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Cement Mortar Reinforced with Natural Fibers

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by Jose Castro and Antoine E. Naaman

The relatively high cost of man-made fibers and wire meshes used in fiber reinforced concrete and ferrocement, combined with a reduction in the usage of asbestos fibers, make it necessary to evaluate natural fibers as possible substitutes. This is particularly true in some low-cost housing applications, such as those used in Mexico, where the cost of the reinforcement represents a major portion of the total cost. Some natural fibers of the agave family, which are widely available in Mexico, show surprisingly high mechanical properties; yet little effort has been devoted so far to using them efficiently. This paper describes the results of a cooperative research project to study the use of natural agave fibers as possible reinforcement for portland cement-based matrixes. The following questions are answered: 1) What are the essential mechanical properties of these fibers? 2) What are the difficulties encountered in mixing them with a mortar matrix? 3) What are the optimum and practical maximum amounts of fibers that can be mixed? 4) Can a composite showing an elasto-plastic behavior (or better) under loading accompanied by multiple cracking be obtained? 5) Does the composite have a fairly good durability under various environmental exposures? The results so far are very encouraging and necessitate further systematic research in the use of natural fibers.

Keywords: ferrocement; **fiber reinforced concretes;** fibers; flexural strength; mix proportioning; **mortars (material); natural fibers;** tensile strength.

The last few years have seen substantial increases in the development and usage of ferrocement and fiber reinforced concrete.[1-6] These advances are accompanied by a current decline in the leading usage of asbestos fibers as reinforcement for various asbestos-cement products, such as roofing elements, pipes, tiles, and the like. As asbestos fibers pose a health hazard, there is an urgent need to find substitute fibers which would be comparable in cost and reinforcing efficiency. Current candidates include steel fibers; glass fibers; organic man-made fibers such as polypropylene; and organic natural fibers, also called vegetable fibers.

Natural organic fibers exist in reasonably large quantities in many countries of the world; if properly exploited, they can represent continuously renewable resources. The use of some of the best known fibers such as sisal or jute has been limited mostly to the production of fabrics, ropes, and the like. Although, historically, straw fibers have been used to reinforce adobe, little scientific effort has yet been devoted to the use of natural vegetable fibers as reinforcement for various building materials. This is unfortunate since some of these fibers show surprisingly high mechanical properties. Sisal fibers have been reported[7,8] to have tensile strengths of up to 100,000 psi (689 Mpa), while strengths of between 30,000 to 75,000 psi (207 to 517 Mpa) have often been reported for bamboo fibers.[9-12] Moduli of elasticity of between 2×10^6 to 4×10^6 psi (14 to 28 Gpa) are commonly encountered.[11,12]

The housing shortage problem is assuming increasing dimensions with the recent exponential increases in cost of building materials and labor. Particularly affected is the low-cost housing sector not only in developing countries but also to a certain extent in industrialized ones. Costs can be reduced at least two ways, namely, using self-help construction for labor and local and preferably renewable materials. Self-help construction has been successfully achieved in Mexico where local villagers have built their own housing units.[13] As the roof is the most important and difficult element of the structure, ferrocement domes were selected and built according to specially prepared graphical "how-to-do-it" instructions.[14] Even with such efficient structures as ferrocement domes, it was found that the cost of the roof represented up to 50 percent of the total cost of the housing unit and that the steel reinforcement, mostly wire mesh of the roof, accounted for about 70 percent of the total cost of the roof. It becomes clear that if a cheap substitute reinforcement can be found, it would have a substantial impact on the low-cost housing sector. Several attempts are being made in that direction.[15-18]

Mexico is rich in natural vegetable fibers, especially in the agave family.[19,20] For instance, the name "sisal," the most common agave fiber, comes from a harbor town in Yucatan, Maya, Mexico, and means

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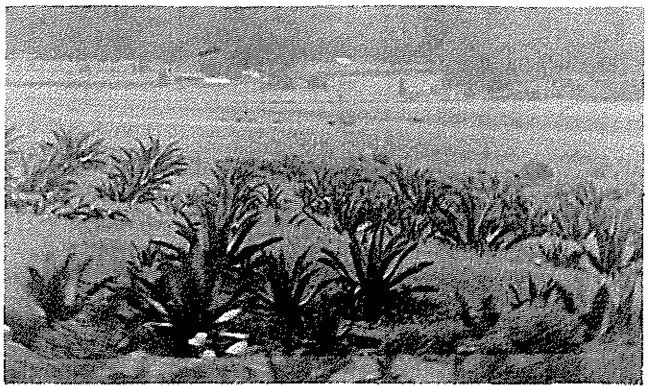
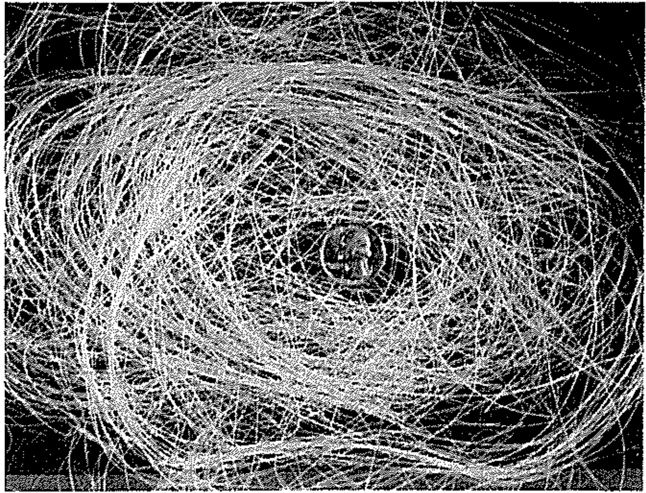
"cold water." Agave plants were grown by the Mayan Indians before the arrival of the Europeans and were used to produce ropes, carpets, and clothing. Two other species of agave plants are widely available in Mexico and currently seem to have little usage: Lechuguilla and Maguey. Maguey (Fig. 1) is also known as "Maguey pulquero" as it is used to produce "pulque," a syrupy kind of beer used by Mexicans in the countryside.



(a) Maguey plants



(b) Maguey fibers

Fig. 1 — Maguey pulquero

The research reported here is a cooperative project between the Universidad Autonoma Metropolitana of Mexico and the University of Illinois at Chicago Circle to study the use of natural agave fibers as possible reinforcement for portland cement-based matrixes. An attempt is made to answer the following questions: (1) What are the essential mechanical properties of these fibers? (2) What are the difficulties encountered in mixing them with a mortar matrix? (3) What are the optimum and practical maximum amounts of fibers that can be mixed? (4) Is it possible to obtain a composite which shows an elasto-plastic behavior (or better) under loading with development of multiple matrix cracking after the first cracking? (5) Does the obtained composite show fairly good durability under various environmental exposures?

The results so far achieved are very encouraging and necessitate further systematic research in the use of natural fibers.

DESCRIPTION OF THE EXPERIMENTAL PROGRAM

The experimental program comprised tests on the fibers and on fiber reinforced mortar specimens. The tests on the fibers included measurements of diameter, modulus, tensile strength, elongation to failure under static load, density, water absorption, and strength after exposure to different environmental conditions. The tests on fiber reinforced mortar specimens were all flexural tests under static loading; variables included the volume fraction of the fibers, the use of superplasticizers in the matrix, and exposure conditions.

TEST ON FIBERS

Two types of fibers of the agave family were used: Lechuguilla and Maguey pulquero (also called Maguey atroviens). The fibers [a sample is shown in Fig. 1(b)] were bought in a marketplace in Mexico City where they were sold in bulk for use in brooms and cleaning pads. They looked almost identical. Their surface was observed to be somewhat covered by a natural, tacky substance (wax-type) which, if the fibers were placed in water, would dissolve producing a kind of foam similar to a commercial soap or detergent. All of the fibers used in this investigation were washed in a bath of continuously flowing fresh water for 3 to 4 days to clean their surfaces, then dried in an environmental chamber at 90 C (194 F) before being used.

Length and diameter

The length of the fibers as bought varied from about 12 to 20 in. (304 to 508 mm) with an average of about 15 in. (381 mm). Maguey fibers were generally longer than Lechuguilla. As expected from natural vegetable-type fibers, they showed a thicker portion near their roots and a thinner portion toward their other end. Microscopic observations and measurements with a micrometer revealed, however, that the diameter of the Maguey fiber (of the sample available) remained almost constant throughout its intermediate portion, while the diameter of Lechuguilla fiber decreased continuously from one end to the other. This observation may be due to the difference in length of the fibers; it was not systematically explored but is re-

Table 1 — Typical values of diameters for a sample of fibers

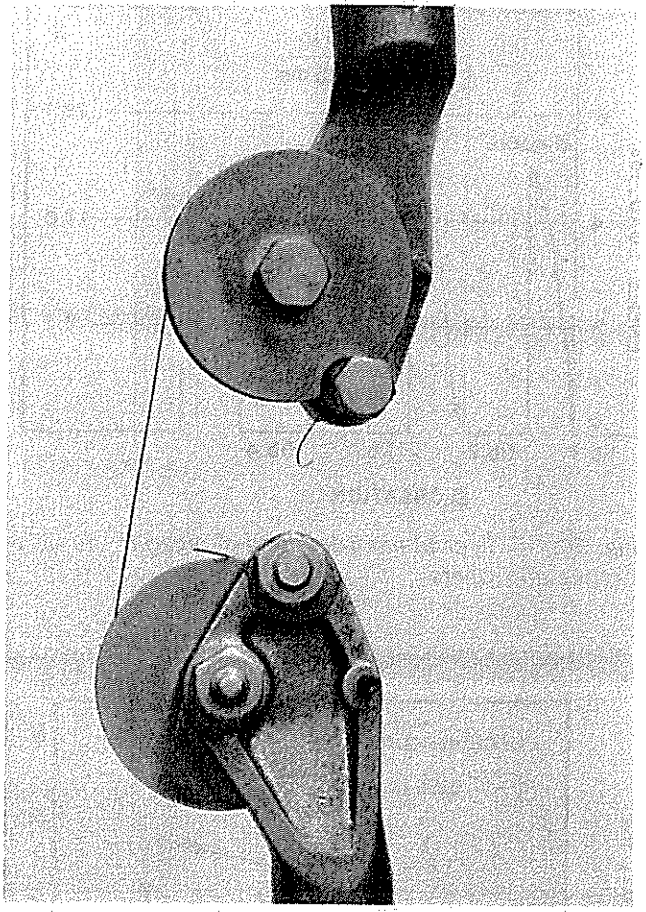
Fiber diameters, in.			
Lechuguilla			Maguey
Near one end	Near the other end	In the middle	In the middle*
0.012	0.006	0.011	0.012
0.023	0.009	0.014	0.020
0.022	0.010	0.014	0.012
0.018	0.007	0.011	0.013
0.016	0.008	0.009	0.017
0.016	0.009	0.011	0.014
0.018	0.008	0.010	0.019
0.026	0.009	0.012	0.008
0.015	0.006	0.012	0.010
0.018	0.008	0.010	0.016
Average			
0.0184	0.008	0.0114	0.0139
Standard deviation			
0.0042	0.0013	0.0016	0.0038

*Measured along the portion where the diameter was about constant
1 in. = 25.4 mm

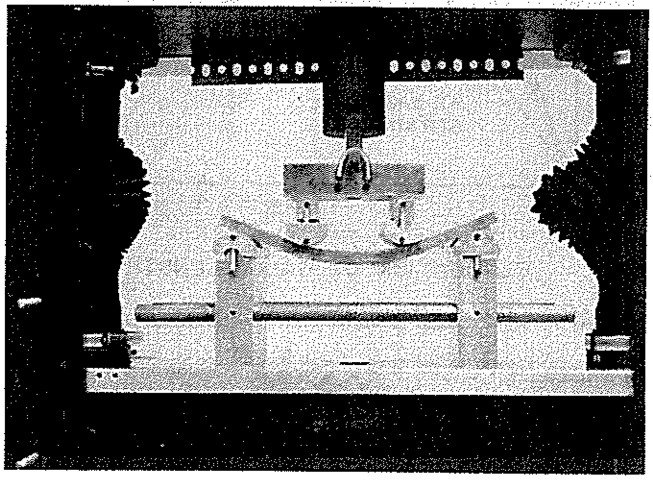
ported here for information. Typical values of fiber diameter of a sample of ten fibers each of Maguey and Lechuguilla are shown in Table 1. It can be observed that the average values are essentially of the same order of magnitude, say 0.014 in. (0.35 mm) for Maguey and 0.012 in. (0.30 mm) for Lechuguilla. Note also that these fibers are comparable in diameter to currently used steel fibers or glass strands.

Fiber tensile strength

A random sample of washed and dried fibers were tested in uniaxial tension in an Instron Universal testing machine using a special test setup shown in Fig. 2(a). The free length of fiber was about 3 in. (75 mm); elongation was applied at the rate of 1 in. per min. The diameter of the fiber in the middle portion of the gage length was measured prior to testing. In some instances, as failure did not occur within the gage length, the fiber was retested with a smaller gage length to determine more accurately the strength for the measured diameter. Typical load-elongation curves as recorded from the testing machine are shown in Fig. 3(a), while a typical determination of fiber modulus as described in the next section is shown in Fig. 3(b). The tensile strength of the fibers was based on the outside diameter of the fibers measured prior to loading. As strength and diameter seemed related, results observed are plotted in Fig. 4(a). It can be seen that, in general, the smaller the diameter the higher the strength. A similar trend is observed for the modulus of elasticity of the fiber in function of the diameter, as shown in Fig. 4(b).



(a) Tensile tests of fibers



(b) Flexural tests of fiber reinforced mortar beams

Fig. 2 — Testing setup

Elastic modulus

For some of the fibers tested in tension, two ink markers were made exactly 2 in. (25 mm) apart [within the free 3-in. (75-mm) gage length]. The distance between these markers was measured at different levels of loading, and the corresponding values of modulus of elasticity were computed. Note the stress was based on the initial value of fiber diameter measured. Results are summarized in Fig. 4(b). Note also that although the modulus of these fibers is not as high as steel or glass fibers, it seems to compare very favorably with organic synthetic fibers where generally reported moduli are less than 10^6 psi (7 GPa).[21]

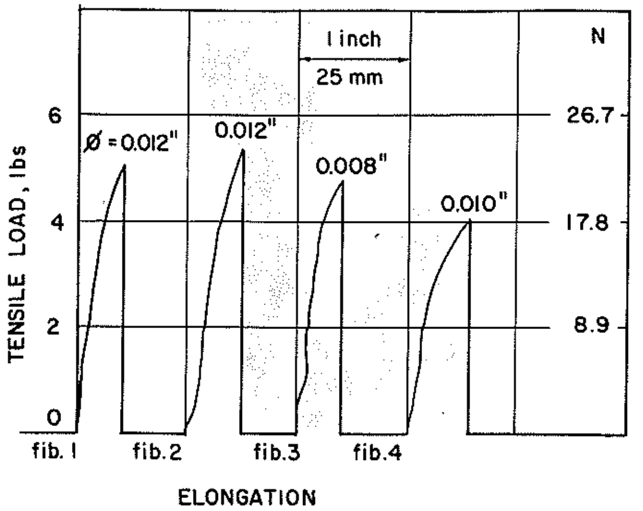


Fig. 3(a) — Typical recorded load-elongation curves of Lechuguilla fibers

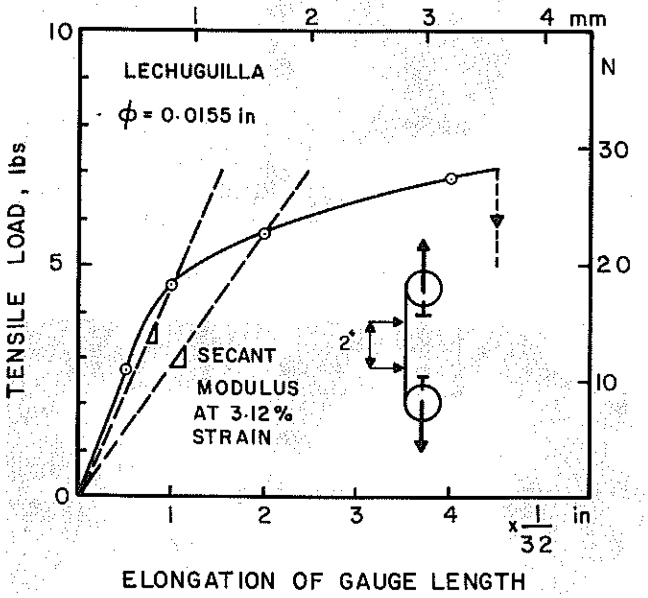


Fig. 3(b) — Typical measurement of fiber modulus

Table 2 — Typical water absorption properties of the fibers

Fibers	Wetting time, min	Weight of dry fibers, g	Weight of wet fibers, g	Weight of water absorbed, g	Percent absorption relative to weight of dry fibers
Lechuguilla	1	23.3	45.6	22.3	96
	3	24.0	49.6	25.6	107
	5	27.4	52.8	24.4	89
	10	24.9	51.0	26.1	105
	20	26.9	53.8	26.9	100
Maguey	1	12.4	21.0	8.6	69
	3	7.1	12.0	4.9	69
	5	6.0	9.7	3.7	61
	10	6.0	10.0	4.0	60
	20	11.3	18.1	6.8	67

1 g = 0.035 oz

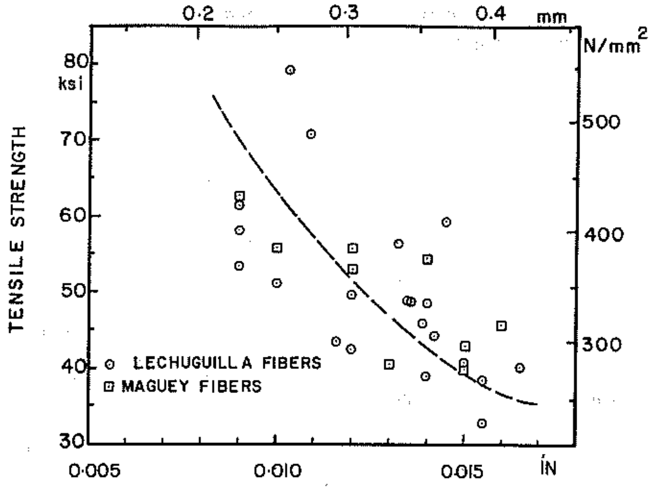


Fig. 4(a) — Variations of fiber strength versus diameter

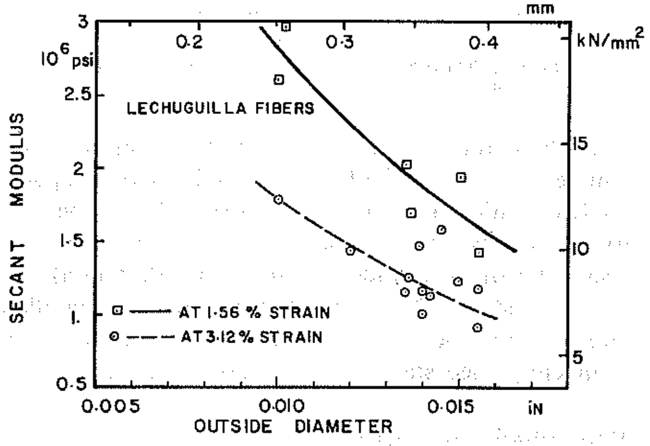


Fig. 4(b) — Variations of fiber modulus versus diameter

Water absorption

Samples of dried fibers cut in lengths between 2 and 3 in. (50 and 75 mm) were weighed and placed in water for a specified period of time. Upon removal, their surfaces were dried by rubbing without squeezing between paper towels to achieve somewhat saturated, dry surface conditions. They were then weighed to determine the amount of water absorbed. Typical results are shown in Table 2. It can be seen that maximum water absorption is achieved very rapidly due most likely to capillary action, and that Lechuguilla absorbs relatively more water than Maguey. This fast water absorption is one of the drawbacks of using the fibers with cementitious matrixes because as soon as the fibers are introduced in the mix, they absorb part of its water, rendering it very harsh.

Density measurement

Density was measured as the ratio of weight to volume using a pycnometer where volume displacement of water is measured. Some difficulties were encountered in arriving at acceptable values of volume: for example, as soon as the water is introduced in the pycnometer, the fibers start absorbing the water and

Table 3 — Typical computation of fiber density

Type of fiber	Weight measurements, g				Fiber density
	$W1$	$W2$	$W3$	$W4$	
Maguey	454.6	1455.7	479.8	1460.6	1.24
Lechuguilla	454.8	1455.9	494.1	1466.2	1.36

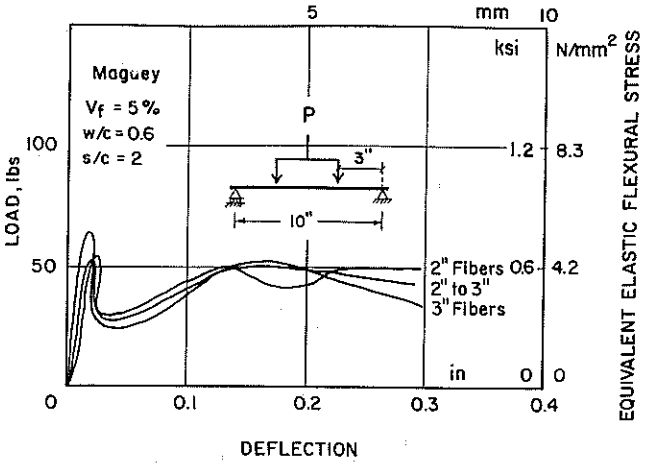
Note: $W1$ = weight of empty pycnometer
$W2$ = weight of pycnometer with water
$W3$ = weight of pycnometer with dry fiber
$W4$ = weight of pycnometer with water and fibers
γ = density of water
Volume of fibers = $[(W_2 - W_1) - (W_4 - W_3)]/\gamma$ cm^3
Fiber density = $(W_3 - W_1)$/volume of fibers
1 g = 0.035 oz; 1 cm^3 = 0.06 in.^{3}

consequently swell, thus producing a change in volume. The continuous swelling, which may take several min, tends to let the water overflow from the pycnometer. To reduce this effect, the experimental part where the water is added to the pycnometer containing the fibers was run very rapidly (to reduce the effect of swelling), and the pycnometer was kept on the platten of the balance to measure the total weight (note, even if some water overflows from the pycnometer to the platten, the total weight should remain constant). Typical sample results representative of the averages obtained are shown in Table 3 leading to densities of dry fibers of the order of 1.36 for Lechuguilla and 1.24 for Maguey. These values seem quite high, but they are comparable to those reported for sisal fibers. Also, it may be that the effect of squeezing the fibers during their production tends to increase their apparent density.

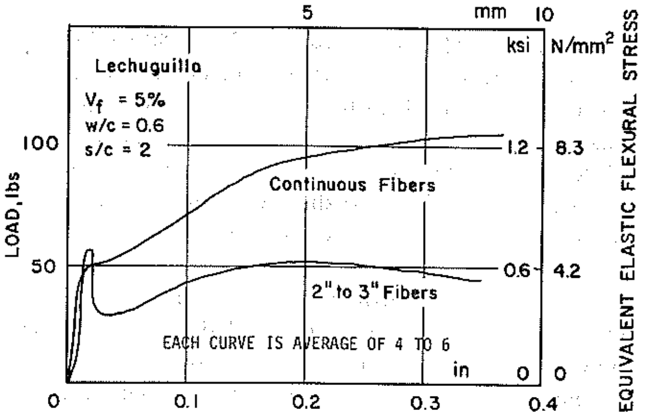
FLEXURAL TESTS ON FIBER REINFORCED MORTAR BEAMS

All specimens were 12 in. (300 mm) long, 3 in. (75 mm) wide, and ½ in. (12.5 mm) thick. The mortar matrix consisted of ASTM Type III cement and river sand passing sieve No. 8, with a sand-cement ratio of 1 for all series of tests except for the preliminary tests. The water-cement ratio was taken as 0.6 or 0.5 when a superplasticizer additive was used and is given in the descriptive table for each series of tests. When used, the superplasticizer was added in the proportion of 30 fluid oz (850 g) per bag of cement. This corresponds approximately to 2.3 percent by weight of cement.

In a preliminary series of tests, the component materials were premixed in a food-type mixer with a pan capacity of 1 cu ft (0.028 m^3). However, the mix became very harsh and occasionally led to fiber balling and failure of the blade of the mixer; thus, manual mixing was used. Sand and cement was first premixed, then the water, then the fibers and the superplasticizer were added slowly in steps. The specimens were placed in acrylic resin molds vertically along their width; vibration and tapping with a small rod were needed to insure good compaction. All specimens were kept in the molds for 24 hr, removed, stored in a curing room at 100 percent relative humidity and 75 F (23 C) for 7 days, then air dried under ambient conditions for 1 day before testing (except for the series subjected to various environmental conditions).



(a) Using 2 or 3 in. (50 or 75 mm) long fibers



(b) Using continuous or discontinuous fibers

Fig. 5 — Average load-deflection curves of flexural beams

The flexural beams were tested in a testing machine with an initial rate of stroke of 0.02 in./min (0.50 mm/sec); later in the test the rate was increased to speed up the process. A four-point loading arrangement with a 10-in. (254-mm) span and a 4 in. (100 mm) constant bending moment zone was used [Fig. 2(b)]. The load-deflection curves were automatically plotted on the testing machine *x-y* recorder. The beams were loaded until failure or a deflection of about 0.5 in. (12.5 mm), whichever occurred first.

Preliminary flexural tests

A preliminary series of flexural tests was undertaken to answer the following questions: (1) How accurately in length should the fibers be cut? (2) What is the difference in flexural behavior between using continuous or discontinuous fibers?

No attempt was made in this investigation to study the influence of the length or aspect ratio of the discontinuous fibers. Previous experience would indicate that the longer the fiber the better it is, provided proper mixing can be achieved. Some trial mixes in-

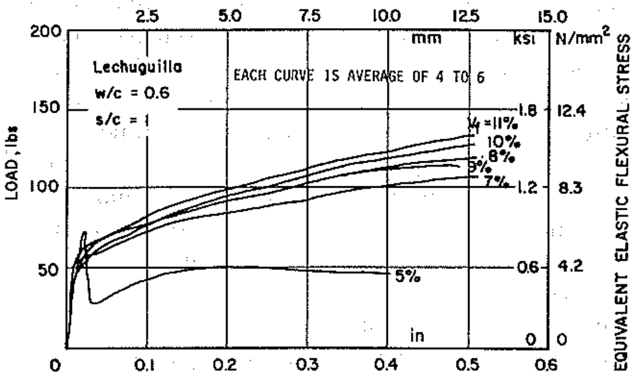
Table 4 — Summary of the short-term flexural tests program

Series	Fiber type and state	Mortar mix proportions			Volume fractions of fibers for different subseries†
		Sand-cement ratio	Water-cement ratio	Super-plasticizer*	
A-M	Maguey dried	1	0.6	0	5, 6, 7, 8, 9, and 10 percent
B-M	Maguey dried	1	0.5	2.3 percent	0, 7, 8, 9, and 10 percent
C-L	Lechuguilla dried	1	0.6	0	5, 7, 8, 9, 10, and 11 percent
D-L	Lechuguilla dried	1	0.5	2.3 percent	0, 7, 8, 9, and 11 percent

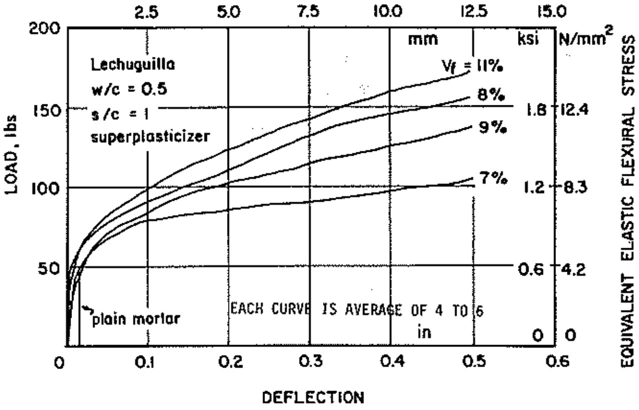
*Given in percent weight of cement
†At least three specimens for each subseries

dicated acceptable lengths of 2 to 3 in. (50 to 75 mm). As these fibers were cut from longer fibers and, as cutting to accurate lengths would have been very time consuming, a comparison of flexural specimens reinforced with the same volume fraction of fibers (V_f = 5 percent) having two different lengths, namely, 2 and 3 in., was made. Typical results are shown in Fig. 5(a). It can be seen that the average load-deflection curves are not significantly different for the two lengths of fibers. It was thus decided to cut the fibers anywhere between 2 to 3 in. to reduce cutting time. All the fibers used in the flexural specimens had the above range of lengths.

To compare the behavior of flexural specimens reinforced with continuous or discontinuous fibers, two series of tests were prepared using 5 percent fibers by volume. The first series contained the discontinuous fibers, 2 to 3 in. long. The second series contained continuous [12 in. (300 mm)] long fibers; for this series flat molds were used, i.e., the width of the specimen was in the horizontal direction; the fibers were placed in the mold more or less uniformly and aligned; then the mortar matrix was placed. Average load-deflection curves are shown in Fig. 5(b). It can be seen, as expected, that the continuous fibers give better reinforcing characteristics than the discontinuous ones, indicating that, after cracking of the matrix, there is certainly fiber pullout for the short discontinuous fibers.



(a) Without superplasticizer



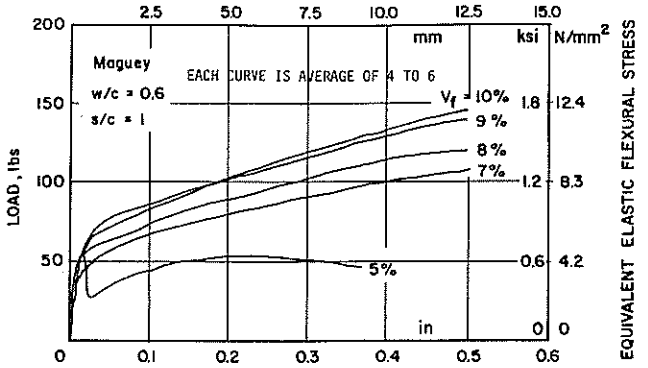
(b) With superplasticizer

Fig. 6 — Average load-deflection curves of beams reinforced with Lechuguilla fibers

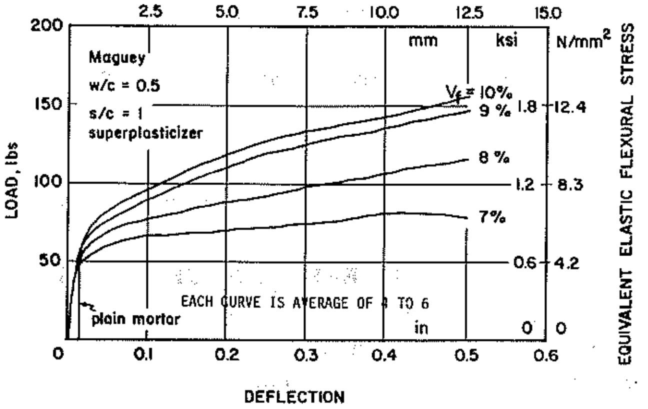
Influence of the volume fraction of fibers

The influence of the volume fraction of fibers V_f was first explored in a preliminary series of tests with V_f values of less than 5 percent. The results were often erratic with great variabilities, and the load-deflection curves showed a sharp drop after first matrix cracking. It was then decided to use a V_f value above 5 percent in all tests.

The various series of tests are described in Table 4. It can be seen that the two types of fibers described earlier were used in amounts of up to 11 percent by volume. In addition, similar test series were run with and without superplasticizer. In the nomenclature identifying each series, M refers to Maguey, L to Lechuguilla, and S to superplasticizer. Average load-deflection curves for each series of three specimens are plotted in Fig. 6 and 7. It can be generally observed that: (1) first cracking (deviation for linearity) is not significantly influenced by the volume fraction of fibers; (2) for V_f above about 7 percent, the load keeps increasing after first cracking, providing a desirable post-cracking ductility; (3) there is no significant difference in the load-deflection curves when super-



(a) Without superplasticizer



(b) With superplasticizer

Fig. 7 — Average load-deflection curves of beams reinforced with Maguey fibers

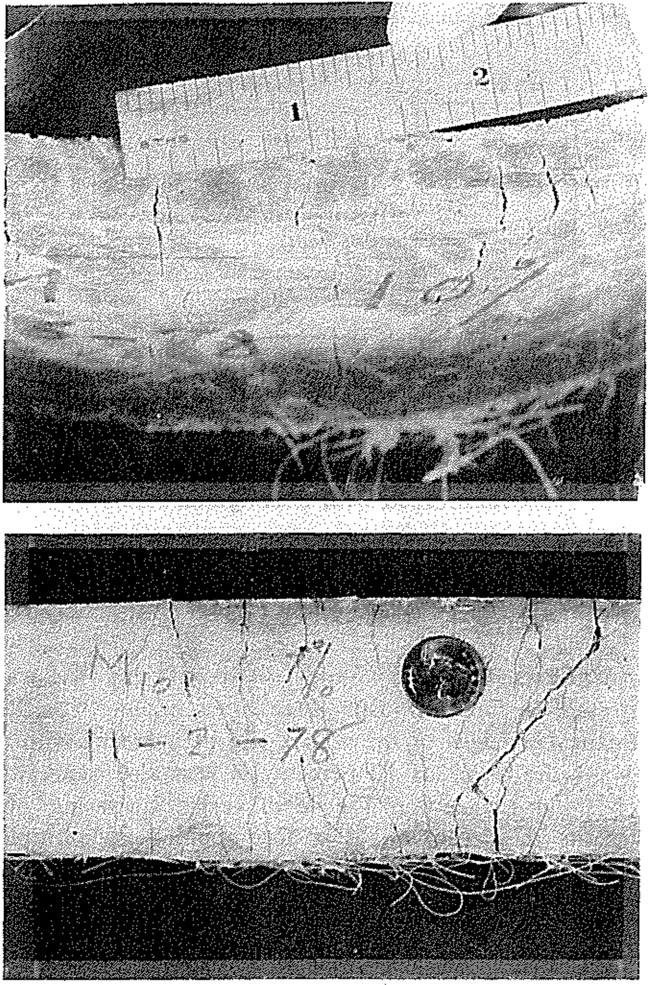


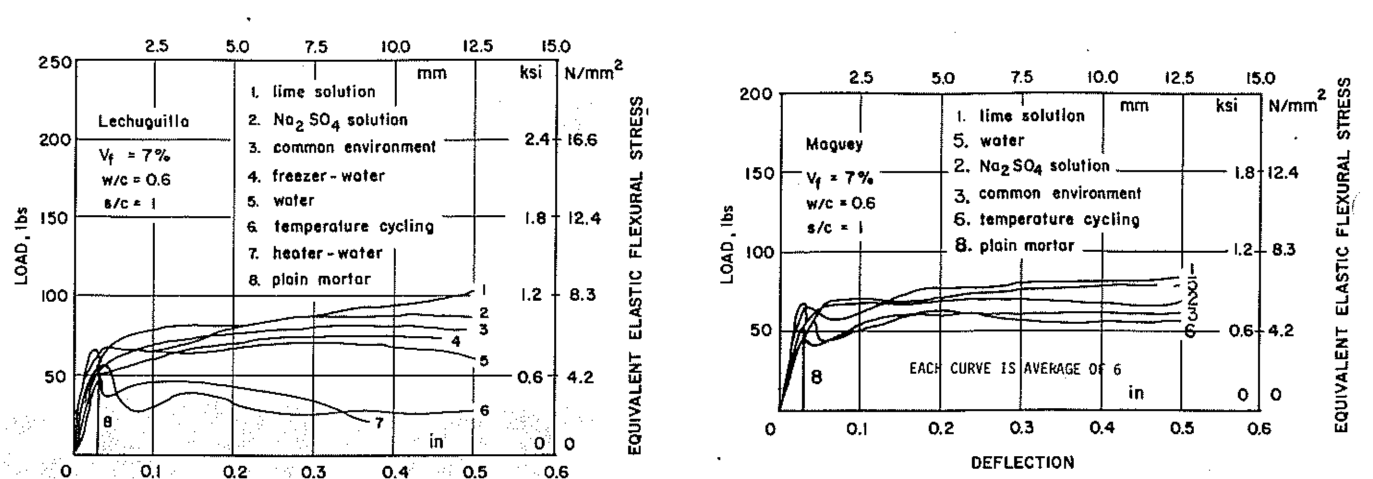
Fig. 8 — Multiple cracking characteristics of flexural specimens

Table 5 — Summary of the various exposure conditions for the long-term testing program

Series*	Fiber type (dried)	Exposure conditions between end of curing and testing	Exposure number
E-M	Maguey	Laboratory environment in air at ≅ 20 C and ≅ 60 percent relative humidity for 88 days	3
E-L	Lechuguilla		
F-M	Maguey	In water at ≅ 20 C for 88 days	5
F-L	Lechuguilla		
G-M	Maguey	In lime-water solution (10 percent lime by weight of water) at ≅ 20 C for 88 days	1
G-L	Lechuguilla		
H-M	Maguey	In sodium sulfate solution (10 percent Na_2SO_4 by weight of water) at ≅ 20 C for 82 days	2
H-L	Lechuguilla		
I-M	Maguey	62 cycles in an environmental chamber at 95 percent relative humidity with temperature changing from 2 C to 75 C (Total cycle time = 6 hr; rate of temperature change = 30 min)	6
I-L	Lechuguilla		
J-L	Lechuguilla	54 cycles in a freezer for 24 hr at −25 C and then in water at 20 C for 24 hr, and vice versa	4
K-L	Lechuguilla	54 cycles in a stove at 50 C for 24 hr and then in water at 20 C for 24 hr, and vice versa	7

*Each series had six specimens with the following mix proportions: water-cement ratio = 0.6, sand-cement ratio = 1, and 7 percent volume fraction of fibers.

$t_F = 1.8 t_C + 32$



(a) *Reinforced with Lechuguilla fibers*

(b) *Reinforced with Maguey fibers*

Fig. 9 — Average load-deflection curves of beams exposed to various environmental conditions

plasticizers are used; and (4) equivalent flexural stresses in the composite three times higher than the flexural strength of the matrix can be achieved with a V_f of the order of 10 percent. It was also generally observed that when the load keeps increasing after the first cracking, it is accompanied by multiple cracking in the matrix. At high values of V_f, multiple cracking can be significant, as shown in Fig. 8.

LONG-TERM BEHAVIOR OF COMPOSITE

Several series of flexural specimens all with a volume fraction of fibers of 7 percent and without superplasticizer were fabricated and exposed to various environmental conditions before testing. Each series comprised six specimens. A sample of uncut fibers accompanying each series was also exposed to the same treatment before being tested simultaneously in tension. The description of these series and their exposure conditions is given in Table 5. Testing was done as previously described for the static tests. Average load-deflection curves are summarized in Fig. 9(a) for the series with Lechuguilla fibers and Fig. 9(b) for the series with Maguey fibers. The following observations can be made.

1. For both types of fiber reinforcement, temperature cycling between 2 C to 75 C at 95 percent relative humidity leads to a substantial decrease in load-deflection response, especially after first cracking.

2. Exposing the specimens (unloaded) in a lime-water solution or in a sodium sulfate solution does not seem to deteriorate their properties; to the contrary, flexural response seems to improve.

3. The effect of keeping the specimens in water is not clear. In the case of Lechuguilla fiber reinforced specimens, there seems to be a deterioration [Fig. 9(a)] in properties, while for the series with Maguey [Fig. 9(b)] there is an improvement.

4. Deterioration of properties is observed after exposure to heating or freezing cycles.

LONG-TERM BEHAVIOR OF FIBERS

Tensile test results on the fibers exposed to the same environmental conditions as the flexural beams are summarized in Table 6. The individual results are given as well as the averages and standard deviation because there is a consistent trend in each series of tests between the strength and the fiber diameter. Values obtained should be compared with those described in Fig. 4(a). In view of the variabilities observed, no definite conclusion can be made about the effect of fresh water and sodium sulfate solution on fiber strength. It seems, however, that exposure to a lime solution as well as cyclic heating or freezing leads to a deterioration of tensile properties.

CONCLUSIONS

Based on this study, the following preliminary conclusions can be drawn:

1. Natural fibers of the agave family have significant mechanical properties that make them eligible as potential reinforcement of cementitious matrixes.

2. Tensile strengths of up to 80 ksi (552 MPa) and elastic moduli of up to 3 x 10^6 psi (21 GPa) were observed on fibers tested in this study.

3. No significant difference was observed in either the mechanical properties or the reinforcing efficiency of Maguey or Lechuguilla fibers used in this investigation.

4. Lengths of fibers of up to 3 in. (75 mm) and volume fractions of up to 11 percent can be mixed with a portland cement mortar matrix. Higher water contents and/or the use of superplasticizer are generally necessary to reach such limits under normal mixing conditions.

5. Elasto-plastic behavior in flexure and multiple matrix cracking were achieved for volume fraction of fibers above 7 percent.

Table 6 — Tensile tests results of fibers exposed to various environments

	Maguey			Lechuguilla		
Fiber exposure same as flexural series (Table 5)	Diameter, in.	Ultimate load, lb	Strength, psi	Diameter, in.	Ultimate load, lb	Strength, psi
F-M F-L (Fresh water for 88 days)	0.012	6.0	53051	0.009	3.4	53444
	0.012	6.3	55704	0.010	4.0	50929
	0.015	7.6	43007	0.009	3.7	58160
	0.008	4.4	87535	0.009	3.9	61304
	0.013	5.4	40683			
			μ=55996			μ=55955
			σ=18752			σ=4656
G-M G-L (Lime water solution for 82 days)	0.009	3.3	51872	0.012	4.0	35367
	0.009	3.6	56588	0.010	3.1	39470
	0.015	6.7	37914	0.008	2.3	45757
	0.014	6.1	39626	0.011	4.0	42090
	0.006	1.6	56588	0.012	4.9	43325
			μ=48517			μ=41202
			σ=9124			σ=3971
H-M H-L (Sodium sulfate solution for 82 days)	0.009	3.7	58160	0.010	4.8	61115
	0.011	4.8	50508	0.010	4.3	54749
	0.011	5.5	57874	0.010	4.6	58569
	0.010	4.6	58569	0.011	5.5	57874
	0.012	6.8	60165	0.012	5.8	51283
			μ=57055			μ=56718
			σ=3767			σ=3792
J-M J-L (54 cycles from freezer to water and vice versa)	0.011	4.7	49456	0.011	4.9	51560
	0.010	3.6	45836	0.012	5.6	49514
	0.012	5.1	45093	0.013	7.7	58011
	0.008	2.9	57693	0.012	6.2	54820
	0.011	4.7	49456	0.011	4.6	48404
			μ=49506			μ=52426
			σ=4999			σ=3947
K-M K-L (54 cycles from stove to water and vice versa)	0.013	5.4	40683	0.011	3.9	41038
	0.009	2.7	24441	0.011	3.5	36829
	0.008	2.1	41778	0.010	2.8	35650
	0.012	5.3	46862	0.012	5.0	44209
			μ=42941			μ=39431
			σ=2712			σ=3936

Note: μ = average; σ = standard deviation
1 in. = 25.4 cm; 1 lb = 0.45 kg; 1 psi = 6.895 kPa.

6. There is a strong indication that a cementitious matrix reinforced with natural fibers can achieve good resistance to normal environmental exposures.

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