Moisture Barrier Effects on Pavement Roughness

by

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Abstract

Pavements built on expansive clay are a type of shallow foundation. By their flexural action, they filter out the roughness that develops due to differential moisture change in the subgrade. The moisture change beneath pavements comes in the vicinity of cracks which carry liquid water under hydrostatic pressure to wherever the crack travels beneath a pavement. Thus, the roughness that appears on the surface of pavements reflects the pattern of major water bearing cracks (and other water bearing seams and lenses) that exist in the natural soil.

In order to prevent the intrusion of water in these cracks beneath pavements field experiments in Texas have investigated the use of vertical moisture barriers. Three types of barrier were used: Ethylene vinyl acetate (EVA)-coated fabric, injected lime slurry, and injected lime-fly ash slurry. Two depths were used: six feet and eight feet. Control sections were also designated in which no barrier was used. Periodic measurements of the right- and left-wheelpath profiles were made on each section. Matrix suction measurements were made even more frequently with thermal moisture sensors which were embedded both inside and outside the moisture barriers at different depths.

The data that have been reduced show how the roughness spectra have changed with time on each of the test sections as compared with the control sections.

These observations lead to the practical conclusions of the relative effectiveness of each of these moisture barrier types.

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Introduction

Pavements built on expansive clays are a type of shallow foundation. By their flexural action, they filter out the roughness that develops beneath them due to differential moisture changes in the subgrade. The moisture change beneath pavements comes in the vicinity of cracks which carry liquid water under hydrostatic and capillary pressure gradients to wherever the crack travels beneath a pavement. The water soaks into the soil on each side of the crack and causes swelling that is centered on the crack. Thus, the roughness that appears on the surface of pavements reflects the pattern of major water bearing cracks (and other water bearing seams and lenses) that exist in the natural soil.

In order to prevent or retard the exchange of moisture from beneath the pavement to the soil outside the pavement, vertical moisture barriers have been investigated in field experiments in Texas. Fabric barriers impregnated with ethylene vinyl acetate (EVA) have proven to be very effective in experiments conducted in San Antonio (Picornell, Lytton, and Steinberg, 1985) when placed to a depth of 8 feet (2.4 m) on each side of the paved surface. This raised the question of whether other types of barriers and other depths of barrier would work as well, and triggered the experiments near Greenville, Texas which are the subject of this paper.

Three types of barrier were used: EVA-coated fabric, injected lime slurry, and injected lime-fly ash slurry. Two depths were used: six feet (1.8 m) and eight feet (2.4 m). Companion control sections were also designated in which no barrier was used, and these provided a comparison to determine the effectiveness of the barrier. Periodic measurements of the right- and left- wheel path profiles were made on each section and the roughness spectrum of each was characterized using the Fast Fourier Transform and regression analysis. Matrix suction measurements were made even more frequently with ceramic-tipped thermal moisture sensors which were embedded both inside and outside the moisture barriers at different depths.

The data that have been reduced show how the roughness spectra have changed with time on each test section as compared with the control sections. A mathematical method of determining the amount of change of roughness has been developed to assist in making an objective comparison. The trends are consistent with the trends of the matrix suction measurements which show wide variations with the seasons outside of the barriers and smooth monotonic increases toward a final equilibrium value on the inside. The results of these measurements and comparisons and the conclusions drawn from them will be presented later in the text.

Location of Field Experiments

The field experiments are located in northeast Texas along Interstate Highway 30 in the vicinity of Greenville, Texas, as shown in Figure 1. The experiment was laid out to have each type of vertical moisture barrier placed for a distance of at least 1000 feet (305 m) on each side of the eastbound lanes and the unprotected companion control sections on the same stations in the westbound lanes. The moisture barriers were placed in December, 1983. The vertical fabric barriers were placed against the inside wall of trenches, with the top of the fabric folded over and tacked with bitumen to the shoulders of the eastbound lanes. The trenches were backfilled with the native soil up to within 2 feet (0.6 m) of the surface and then were capped with a layer of 1-sack per cubic yard concrete. The entire section was then overlayed with a 1 1/2-inch (3.8cm)-thick hot mix asphaltic concrete layer. The cross section of the vertical fabric barrier placement is shown in Figure 2a. The injected slurry barriers were placed by injection in three rows parallel with the travel lanes, one foot (0.3 m) apart with the injection holes staggered. The pattern of injection holes is illustrated in Figure 2b. Injection was carried to a depth of 8 ft. (2.4 m).

The soil underlying the two sites is from the same surficial soil group as identified by the U.S. Soil Conservation Service, the Houston Black and Leson Soil groups, Atterberg limits of the soil give the results shown in Table 1.

The soil in the two sites is a highly expansive clay. However, being three miles apart, the soils and the sites are not identical, and this fact required the unusual analyses reported later in this paper in order to make an objective determination of the relative effectiveness of the moisture barriers.

As part of the planned stage construction of the new surface on Interstate 30, a 3/4-inch (1.9 cm) open-graded friction course was placed over all sites in August, 1986. Thus, the profile measurements and serviceability indexes measured after that date must be regarded as starting from a new datum.

Measurements

Two types of measurement were made on each of the eight sites: profilometer and matrix suction measurements. Profilometer runs were made on the following dates:

Before construction:	Dec. 20, 1983
After construction:	July 10, 1984
	March 5, 1986
	May 12, 1987

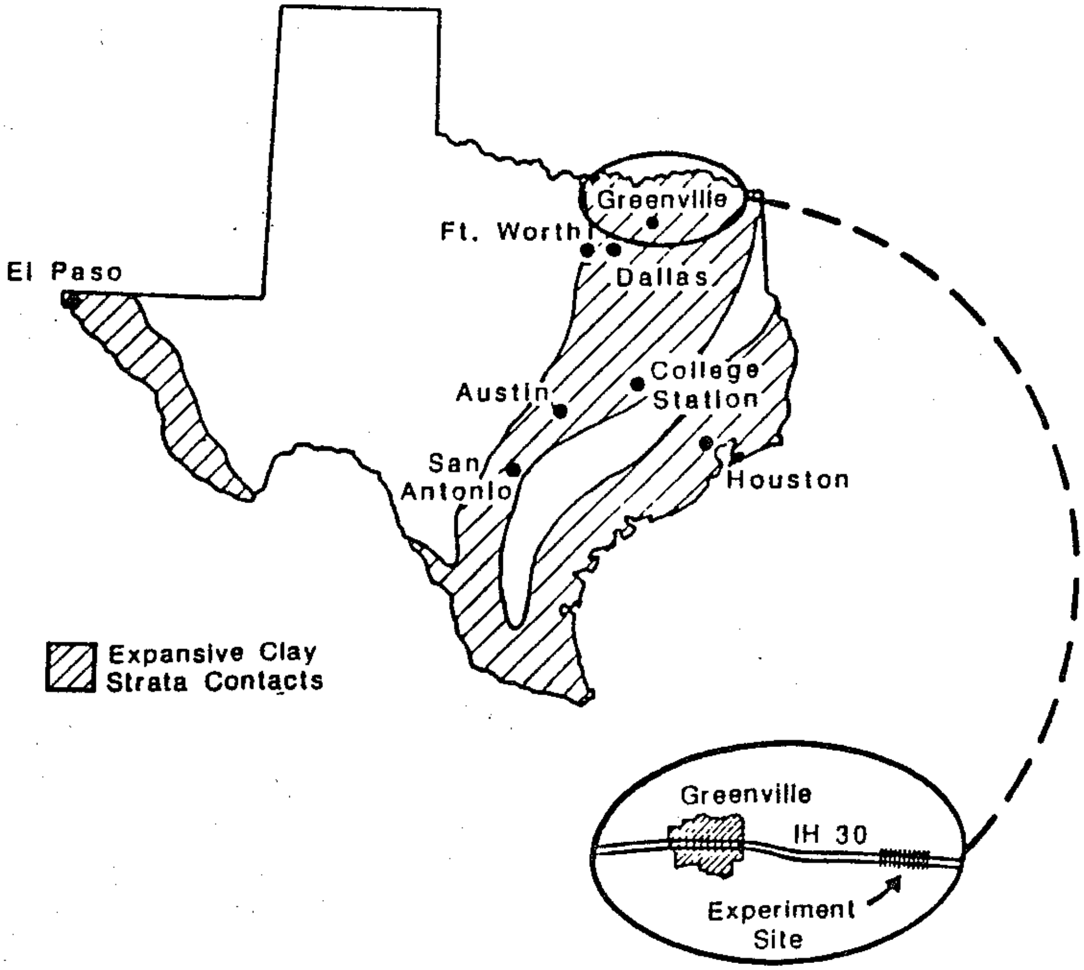

Figure 1. Location of Field Experiment Site Near Greenville, Texas.

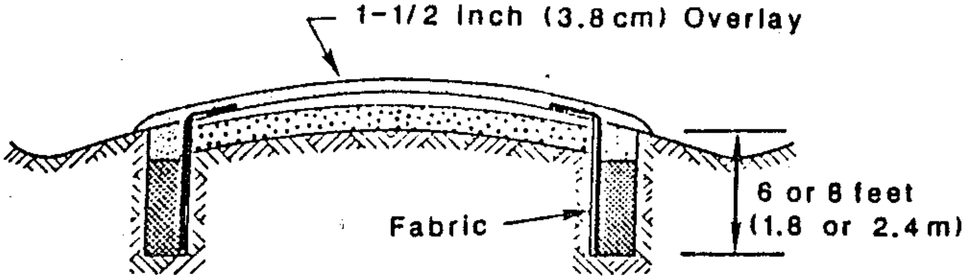

Figure 2a. Cross-Section of Vertical Fabric Barrier Placement.

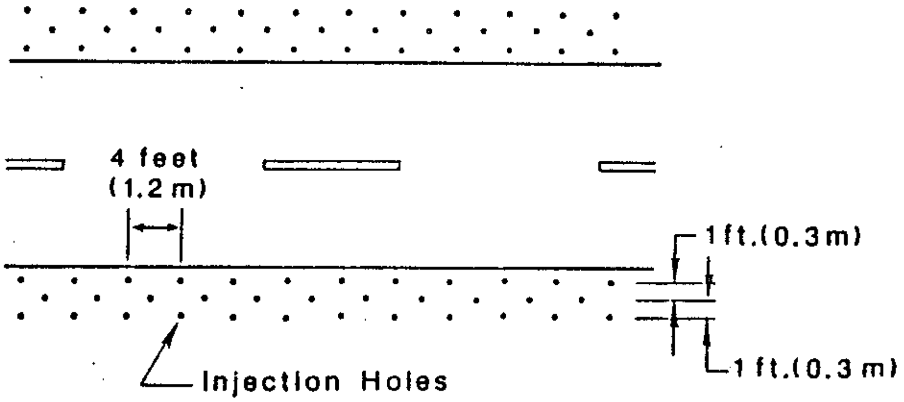

Figure 2b. Pattern of Injection Holes for Slurry Injected Barriers

Profile measurements were made in the right and left wheel paths and were digitized to give elevation measurements every 0.5 ft. (0.15 m). The digitized profile elevation data was used to calculate the roughness spectrum, the maximum bump height, and the serviceability index, as will be explained later.

Matrix suction measurements were made with the Aqwatronics thermal moisture sensor, which senses the change of thermal conductivity in a standard baked ceramic tip due to the amount of water held in the pores of the ceramic tip. (Picornell, Lytton and Steinberg, and Raadt, et al, 1987). Under greater levels of moisture tension, water is extracted from the pores of the ceramic tip and its thermal conductivity goes down. The thermal conductivity measurement can be calibrated with the level of matrix suction and thus the electrical reading can be converted into matrix suction. The manufacturer provides a calibration equation, but in checking this with laboratory instrumentation at Texas A&M University discrepancies were found in the manufacturer's calibration equation. The error gives matrix suction measurements that are too high, indicating that the manufacturer's calibration procedure may not allow the ceramic tip to come to equilibrium.

Assuming the calibration has been done properly, the thermal moisture sensors are generally accurate within the matrix suction range of 0 to -2 bars (-2 atmospheres).

The sensors were installed on March 14, 1986 at depths of 1.5 ft.(0.5 m), 4.0 ft.(1.2 m) and 7.5 ft.(2.3 m) on each side of three different moisture barriers: the 8-foot (2.4 m) fabric barrier, the lime injected barrier, and the lime-fly ash injected barrier.

Analysis of Profile Measurements

The analysis of the measured and digitized profiles in the right and left wheel paths was analyzed using the Fast Fourier Transform (FFT). A complete description of this mathematical tool is found in the literature (Brigham, 1974). Basically, the FFT decomposes the road profile into a family of sinusoidal functions at discrete frequencies. The FFT program used in the analysis of the data collected on IH 30 was designed to perform the following operations in each profile:

1. Sample the profile elevation at equally spaced intervals of 0.5 ft. (0.15 m);
2. Take 256 of those data samples, which represent a length of 128 feet (39.0 m);
3. Apply the FFT algorithm to that length, obtaining the distribution of one-half amplitudes (a/2) of sinusoids at the following frequencies:

$$f = \frac{j}{128} \quad \frac{\text{cycles}}{\text{foot}} \qquad j = 2,3,4.......,255$$

4. Using the amplitude and frequency data determine a maximum expected bump height, given by the sum of the amplitudes of all frequencies.
5. Repeat operations 2 through 4 for consecutive lengths of 128 ft. (39.0 m) for seven such lengths making a total of 896 feet (273m).
6. Average the distribution of half-amplitudes for the seven lengths and plot the results
7. Using linear regression analysis determined a relationship between the average half-amplitudes and the frequencies, in the form:

$$\frac{a}{2} = cf^{-n}$$

where c,n are regression constants.

A typical plot of the average half-amplitude versus frequency (the roughness spectrum) is shown in Figure 3, this one for the 8-ft. (2.4 m) fabric barrier section measurements made in 1987.

There is a reciprocal relation between the frequency, f, in cycles per foot and the wave length, λ, in feet per cycle, i.e., $\lambda = 1/f$. This makes the equation for amplitude as a function of wavelength to be

$$a = 2\,c\lambda^{n}$$

where a = the amplitude in inches (= 2.54 cm)

λ = the wave length in feet, (= .305 m)

The maximum bump height is equal to the sum of all of the amplitudes of each frequency, which is given by maximum bump height = $\sum_{j=1}^{v} a_j$

A measure of the roughness of a pavement is the area under the amplitude (a) versus wavelength (λ) curve which is

$$R = 2c\lambda^{n+1}/(n+1)$$

The criterion for an increase in roughness from one profile measurement to the next is given by the change of log R over the full range of wave lengths represented in the roughness spectrum which, in this case, is 64 ft. (19.5 m). The criterion is that (log R) is greater than zero. This, in turn, results in the following criterion:

$$\Delta(\log R) = \log \lambda_m (n' - n) - \log\left(\frac{c}{n+1}\right) + \log\left(\frac{c'}{n'+1}\right) > 0$$

where c, n = the coefficients of the original roughness spectrum and

c', n' = the coefficients of the subsequent roughness spectrum.

λ_m = the maximum wave length measured. In this case, it was 64 ft. (=19.5 m)

An objective measure of the change of roughness is given by the calculation of $\Delta(\log R)$. The number is roughly indicated by the length of the line on the graph of log c versus n which joins the intitial state coefficients with those of the final state.

Results of Profile Analysis

The results of profile analysis are considered in three parts: (a) change of roughness spectrum; (b) change of maximum bump height; and (c) change of serviceability index. Comparisons are made between the conditions in 1984 and 1986 on each section and between the treated section and its companion control section. Table 2 lists the values of log c and n for the right wheel path in each pavement section in 1984 and 1986. A graph of these data is shown in Figure 4 in which the direction of change is indicated by arrows. The amount of change of the roughness spectrum may be approximated visually by the length of the arrow. The actual change of spectrum is given in Table 3. The 8-ft (2.4 m) fabric

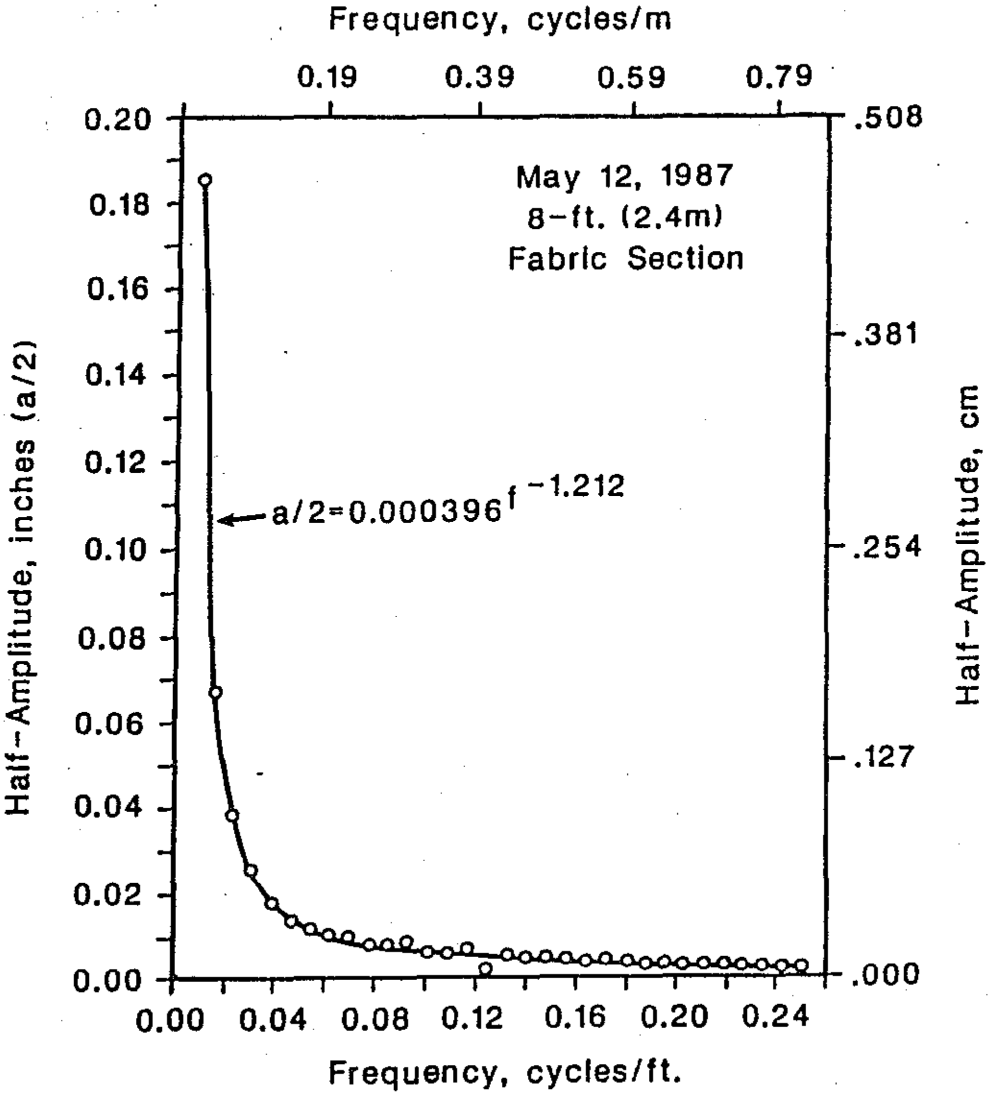

Figure 3. Roughness Spectrum for the 8 foot (2.4 m) Fabric Section (Measured May 12, 1987)

Table 1. Ranges of Soil Index Values for Barrier Sites

Site	Liquid Limit%	Plasticity Index%	Unified Class
Fabric Barrier	55-98	34-70	CH
Injection Barrier	60-90	40-75	CH

Table 2. Roughness Spectrum Coefficients - Interstate Highway 30 Sections, Outside Lane, Right Wheel Path.

Year	8 ft. (2.4 m) Fabric		6 ft. (1.8 m) Fabric		Lime Injected		Lime/Fly Ash Injected	
	log c	n	log c	n	log c	n	log c	n
Barrier								
1984	-3.509	1.249	-3.359	1.174	-3.297	1.128	-3.468	1.180
1986	-3.327	1.196	-3.417	1.206	-3.351	1.145	-3.515	1.257
Control								
1984	-3.266	1.154	-3.321	1.222	-3.538	1.221	-3.364	1.131
1986	-3.301	1.191	-3.204	1.182	-3.312	1.183	-3.304	1.162

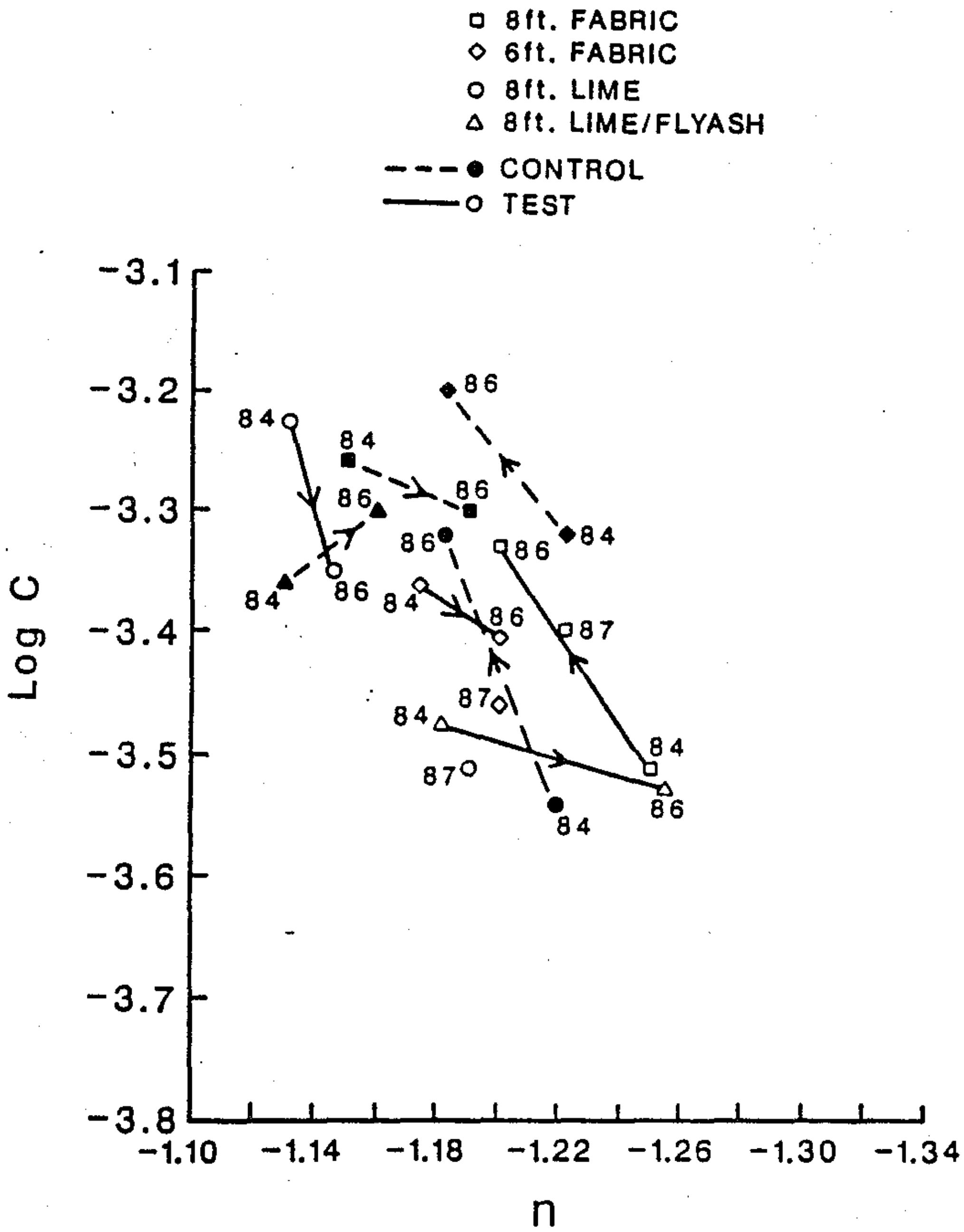

Figure 4. Roughness Spectrum Coefficient Changes from 1984 to 1986.

barrier and the lime-flyash barrier caused the pavement to become rougher. With both the 6 ft. (1.8 m) fabric barrier and the lime slurry injected barrier, the pavement surface became smoother with time. In comparison with its companion control section, the 8 ft. (2.4 m) fabric barrier is the only one that became rougher than its control.

The maximum bump heights are given in Table 4, along with the changes in each section from 1984 to 1986, and the difference between the changes from the test section to its companion control section. In every case the maximum bump heights increased with time but the change of maximum bump height is smaller in the control sections than in the barrier sections, as indicated by the negative differences. This indicates that all of the barriers are retaining water beneath the pavement, promoting more swelling, and approaching a stable moisture condition more than in the subgrade soils under their unprotected companion control sections. This is a strong indication that the subgrades were not in a stable moisture condition prior to the construction of the barriers.

The negative differences in percentages indicate the effectiveness with which the barriers retain the moisture, showing that the lime-fly ash slurry injected barrier and the 8 ft. (2.4 m) fabric barrier are the most effective in controlling moisture loss. This assessment must be verified with the results of the moisture sensor measurements to be presented later.

The increases in bump heights in the barrier sections follows the same trends and relative order as the changes of roughness spectrum shown in Table 3.

Serviceability index measurements were calculated using the measured profile in a computer program that estimated the root mean square vertical acceleration of the measured profile (Roberts, et al, 1970.) Table 5 shows the serviceability indexes of each section in 1984 and 1986 and the changes between them.

All sections developed a rougher ride in the two years since the installation of the barriers. The negative differences show that the barrier sections became rough at a faster rate than their companion control sections, one more indication of the ability of the barriers to retain moisture beneath the pavement. As was the case with the change of bump heights, the most effective barrier in the control of moisture loss was the lime-fly ash slurry injected barrier. The next two in order are the 6 ft. (1.8 m) and 8 ft. (2.4 m) fabric barriers. The implications of small differences of serviceability index on the order of 0.1 units must be assessed with caution since the serviceability index follows a non-linear scale of absolute roughness or change of elevation. This caution should be observed generally in using measurements of the effectiveness of pavement treatment. In this case, the changes in serviceability index between the barrier sections and their companion control sections provides nearly the same relative ranking of the effectiveness of the barriers as does the change of bump height.

The change of roughness spectrum favors the longer wave lengths and the change of bump height favors the shorter wave lengths because there are more of them. Between the results reported in Tables 3 and 4, the following is apparent.

1. The barrier sections are retaining water beneath the pavements, swelling more, and approaching moisture equilibrium faster than their companion control sections.

2. The barrier sections are becoming rougher than their corresponding control sections. As indicated by the change of roughness spectrum, the 8 ft.(2.4 m) fabric barrier is more effective at developing the longer wave lengths, and the lime-fly ash slurry injected barrier is more effective with the shorter wave lengths (as indicated by the change of bump height). These two barriers are the most effective of those that were constructed.

Table 4. Maximum Bump Heights and Changes Between 1984 and 1986 (inches).

Year	Treatment			
	8 ft. (2.4 m) Fabric Barrier	6 ft. (1.8 m) Fabric Barrier	Lime Slurry Injected Barrier	Lime-Fly Ash Slurry Injected Barrier
Barrier				
1984	.526	.511	.446	.437
1986	.640	.586	.497	.558
Change	+.114	+.075	+.051	+.121
Percent	21.6	14.7	11.4	27.7
Control				
1984	.490	.648	.422	.355
1986	.515	.664	.464	.358
Change	+.025	+.016	+.042	+.003
Percent	5.1	2.5	10.0	0.8
Difference	-.089	-.059	-.009	-.118
Percent	-16.5	-12.2	- 1.4	-26.9

1 inch = 2.54 cm

Table 3. Changes of Roughness Spectrum* from 1984 to 1986

Treatment	Barrier	Control	Change	Percent
8 ft. (2.4 m) Fabric	+0.0980	+0.0236	+0.0744	+315
6 ft. (1.8 m) Fabric	-0.0064	+0.0520	-0.0584	-112
Lime Slurry Injected	-0.0250	+0.1647	-0.1397	- 85
Lime-Flyash Slurry Injected	+0.0769	+0.1088	-0.0319	- 29

* A negative change means that the pavement surface has become smoother, and a positive change means that it has become rougher.

Table 5. *Serviceability Indexes and Changes Between 1984 and 1986.

Year	Treatment			
	8 ft. (2.4 m) Fabric Barrier	6 ft. (1.8 m) Fabric Barrier	Lime Slurry Injected Barrier	Lime-Fly Ash Slurry Injected Barrier
Barrier				
1984	3.71	4.06	4.11	4.04
1986	3.31	3.73	4.03	3.73
Change	-0.40	-0.33	-0.08	-0.31
Control				
1984	3.67	3.51	3.86	3.79
1986	3.41	3.39	3.71	3.71
Change	-0.26	-0.12	-0.17	-0.08
Difference	-0.14	-0.21	+0.09	-0.23

*S.I. Scale: 5.0 Very Good - 1.0 Very Poor

3. The eight foot (2.4 m) deep fabric barrier is considerably better then the six foot deep (1.8 m) barrier in preventing moisture exchange from beneath the pavement to the soil outside.

These conclusions lead to the following conjectures concerning the behavior of pavements with moisture barriers:

1. When a barrier is placed along each side of a pavement, it will permit the moisture beneath to move more quickly toward a stable condition.

2. If the soil beneath the pavement is not already in an equilibrium condition, the placing of a barrier may cause the pavement to become rougher at a faster rate than other pavements, but in the long term it will achieve a stable moisture condition and make all subsequent overlays and level-up courses more effective.

3. If the soil beneath the pavement is in a stable condition at the time the barrier is placed, the barrier will act to prevent further change of moisture and should preserve the surface profile of the pavement very well. This was the case in San Antonio, along IH-37 where the subgrade soil was in a very wet condition prior to the placement of 8 ft. (2.4 m) fabric barriers (Picornell, Lytton, and Steinberg, 1985).

4. The moisture barrier must extend to a sufficient depth to prevent or to reduce substantially the exchange of moisture from beneath the pavement to the soils outside.

5. As a final point, it is very important in the long-term planning of the rehabilitation of a pavement on expansive clay to know the initial moisture state and to know the depth to which a moisture barrier should be carried in order to be effective.

Matrix Suction Measurements

As is apparent from the foregoing discussion, the real proof of the effectiveness of moisture barriers is their effect on the surface profile of the pavement. Moisture measurements are made, not as primary proof, but as confirmatory evidence of the trends that are noted.

The data shown in Table 6 are the dates, the days in service, and the matrix suction in bars of the sole moisture sensor that has provided readings inside the 8 ft. (2.4 m) fabric moisture barrier. Because the manufacturer's calibration equation was used in reducing the data, some of the matrix suction values in the table appear as positive, i.e., compressive which is highly unlikely. Nevertheless, the trend is important since it indicates a gradual, steady decrease of matrix suction with time which indicates that the soil is wetting up.

The data in Table 6 are shown graphically in Figure 5a and 5b. Fig 5a shows the matrix suction inside the moisture barrer and Fig. 5b shows the matrix suction outside the moisture barrier. The striking feature about these two graphs is the wide variation outside and the smooth increase inside the moisture barrier, tending to confirm the inferences from the analysis of the profile data. The moisture sensor at the 4.0 ft. (1.2 m) depth outside the barrier became so dry that it went out of operation.

By way of contrast, the matrix suctions measured inside and outside the lime slurry injection barrier are given in Table 7, and illustrated in Figures 6a and 6b. This is the barrier that was judged to be least effective in preventing moisture exchange from the analysis of the profiles. The patterns of matrix suction vary somewhat more on the outside of the barrier than on the inside, but in general, the trends and the measured values are nearly the same. The dip in the readings around 150 days in place is the reading in August at the end of the summer. Because of the relatively small differences between the matrix suction patterns inside and outside the lime slurry injection barrier, this tends to confirm the findings of the profile analysis that this type of barrier is least effective in preventing moisture exchange.

Conclusions

Two types of measurement were made: profile measurements and matrix suction measurements. Of the two, the profile measurements and subsequent analysis are more definitive and the matrix suction measurements tend to confirm the profile analysis results. Profile analysis produces three ways of looking at the same data: roughness spectrum, maximum bump height, and serviceability index. Of the three, the first two are more objective with the roughness spectrum favoring the larger wave lengths and the bump height favoring the smaller wave lengths.

Because the subgrade was initially drier than it would eventually become, the effect of moisture barriers is to retain moisture beneath the pavement and to accelerate swelling and the development of roughness faster than companion sections without barriers. The most effective barrier to accelerate this process by preventing moisture exchange is the 8 ft. (2.4 m) fabric barrier followed by the lime-fly ash slurry injected barrier, the 6 ft. (1.8 m) fabric barrier, and the lime slurry injected barrier. The installation of a barrier may not prevent future overlays but in the long term, by stabilizing a moisture regime beneath the pavement, it will make future overlays more effective.

In planning for the long-term rehabilitation of pavements on expansive soils, the initial moisture state of the subgrade soil must be

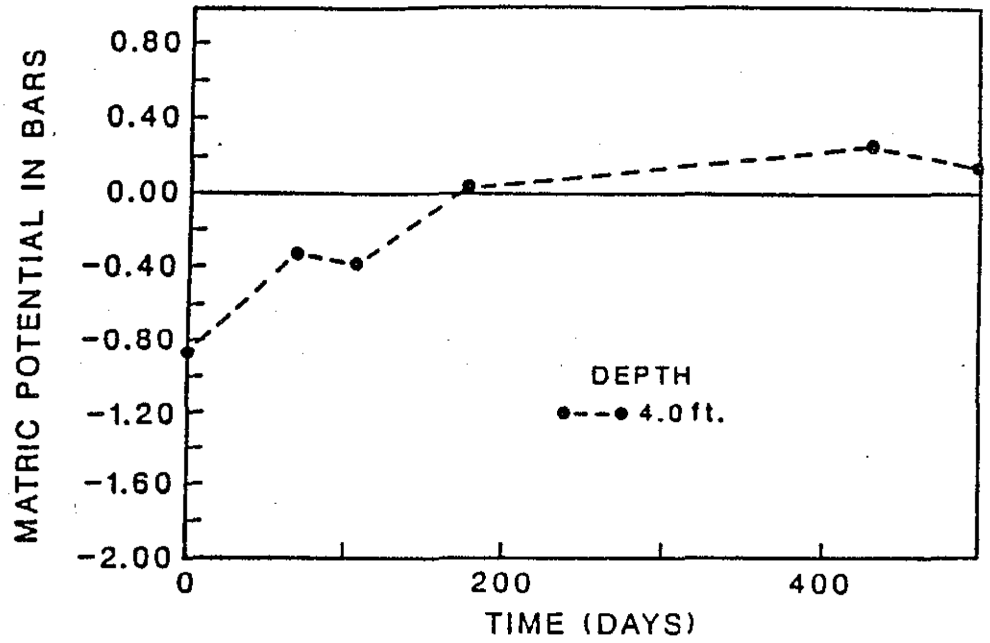

Figure 5.a. Matrix Suction Inside the 8 ft. (2.4m) Fabric Moisture Barrier.

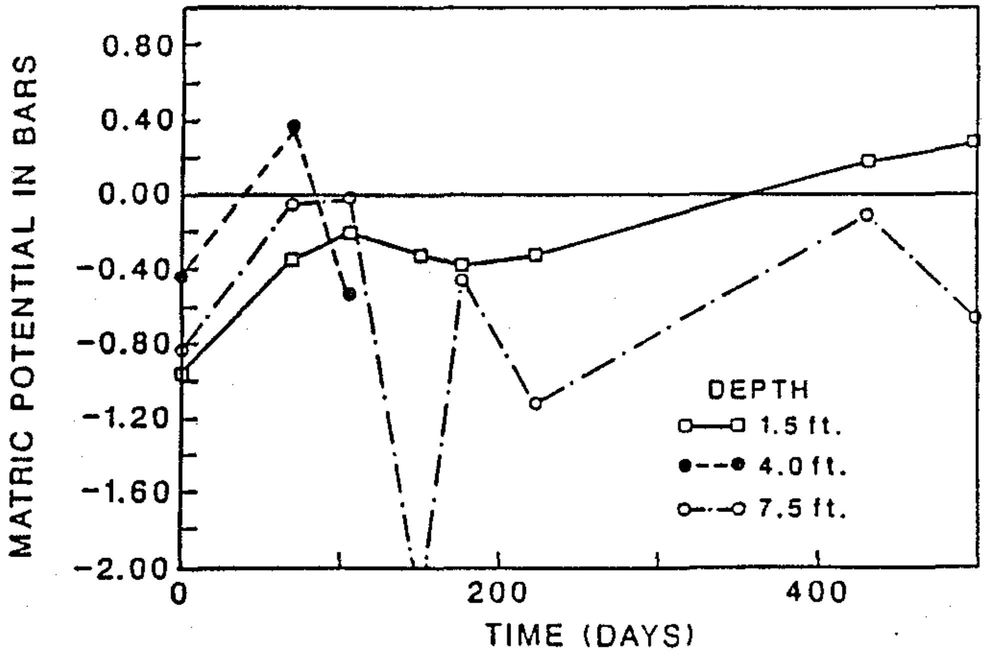

Figure 5.b. Matrix Suction Outside the 8 ft. (2.4m) Fabric Moisture Barrier.

Table 7. Matrix Suction Measurements Inside and Outside the Lime Slurry Injected Barrier.

Date of Measurement	Time in Place, Days	Matrix Suction Measurement (Bars)					
		Inside Moisture Barrier Depth, ft.			Outside Moisture Barrier Depth, ft.		
		1.5	4.0	7.5	1.5	4.0	7.5
March 14, 1986	0	-0.72	-0.74	-0.71	-0.71	-1.10	-0.94
May 23, 1986	69	-0.64	-0.38	-0.25	-0.38	-0.73	-0.49
June 30, 1986	106	-0.35	-0.29	-0.23	-0.32	-0.64	-0.43
Aug. 15, 1986	151	-0.39	-0.26	-0.22	-0.89	-0.66	-0.47
Sept. 11, 1986	177	-0.43	-0.27	-0.18	-0.48	-0.30	-0.48
Oct. 27, 1986	223	-0.41	-0.04	-0.10	-0.42	-0.48	+0.01
May 27, 1987	431	-0.01	-0.07	+0.02	+0.07	+0.28	-0.04
July 24, 1987	495	-0.05	-0.00	-0.09	+0.13	+0.13	+0.03

(1 ft. = 0.305 m)

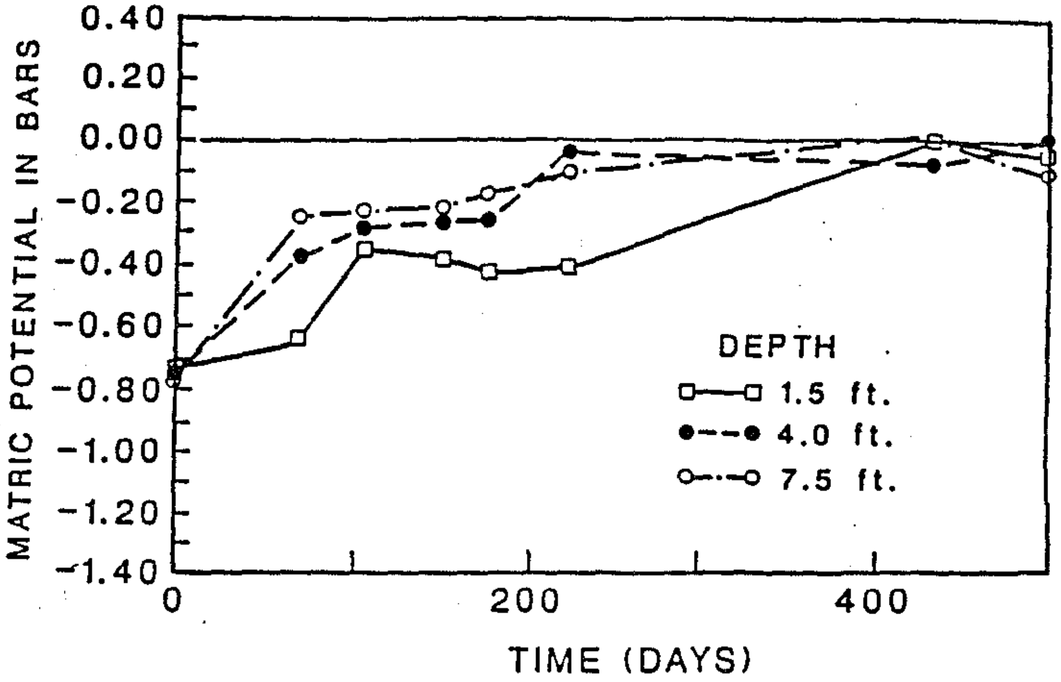

Figure 6a. Matrix Suction Inside the Lime Slurry Injected Moisture Barrier.

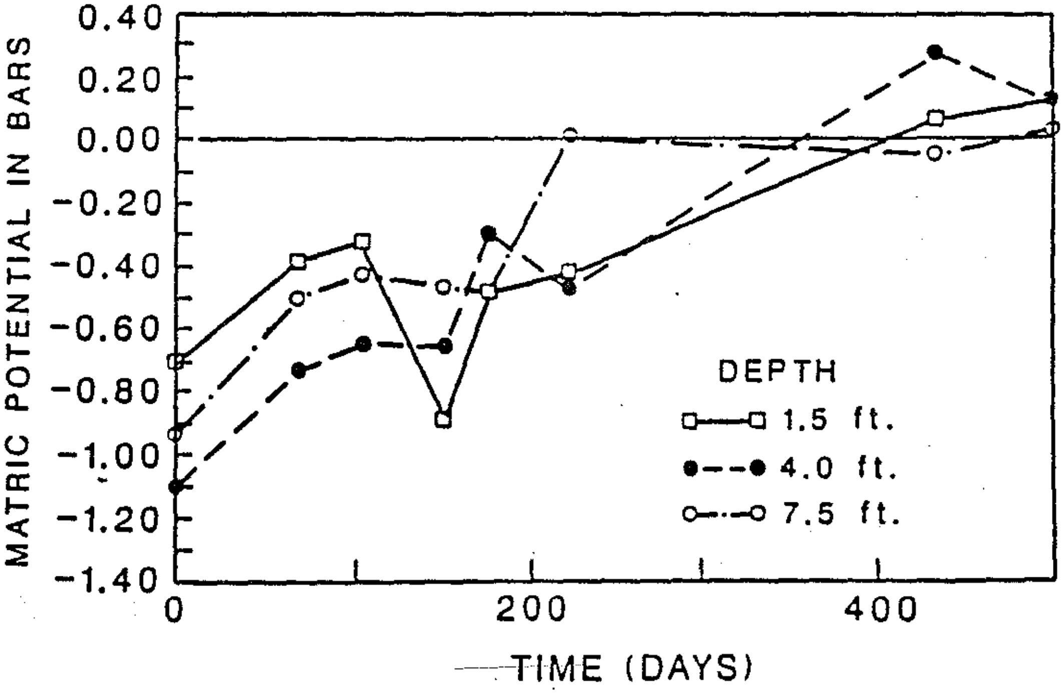

Figure 6b. Matrix Suction Outside the Lime Slurry Injected Moisture Barrier.

known and the depth of the moisture barrier in order to prevent moisture exchange must be chosen carefully to provide the desired growth of roughness with time, consistent with expected availability of funds for level-up courses and overlays.

References

1. E. Oran Brigham. The Fast Fourier Transform. Prentice-Hall, Inc., Englewood Cliffs, N.J., 1974.

2. M. Picornell, R. Lytton, and M.L. Steinberg. Assessment of the effectiveness of a vertical moisture barrier. 5th International Conference on Expansive Soils, 1985.

3. F.L. Roberts and W.R. Hudson, Pavement serviceability equations using the surface dynamics profilometer. Research Report 73-2, Center for Highway Research, The University of Texas at Austin, April, 1970.

4. R.O. Stone and J. Duqungi. A study of micro-relief-its mapping, classfication, and quantification by means of fourier analysis. Engineering Geology Vol. 1 No. 2. 1965-66, pp. 91-187.

5. P. van der Raadt, D.G. Fredlund, A.W. Clifton, M.J. Klassem, and W.E. Jubien. Soil suction measurements at several sites in Western Canada. Transportation Research Board, Washington D.C., 1987.

6. M.O. Velasco and R.L. Lytton. Pavement roughness on expansive clays. Transportation Research Record 790, 1981.