixture, which can influence the properties of each mixture, either by temperature, extraction method, storage and particle size, for the case of the dehydrated addition.

3.6.2 Chloride penetration

The technique implemented to measure the capacity of a material against the penetration of chloride ions is given by the ASTM C-1202 and NT BUILD 443 standards in which the specimen under study is subjected to an electric charge, forcing the chlorides to transit through the solid medium and obtaining the depth of penetration of chlorides in the specimens, as well as the migration and diffusion coefficient. Chloride penetration has been studied when OM is added in concrete prisms of 100 x 200 x 50 mm with W/C ratios of 0.30 and 0.60 according to the ASTM C-1202 standard and exposure to a 16.5% sodium chloride solution, which were cured 28 days to estimate the effect of the nopal addition on the mixtures and verify the changes that could occur in the cementing matrix. Also, chloride diffusion coefficient results were obtained using 120-day-old concrete specimens. These results showed that the samples with a W/C ratio of 0.30 and nopal mucilage addition improved at late ages, presenting a very low electrical charge, reducing permeable pores, due to the nopal's ability to store water inside its pores, making it denser and showing improvements at ages of 120 days, with 28 days of curing. This could be attributed to the development of calcium complexes and the decrease in calcium hydroxide (13).

Similarly, mixtures with a W/C ratio of 0.60 were assessed, presenting a very high electrical charge passage, which are classified as high permeability mixtures, according to the ASTM C-1202 standard. This can be attributed to the water volume that the mixture can absorb, which interacts with the organic addition, showing a decrease in the capacity against the penetration of chloride ions, which was high. In this case, curing did not show any effect. This property had an influence on the compressive strength, showing high values when the electric charge passage in the specimens was low (W/C = 0.30) and the opposite happened in the specimens with W/C = 0.60, in which compressive strength values decreased considerably. For the calculation of the coefficient, the mixtures with W/C = 0.30 presented the lowest diffusion coefficients, they had a chloride diffusion coefficient of 4.93×10^{-6} mm^2/s, with mucilage addition at 120 days. This is related to the improvement in permeability, the lower the coefficient diffusion, the better the mixture resistance to the aggressive agents in the environment, so porosity is also affected, which is reflected in capillary absorption, related to the low W/C ratios that provided greater hydration. For the W/C ratio of 0.60, low diffusion coefficients were presented with the addition of mucilage at 120 days. The chloride ion diffusion coefficients were 3.49×10^{-5} mm^2/s with 0 and 28 days of curing, which may again be attributed to the mucilage extract density, containing proteins and polysaccharides, which in turn can act as seals in the pores, preventing the intrusion of these aggressive agents (56).

In the same way, dehydrated nopal and aloe vera have been implemented in proportions of 1, 2 and 4%, using 2 cm thick slices of concrete cylinders, which were crushed to be able to analyze the powder and the chloride concentration of the mixtures, the chloride exposure time for this investigation was ∼5 months (12 888 000 s), to confirm if the mucilage addition had an impact on the matrix of the mixture or any intervention in the chemical reactions, during the hydration process that could improve the mixtures capacity against the presence of aggressive agents like chloride ions. Results showed a low concentration of chlorides in the mixtures of 1 and 2% nopal mucilage addition (similar values between 1% and 2%: 25 and 11 kgm^{-3}, respectively), lower than the control sample (30 and 17.5 kgm^{-3}, respectively) because this acts as a barrier against the transport of chloride ions, but higher than 2%, the chloride penetration increases and the sample became more permeable, this may be due to the nopal's ability to act as a barrier against the passage of chloride ions, reducing its absorption. Other results coincide with this investigation, in which the addition of nopal decreased the passage of the electric charge in the mixture, so that the presence of chloride ions was almost nil. In the case of aloe vera, the presence of the material put the properties of the mixtures at risk, increasing the penetration and absorption values (57).

Likewise, studies have been carried out on cement-based mixtures where the resistance to chloride penetration was evaluated at ages of 30, 90, 180 and 400 days, according to the ASTM C-1202 standard, using concrete slices of approximately 10 cm, which were saturated in water in order to apply a current potential and obtain the permeability of the concrete mixture before the passage of chloride ions. The mixtures cNm and eNm with percentages of mucilage of 8, 15 and 30% improved the mixture permeability, decreasing the current flow with respect to the control mixture. In the case of the dNp mixture, the values did not change when adding 1 and 2% of nopal by weight of cement. In the case of dNp mixtures greater than 4%, they presented a detrimental effect on the mixture. This improvement in mixtures with additions may be due to the nopal inclusion, which absorbed water and decreased the passage of chloride ions, filling the pores in the cementing matrix (14). In short, the addition of nopal reduces the penetration of chloride ions in the mixture, helping it not to allow the free transport of aggressive agents that can be found in the environment, acting as a sealer between the permeable pores of the matrix, as it can be observed in the results of sorptivity and porosity. These properties are important if the construction element will be exposed to an aggressive environment. In addition to chlorides, another damaging agent can be the presence of CO_2, known as carbonation, a property that is discussed in the next section.

3.6.3 Carbonation

The accelerated carbonation technique has been carried out in test specimens exposed in a chamber saturated by CO_2, with constant temperatures ranging between 25 ± 2 ºC and a relative humidity of 50-70%. Over time, penetration is measured by an acid-base indicator developer verifying the shades, indicators of the mixture quality (55).

Several research works based on this technique are described, in which tests were carried out on 180-day-old concrete specimens in a carbonation chamber, exposing the curved faces of the cylinders to 4.4% CO_2 and covering the flat faces with a type of epoxy resin, with a relative humidity (RH) of 65 ± 5% and a temperature of 23 ± 2 ºC for a period of 120 days. These parameters were used to observe the behavior before the carbonation phenomenon when adding nopal, which is an indicator of durability for the quality and useful life of the mixtures. For the carbonation depth results, 1% acid-base indicator was implemented in the samples along the cylinder diameter with a total of 8 measurements. The mixtures with nopal mucilage showed a better response to CO_2 penetration with respect to the control. For the case of the mixes with a w/c ratio of 0.60, this had a carbonation coefficient of 2.19 $mm/days^{1/2}$ and 0.05 $mm/days^{1/2}$, while for the w/c ratio of 0.30 and 3.07 $mm/days^{1/2}$ for the control. These results may be related to the improvement in porosity and water absorption, described in previous sections, which does not allow the transport of this agents because the addition of nopal acts as a pore sealer, retaining water and forming Ca products with CH. This was reflected in the calculation of the carbonation front; for the mixtures with a W/C ratio of 0.60, time increased significantly, while for the W/C ratio of 0.30, the time for carbonation to reach the reinforcement steel reached 60 years of useful life compared to 20 years for the control mixture (56). As for chloride penetration, this organic addition helps to mitigate carbonation, causing the mixture to extend its lifespan, so the durability of the mix could be improved, compared to a traditional mixture. By improving these transport properties within the matrix, they are not so exposed to the inclusion of agents that can decrease the properties of the mixture, such as compressive strength, an important parameter for concrete mixtures, so the study of these materials, when presenting favorable results, could be a good proxy for their application on a large scale, but this cannot be carried out, if there is not a solid base that supports their optimal application in the cement industry.

4. Conclusion and perspective

After considering different aspects related to the application of cacti plants in cement-based mixtures and their performance in the evaluation of physical, mechanical and durability properties, it has been observed that the most studied species is that of the OFI genus, generally encompassing the assessment of microstructure and curing times, leaving aside the property of durability, which limits the information available in the literature. The use of cacti plants in cement-based mixtures is still undergoing a study process, therefore, the research works described above have only focused on a few species, such as nopal and aloe, the latter limited in information due to the unfavorable results, however, it is necessary to expand the research in the applications for the construction industry. On the other hand, it was noticed that the extraction methods for the addition of cacti plants in cement-based mixtures may have an influence on their chemical and physical properties, so that it is imperative to study the optimal temperature for the case of mucilage in cooked form, the appropriate particle sizes for addition in dehydrated form and carry out the pertinent comparisons. In the same way, physicochemical characterization techniques are necessary to correctly understand the behavior of organic material, therefore, studies should not be restricted to standardized tests in the construction field, but rather be complemented with other appropriate techniques. Finally, it is important to continue studying the durability properties, since, in the reviewed reports, NOAs presented potential characteristics for their implementation. In this sense, research in natural environments would provide important results for their application in the construction industry.

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