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USE OF CACTUS IN MORTARS AND CONCRETE

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ABSTRACT

Natural polymers have been used in ancient times to improve the durability of lime-based mortars and concretes. The natural polymers used were locally available. In this work, cactus extract from Mexico has been tested in a Portland cement mortar. It is seen that cactus extract increases the plasticity of the mortar and improves water absorption and freeze-salt resistance. Calcium hydroxide produced by Portland cement hydration interacts with the components of cactus extract, polysaccharides or proteins, and forms complexes. It affects the crystallization process. Painting of the concrete with this extract has also shown improved water resistance. © *1998 Elsevier Science Ltd*

Introduction

In ancient times, lime was the major binder used. The strength of lime-based mortars and concrete is low and it is not durable. The durability of structures was improved with the use of organic material. These products were mostly locally available and were not expensive. These are called natural polymers. The historical background of the natural polymers has been described by Chandra (1). However, in some studies for improving the moisture resistance of adobe structures, expensive and at times locally unavailable materials have been used. For example, in Africa and South America, latex from the rubber plant (*Euphoria lacter*) was used as a water-proofing paint on adobe masonry (2). In other areas, paints were made by boiling the stems and leaves of the banana plant. In Northern Ghana, walls are plastered with mud stuccos mixed with manure and an extract obtained by boiling pods from the locust bean tree (3). In a study by Ernesto et al. (4), it is shown that the moisture resistance of adobe walls improved significantly by using stabilizers made from cactus plants.

A number of other natural products have been used in ancient times. The literature available does not contain scientific details of the products used, nor of the techniques of its application. This leads to unsatisfactory results. Some of the natural products, like black gram, oils, and proteins, have been tested by Chandra in Portland cement mortars and concrete. It is found that by their additions the durability properties are substantially improved (5–7). The aim of this work is to make an investigation of the use of extract of the

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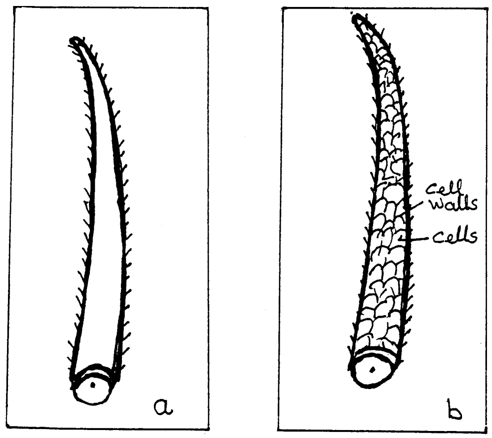

FIG. 1.
Illustration of the cactus "Nopal" leaf and polysaccharide formation.

cactus plant in Portland cement mortars and to study the mechanism of its interaction during the hydration process.

Materials and Method

Cactus

The southwest part of the United States is the largest area of semi-arid land. It is spread over approximately 100,000 square miles in an area covering Arizona, Nevada, southern New Mexico, and parts of Texas and California. The flora of this area is unique and consists largely of cactus and other xerophytic vegetation. There has been very little commercial use of these plants. A large part of the vegetation serves as a grazing range for livestock. In 1945, dehydration of prickly pear cactus has shown a protein content of 7–8% (8), whereas corn has a protein content of over 10%.

There is a pulp-like stuff (gel) underneath the skin of cactus. It is full with the cells producing gel. These cells contain mono- or di-saccharides, which interact in larger therios and produce poly-saccharides (Fig. 1b). Finally, cell walls are dissolved and one large gel is produced (mostly in cactus known as " Opuntia"). Cactus leaf and the cells are shown photographically in Figure 1. Cactus produce more gel in the warm draught period; these are known as "Cholla gum" and are used locally (9). An extended investigation of Cholla gum revealed that L-arabinol, D-galactose, L-rhamnose, and gluconic acids make up the major part of the structure (10). Each of these fractions are capable of being isolated by hydrolysis.

Cactus of "Opuntia" species and perhaps all other types contain a gel of similar nature. More gel is produced in the warm draught period and contain mono- and di-saccharide. It seems that the sugar derivatives differ very much in cactus and has not shown any systematic interesting order of composition. Master (11) found in "Nopalea" the presence of fructose, glucose, saccharide, maltose, and raffinose in traces. Thus the gel in the cactus contains polysaccharides of varying type and composition, as well as proteins, and has water-holding character.

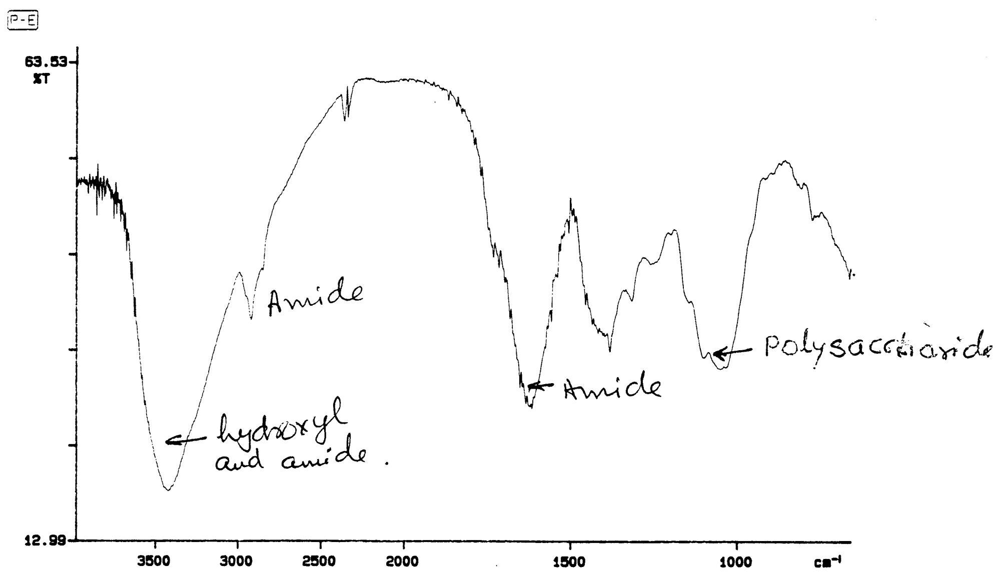

FIG. 2.
Infrared spectra of freeze-dried cactus extract.

In Mexico, this is called Nopal. There exists more than 250 species. This cactus grows in semi-deserted parts of Mexico. The leaves of this cactus have a lot of spines; when the spines are burnt, the cactus is a good and cheap meal for cattle. It is this cactus that is probably used for painting adobe walls in ancient times.

Cactus Extract

Nopal leaves in this work were supplied from Mexico. When these leaves were cut, a very thick gel-type of material was found. These leaves when cut and put in water produce a thick solution. Its consistency changes with time. It was observed that after 2 days a solution with gluey consistency is obtained, after which it started loosing its gluey character and produced a darker solution with an odor of decomposed organic matter. This solution, when used in mortar during preliminary tests, did not produce mortar of as good a quality as could be achieved by the addition of the extract after 2 days. Besides this, due to the bad smell it was not easy to work. As a consequence, the extract used was after 2 days extraction in our experiments.

The Cactus leaves "Nopal" without spines were cut into thin pieces and were mixed in water in the proportion of 1:3 by mass. It was left for 2 days at room temperature in a plastic container with lock. After 2 days, the gel was extracted. The leaves were discarded. The remaining solution, which had a sticky character, was used in the experiments. It will be called Cactus Extract Solution (CEX). This solution was freeze-dried and was analyzed by infrared spectroscopy using FT IR Instrument. The infrared spectrum is shown in Figure 2.

Cement

The cement used was standard Portland, supplied by Cementa AB, Slite, Sweden. Its composition was as follows: C_3S, 64%; C_2S, 13%; C_3A, 5%; C_4AF, 10%; K_2O & NaO, 1.6%; SO_3, 3.2; specific surface area 337 m^2/kg.

Sand

Standard sand, grade 1, 2, and 3 (fine, medium, and coarse, respectively) was used for making mortar specimens as defined in the CEN Sand (European Committee for Standardization, TC51), ISO recommendation 772; Rilem Cembureau method (12), SS EN 196–1.

Mortar Samples

Prisms with dimensions 40 $\times$ 40 $\times$ 160 mm were made with 1:3 cement mortar on a mass ratio. The water-to-cement ratio was kept constant at 0.50. These specimens were cured for 5 days in water after demoulding, and 22 days in a controlled climate room at 20°C and 55% RH. Three series of samples were made:

1. Reference samples without any Nopal leaves extract (R)
2. Samples with 50% cactus extract; CEX and 50% water (C50)
3. Samples with 100% cactus extract solution CEX (C100)

Fresh density of the samples was determined. The consistency was determined by measuring the spread on the flow table according to the Swedish standard SS 137123. Flexural and compressive strengths were measured at different intervals according to SS EN 196–1 (12). The proportion of CEX and water along with the fresh density, consistency, and flexural and compressive strength of the samples are shown in the Table 1A. The strengths reported are the average value of the three 40 $\times$ 40 $\times$ 160 mm prism samples. The standard deviations are calculated and are shown in the Table 1B.

Some of the samples were dried at 105°C and the water content of the samples was determined. It was found that the water content in the samples with CEX mixing was higher than without its addition. Water content was in the following order: C100 $>$ C50 $>$ R.

Water absorption of the prism samples was determined by capillary suction. The results are shown in Figure 3. In another test, a 150-mm concrete cube was cut into 8 small pieces. Skin from the surface was removed, and the samples were impregnated by dipping in 100% CEX, then dried at room temperature. Water absorption was determined in the same way as for the mortar samples. A comparison was done with the same type of unimpregnated samples. The results are shown in Figure 4.

Freeze-thaw resistance was tested on the water saturated prisms according to a German method (13). In this test, the samples were put in saturated sodium chloride solution at -20°C for 16 h during freezing and in water at room temperature for 8 h during the thawing period. Samples were weighed at particular intervals. The results are shown in the Table 2.

X-ray diffraction analysis of the prism samples was done, the composition of which are shown in the Table 1A. The diffractometer used was Siemens 5000, made in Germany. CuK

TABLE 1A
Physical properties of the 1:3 Portland cement:sand mortar made with 0.50 W/C, flexural/compressive strengths (average of 3 samples).

No.	Cactus extract %	Consistency mms.	Fresh density kg/m^3	Flexural/compressive strength MPa 1 day	7 days	28 days	90 days
R	0	124	2230	5.2/16.8	7.5/35.9	9.8/48.0	10.7/51.2
C50	50	128	2190	4.2/15.7	6.8/26.0	10.1/48.5	11.5/54.3
C100	100	132	2160	3.8/14.9	5.9/22.3	10.0/43.5	11.8/57.4

TABLE 1B
Standard deviation of flexural/compressive strength in percent.

No.	1 day	7 days	28 days	90 days
R	2.5/3.4	2.8/4.1	2.6/4.2	3.1/3.8
C50	3.2/3.9	3.8/4.3	3.4/5.2	4.1/5.1
C100	3.4/4.8	4.1/5.3	4.2/5.5	3.8/5.8

radiation and Nickel filter was used. The diffractograms are shown in Figure 5. There are 3 diffractograms: 1) for the reference sample without any cactus extract, 2) with 50% CEX, and 3) with 100% CEX.

These samples were also analyzed using a scanning electron microscope (JSM 5300). The analysis was done on the broken surface. The microphotographs are shown in the Figure 6.

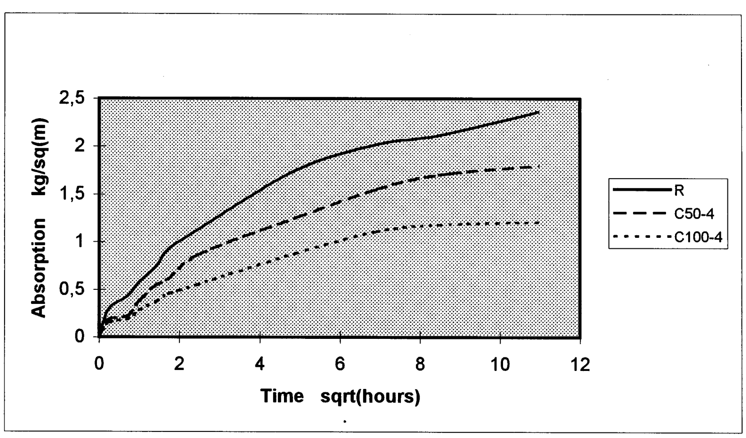

FIG. 3.
Water absorption of the mortar prisms mixed with cactus extract.

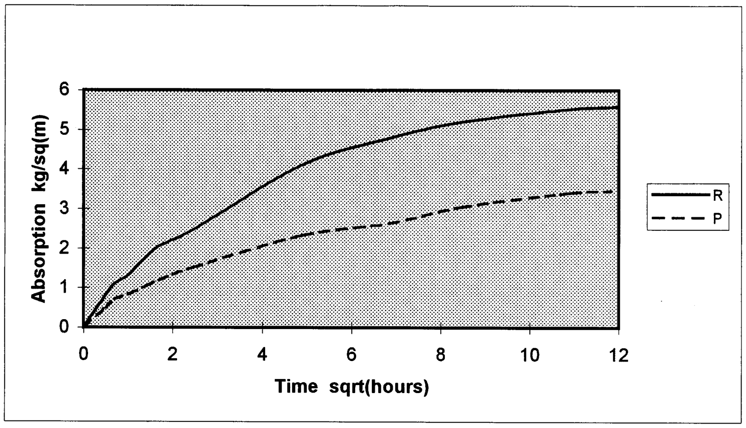

FIG. 4.
Water absorption of the concrete pieces impregnated with the cactus extract.

Results and Discussions

Infrared Spectroscopy

An important application of IR spectroscopy to protein structure has been in the detection of hydrogen bonding, although studies have been limited largely to the model compounds and polypeptides. These groups may cause a shift in the characteristic frequencies of C=O and N-H vibrations. The IR spectra (Fig. 2) shows a peak at 1000 cm^{-1} that belongs to the polysaccharide, a peak at 1620 cm^{-1} that belongs to the amide group $-\underset{\underset{O}{\|}}{C}-N-H$ (protein), a peak at 2920 cm^{-1} that belongs to C-H, and a peak at 3426 cm^{-1} that belongs to the hydroxyl and amide. This shows big stretching in the infrared pattern, and is the overlapping of the peak of hydroxyl and amide group. It generally occurs in the samples containing both proteins and polysaccharides. These show the presence of protein and polysaccharide in the Cactus extract made from the Nopal leaves and confirms the observations of the previous researchers (8,10).

TABLE 2
Mass loss of the 1:3 Portland cement:sand mortar made with 0.50 W/C, with cactus extract addition after various cycles during freezing and thawing test. The mass loss shown is in kg/m^2.

No.	3 cycles	7 cycles	10 cycles	13 cycles	16 cycles	26 cycles	35 cycles
R	+0.643	−0.801	−3.90	−6.60	Broken	–	–
C50	+0.058	+0.06	+0.065	+0.042	+0.031	−0.076	−1.45
C100	+0.040	+0.042	+0.041	+0.041	+0.038	−0.059	−0.58

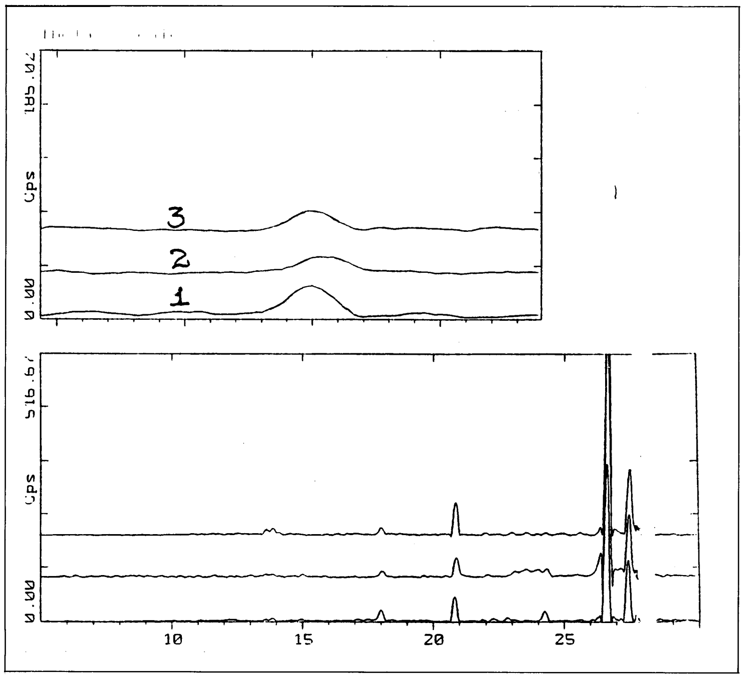

FIG. 5.
X-ray diffraction diagrams of the mortar specimens with cactus extract mixing: 1) Reference, 2) 50% Cactus extract, 3) 100% cactus extract.

Workability and Strength

The workability of the mortar mix with 50% CEX (C50) was found to be better than that of mix R (reference mix), which further improved with the addition of 100% CEX (mix C100). This is because of the effect provided by the polysaccharide from the Nopal leaves, which

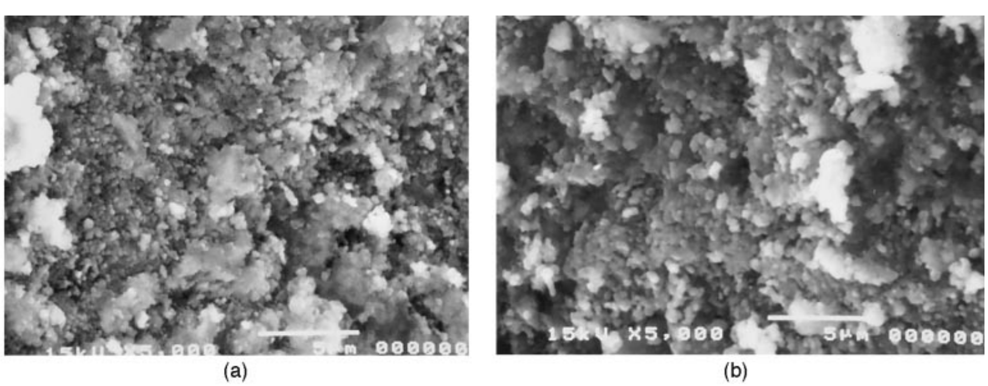

FIG. 6.
a) SEM microphotograph of the specimen with 50% cactus extract. *b*) SEM microphotograph of the specimen with 100% cactus extract.

reduces friction and increases smoothness in the same way as by the use of oil in the machinery. The density of the fresh mortar decreased with the addition of CEX. This may be due to the presence of proteins, which used to work in the same way as other air-entraining agents. Proteins are built up by amino acid residues, arranged in long chains, and joined by peptide bonds, $=CONH_2=$.

In nature, the sequence of amino acid residues along the chain is unique. Some typical features of the side chains are built up by segments. Each of these segments can have polar and nonpolar character, depending upon which amino acid predominates. Polar segments make the chain hydrophilic, whereas the nonpolar one makes it hydrophobic. Thus a single molecule of protein may have several hydrophobic and hydrophilic segments along the chain. Ionic bonds prevail in the hydrophilic region, whereas nonpolar bonds are predominant in the hydrophobic region. This activitates the surface of proteins. This surface activity is the major cause of the air entrainment in the mortar. Polysaccharides have water-holding character. Due to this, though the workability was better with the CEX addition, there was no bleeding. Besides, the rate of drying became slow.

Polysaccharides work as retarders. It is seen by the delay in the strength development at early age. It comes close to the strength of reference mortar after 28 days. This effect is more pronounced with the addition of 100% CEX. Later, the strength improves and surpasses the strength of the reference mortar. It is shown later that the addition of 100% CEX introduces hydrophobicity and thus slows down the drying process. This subsequently decreases the crack formation, which used to occur during drying. Consequently the strength increases. This is seen from the strength at 90 days by the addition of 100% CEX. There is no systematic difference in the standard deviation calculated. The deviations are more in the case of the samples made with the cactus mixing. However these are on the acceptable limit of 5% for the mortar samples made in the laboratory. It indicates that the cactus mixing does not create much heterogeneity in the mortar.

Sugar was extensively used in the East in the common mortars specifically made out of calcined shell. It has significantly improved the weather resistance by many folds. There is, however, a controversy in the behavior of sugars. Vicat (14) implied that sugar accelerates the first solidification of a mortar, whereas Bankhart (15) is convinced that it retards the set. Nevertheless both were in the favor of using sugars for better resisting the weather attack. It is still very common to use coarse sugar dissolved in water in India, for example.

Water Absorption

The water absorption tested on the mortar samples decreased with the addition of 50% CEX (C50). It is further reduced with the addition of 100% CEX (C100; Fig. 3). The decrease in water absorption is partly due to the film formed by the CEX and partly due to the calcium complexes formed during the interaction of CEX and the divalent calcium ions in the same way as in the case of synthetic polymers (16). This seals the pores and thus produces a more dense structure. In the case of concrete samples, it is seen that the water absorption decreased when these were impregnated with CEX (Fig. 4). One possible explanation for this is that the water from the CEX is absorbed by the concrete and the hydroxyl group of polysaccharides, and those formed during the denaturization of proteins make complexes as is explained before and crystallize on the surface, making it more impervious. Due to this and the film formed by the hydrophobic part of the protein, the resistance to the water penetration is substantially increased.

Freeze-Thaw Resistance

The reference sample has shown loss in weight after 7 cycles, whereas the samples both with 50% and 100% CEX mixing have shown the increase in mass, which is due to the absorption of salt solution replacing water in the sample. Loss in mass was observed after 13 cycles, when slight damage was noticed on the edges. The samples were still in good shape otherwise. Substantial mass loss was noticed in the reference samples after 13 cycles, and after 16 cycles the samples were broken, whereas the samples with 50% CEX addition have shown increase in mass upto 10 cycles, and some loss in mass upto 16 cycles. However, the samples were in good condition. There is some increase in mass with 100% CEX addition, which is practically the same upto 16 cycles. Loss in mass was noticed in the 50% sample after 26 cycles and in 100% CEX addition after 35 cycles. However, the damage shown was still not substantial in both the cases.

X-ray Diffraction Analysis

It is seen from the diffractograms that the calcium hydroxide peak (4.910 Å) decreases with the addition of cactus extract. These effects are more evident in the enlargement of the peaks in the left corner of Figure 5. The diminishing of the peaks denotes that the calcium hydroxide is consumed somewhere. The possibility is that it has chemically reacted with some of the component of CEX and has made some calcium complexes. The CEX contains polysaccharides and proteins. It is complex and the actual composition is not easy to establish. These when hydrolyzed form carboxylic bonds, which subsequently interact with the divalent calcium ions. During the denaturization of proteins, the coil in which the proteins are in their natural form opens, exposing more hydrophilic and hydrophobic parts. The hydrophilic part goes to the water phase where it interacts and makes calcium complexes, whereas the hydrophobic part goes to the air phase, and makes the surface hydrophobe. Thus with time the concrete becomes more durable, contrary to the use of synthetic polymers.

The reaction is expected to take place in the same way as in the case of synthetic polymers and calcium hydroxide, where carboxylic group of polymer forms complexes with the divalent calcium ions (14). Chandra has shown that the polymer influences the hydration process of tri-calcium silicate and hinders the formation of big crystals of calcium hydroxide (Portlandite) (17). This shows its influence on the hydration process.

Scanning Electron Microscopic Analysis

Mortar prism samples, with 50% CEX and 100% CEX, were analyzed using JSM 5300 scanning electron microscope, made in Japan. The analyses was done by Lars Eklund of The Swedish Ceramic Institute, Göteborg. The microphotographs are shown in Figure 6. The well defined crystals of Portlandite (calcium hydroxide) and other cement hydration products are not seen here (Fig. 6a). Instead, small crystallites are formed that are cryptocrystalline or amorphous. It thus reduces the crack formations that occurs otherwise with the growth of big crystals. It shows homogeneously distributed amorphous phase. Figure 6b with 100% CEX mixing shows another topography, but here also well defined crystals are not visible. It shows the influence of the interaction of CEX with the hydration products of Portland cement and its consequent effect on the crystallization process. The results are in accordance with those obtained by XRD analysis and confirms the results obtained by Chandra in previous studies (17).

Conclusions

The tests done has shown that the Cactus leaves “Nopal” without spines in contact with water produce a solution having gluey character. It contains proteins and polysaccharides. This Cactus extract mix increases plasticity of the mortar, and substantially improves the resistance to water absorption and the freeze-salt resistance of the mortar. It has also significantly decreased the water absorption when the concrete samples were impregnated with this extract. The effect was more pronounced when 100% cactus solution (CEX 100) was used in comparison to the 50% solution (CEX 50). Calcium hydroxide produced during the hydration of Portland cement interacts with the components of cactus extract, polysaccharides or proteins or both,and forms complexes. It may be possible that it also interacts with the other hydration products. It also influences the crystallization process. Big crystals of Portlandite are not formed. Small crystallites are formed instead that are cryptocrystalline or amorphous. Work is to be done to test the extracts with different concentrations of the cactus, and with the variation of extraction times. This is to be optimized. Cactus is available in abundance in African countries. Making the extract is simple and does not involve so much extra expenditure. This can provide another view of the use of natural polymers in the modern building materials as was the practice in ancient times.

Acknowledgments

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