Behavior and Design of Vertical Moisture Barriers

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Seasonal wetting and drying affect pavements on expansive soils with two main damage types: roughness development and longitudinal cracking. The purpose of the moisture barrier is to isolate the subsoil from these climatic changes. The predominant type of damage and the function of the barrier are found to depend on the initial moisture conditions of the subsoil. For desiccated soils, the barrier must prevent the infiltration of rainfall into the shrinkage cracks to stop the development of roughness. For wet soils, the barrier must prevent excessive drying under the edge of the pavement. The barrier depth is chosen based on the maximum crack depth and the shrinkage of the pavement edge that would occur under the most severe drought intensity expected during the lifetime of the pavement. The drought intensity is chosen based on a statistical analysis of meteorological data for the site. The driest matrix potential profile is obtained from the drought intensity through a simulation of unsaturated water flow. This profile is used to determine the maximum shrinkage. The accumulated shrinkage with depth is used to calculate the total edge shrinkage. A modified shrinkage, which includes the effect of multiple cracks, is used to simulate the propagation of the cracks. The rooting depth of native vegetation is identified as the controlling parameter on the barrier depth. A conservative estimate of the depth of grass roots is 8 ft. A successful moisture barrier must be placed to the depth of the roots in order to stop longitudinal cracking and about 25 percent deeper than the rooting depth to stop the development of roughness.

Two main types of damage affect pavements founded on expansive soils. One is the formation of mounds and depressions responsible for the development of roughness in the pavement and the resulting loss in riding quality and the other is the occurrence of longitudinal cracks near the edges of the pavement, which results in the progressive deterioration of the pavement.

The installation of a vertical moisture barrier enclosing the soils beneath the pavement is a measure that has been used to dampen the moisture variations of the subsoil to reduce the differential volume changes that the pavement must withstand *(1)*.

Described in this paper are the possible roles of the barrier, the design considerations needed to tailor the depth of the barrier to the specific conditions of a site, and a simplified procedure to select the depth of a vertical moisture barrier for practical applications.

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ROLE OF A VERTICAL MOISTURE BARRIER

A vertical moisture barrier can play different roles depending on the moisture conditions of the subsoil at the time of installation of the barrier.

If the subsoil is initially very dry, the soil deposit exhibits a characteristic shrinkage crack fabric that splits the top of the soil deposit into blocks. These cracks permit the access of free water to the soils beneath the pavement. The soils of the crack walls have access to free water and, therefore, can swell. The inner parts of the soil blocks do not swell because they do not have access to water because of the extremely low permeability of the soil blocks. This differential swelling is responsible for the development of roughness *(2)*. The role of the moisture barrier for this condition is to prevent the access of free water to the crack fabric of the soils beneath the pavement. To achieve this goal, the barrier should be installed to the maximum possible depth of the shrinkage crack fabric for the conditions of the site.

If the subsoil is initially very wet, the crack fabric is closed or ineffective in transmitting free water. However, the subsoil beneath the edge of the pavement experiences seasonal moisture changes, whereas the moisture of the subsoil beneath the center of the pavement remains constant. This differential behavior is responsible for the formation of longitudinal cracks along the edges of the pavement *(3)*. In this case the role of the barrier should be to reduce the seasonal moisture changes of the soil under the pavement edges. The depth of the barrier should be chosen to reduce the settlements under the edge so that the angular deflection imposed on the pavement does not cause longitudinal cracks.

The two most frequent cases that are expected to occur in practice are the installation of the barrier with a new pavement or rehabilitation of an old pavement. A new pavement is normally built during the drier months of the year; the subsoil can therefore be expected to be in dry condition and the main role of the barrier in such a case is to prevent the development of roughness. As a contrast, if the barrier is used to rehabilitate an old pavement, the dominant consideration will usually be to mitigate edge drying because the subsoil would be normally expected to be very wet *(4)*.

PRELIMINARY DESIGN CONSIDERATIONS

The soils beneath the pavement are not in direct contact with the atmosphere. The water removed or the water that infiltrates beneath the pavement must pass through the soil profile adjacent to the edge of the pavement. This profile is exposed to the

atmosphere and extends from the edge of the pavement to the flow line of the side drainage ditch. The depth of the barrier must be chosen based on the deepest shrinkage cracks that can occur in this profile to prevent the free water from bypassing the barrier. Furthermore, the volume changes of the soils under the edge of the pavement and located below the depth of the barrier will be approximately the same as the volume changes of the soils at the same elevation but in the exposed soil profile. In summary, the design of the moisture barrier can be based on the volume changes and depth of shrinkage cracks estimated for this exposed soil profile.

The maximum shrinkage crack depth is a function of the driest moisture profile possible. The maximum volume changes are a function of the wettest and driest moisture profiles that are possible in the exposed soil profile. These moisture profiles are driven by the climatic conditions: rainfall and evapotranspiration. As the climatic conditions are stochastic in nature the wettest and driest moisture profiles are also stochastic. The pavement should be designed for the worst conditions that can reasonably be expected to occur during its lifetime. This implies the need for attaching probabilities to different stages of wetness and dryness of the soil profile. The design should be based on the extreme profiles that have the desired probability of not being exceeded in the life of the pavement.

This can be accomplished using the existing record of weather data. The details of this analysis have been described elsewhere *(5)*. The results of this study indicate that the wettest profile can be considered to be near saturation in semidesertic climates. The driest profile is characterized by the depletion percentage of the soil reservoir that has the desired probability of not being exceeded.

The next step is to relate the depletion percentage to the driest moisture content (or matrix suction) profile. This can be accomplished by numerical simulation of water flow through a one-dimensional soil profile. The water movement is driven by the climatic conditions at the exposed ground surface. The water is removed from the section by evaporation from the exposed soil surface and by transpiration of the native vegetation.

There is ample evidence that indicates that the evaporation from the soil surface is very small. This has been observed by Ritchie and Adams *(6)* from measurements in a lysimeter. The same conclusion can be obtained from the comparison of the heave measurements of de Bruijin *(7)* on a base soil surface treated with defoliant and on the same soil deposit covered with a glass-reinforced polyester sheet. The matrix suction profiles monitored by Ritchie et al. *(8)* and Richards *(9)* indicate that the effect of soil evaporation is confined to the uppermost foot of the soil deposit. The effect of the shrinkage in the upper foot on the maximum depth of the shrinkage cracks or on the volume changes of the soils under the edge is small compared to the total amount. Therefore, the driest profile can be obtained by simulation of the transpiration alone. This conclusion is in agreement with the observation of Williams and Pidgeon *(10)* that the vegetation controls the driest moisture profile.

An additional aspect relative to soil evaporation is that the presence of shrinkage cracks causes the exposure of more soil surface to the atmosphere and at wetter conditions than the ground surface. The question is whether, as suggested by Ravina *(11)*, the water removed from the crack faces can cause drying at the tip of the crack that could cause a progressive extension of the crack. The effect of wind drying has been found to decrease with depth inside the cracks *(12)*. The published data on moisture contents around cracks by Ritchie and Adams *(6)* and by Johnson and Hill *(13)* indicate that the removal of soil water from cracks deeper than 2 feet is unlikely. As the design crack depth is the maximum that is likely to occur in the desired return period, the crack depth sought will most likely be considerably larger than 2 feet. Therefore, it appears safe to conclude that crack propagation due to evaporation drying at the crack tip is negligible.

DETERMINATION OF THE DRIEST MOISTURE PROFILE

The driest matrix suction profile that corresponds to the depletion percentage chosen in the statistical analysis is obtained from the numerical simulation of the water flow driven by plant transpiration alone. The flow of water through the soil mass is assumed to obey an extension of Darcy's law proposed by Richards *(14)* for unsaturated soils with the inclusion of a sink term to account for the removal of pore water by the roots of the vegetation.

The approach adopted is to represent the roots by a sink term distributed uniformly within each elemental volume of soil. Molz et al. *(15)* have shown that this approximation is fairly close to reality. The extraction term used is a slight modification of the term proposed by Nimah and Hanks *(16)*. This model was satisfactorily tested under field conditions *(17)*.

A prerequisite to using this extraction term is knowing the root density distribution and rooting depth of the vegetative cover. The most frequent kinds of vegetation growing near pavements are native grasses. There is ample agreement in the literature *(10, 18–20)* about the rooting depths of native and sod-forming grasses, which are reported to be from 6 to 8 ft tall. Molz and Remson *(21)* have proposed a dimensionless root density distribution, which is shown in Figure 1, for rooting depths of 6 and 8 ft. Also shown in Figure 1 are root density distributions obtained from field surveys of soil monoliths by Weaver and Darland *(20)* and Laird *(18)* for typical Texas grasses. Molz's distribution for an 8-ft rooting depth is an envelope enclosing most of the available field data. This is the root density distribution adopted in this study.

The numerical simulation is approached through a finite element technique to discretize the space coordinates and to evaluate the space derivatives, and a finite difference scheme to discretize the time domain. The numerical algorithm used is an expanded version of the algorithm proposed by Nieber *(22)*. The simulation is performed with the program "CRKFLOW", whose FORTRAN deck is listed by Picornell *(5)*. The simulation is carried out with material properties of expansive soils typical of Texas. The permeability function used was fitted through the measurements presented by Ritchie et al. *(8)*. The desorption curve was obtained from laboratory tests on samples from I-37 in San Antonio, Texas *(5)*.

The matrix potential profile at several degrees of depletion of the soil reservoir is obtained from field capacity by imposing a constant transpiration rate of 0.00005 cm/sec. This simulation

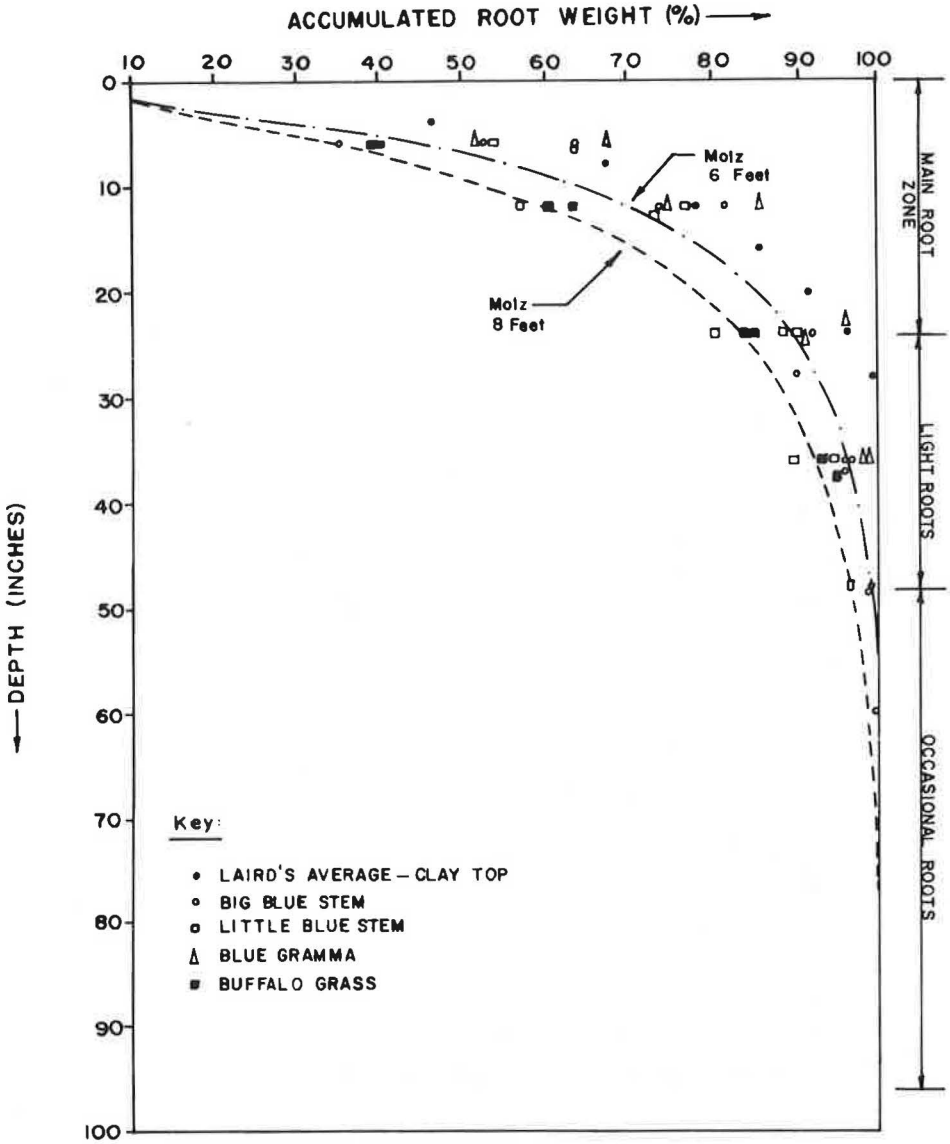

FIGURE 1 Summary of root density distributions for native grasses.

does not include any interruption due to rainy periods or soil water redistribution. The results of the simulation include nine intermediate steps of depletion plus the profile that corresponds to the wilting of the vegetative cover. These results are presented in Figure 2.

Although these results were obtained with a specific combination of permeability function and desorption curve, the resulting matrix potential profiles are considered to be representative for other expansive soils provided that their permeability functions are similar. The desorption curve is relevant when the matrix potential profiles must be related to the degree of water depletion in the soil profile.

These potential profiles were obtained assuming a rooting depth of 8 ft. The extension of these results to slightly different rooting depths can be obtained by scaling the depths. Figure 3 shows a comparison of a field matrix potential profile at the lower limit of water availability (8) for a crop with an observed rooting depth of 5 ft and the results of the simulation at the lower limit of water availability scaled for a rooting depth of 5 ft. This scaled profile compares favorably with Ritchie's field measurements.

DETERMINATION OF SETTLEMENTS AND CRACK DEPTH

The driving mechanism causing the edge settlements or the propagation of the shrinkage cracks is the volumetric strains experienced by the soil upon a change of matrix potential. The volumetric strains are determined with existing methods *(23)*. The linear shrinkage is obtained as one-third of the volumetric strain.

The material properties to apply this model can be obtained from laboratory tests on undisturbed samples *(24)*. However, the expenses involved are seldom justifiable in a routine design. This limitation can be avoided by finding these properties from published correlations *(25)* based on index soil properties.

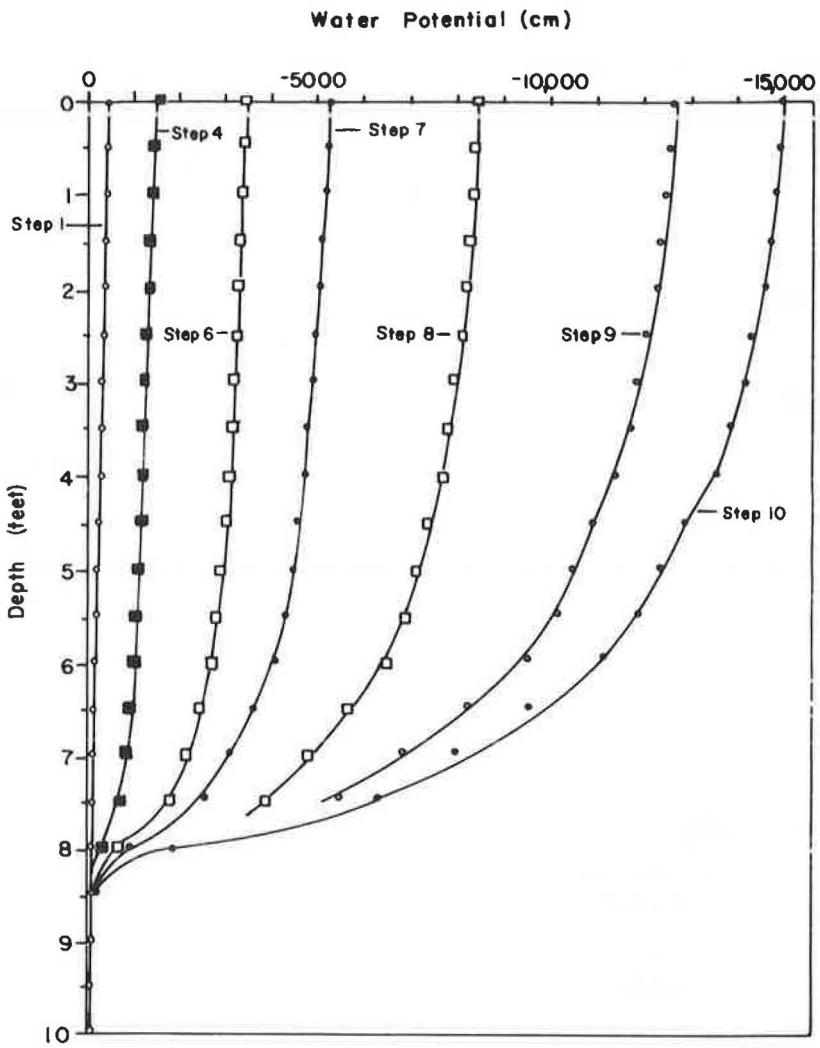

FIGURE 2 Design profiles of matrix potential versus depth.

The shrinkage of the soils under the pavement are estimated by the shrinkage of the exposed soil profile adjacent to the barrier. In this manner, the soils below the bottom of the barrier, the depth interval A–C in Figure 4, are assumed to experience the same movements as those experienced by the soils at the same elevation but outside the barrier. The soils enclosed by the barrier and located above the bottom tip of the barrier, the depth interval B–A in Figure 4, are assumed to remain at constant volume at all times.

From this point of view, the barrier depth is chosen as the smaller depth that would maintain an angular distortion of the pavement edge (ratio of edge settlement to the length of the edge moisture variation) at less than 1/360 on the occurrence of the design meteorological event. The edge moisture variation, E_m in Figure 4, is different depending on the depth of the barrier. A conservative estimate for E_m is the distance A–C between the bottom of the barrier and the bottom of the soil layer affected by the event.

The shrinkage crack propagation is a consequence of the differential shrinkage of the soils at different depths. There is an assortment of cracks with different depths in the soil mass. There is ample evidence *(26, 27)* that the number of shrinkage cracks in a section, their geometric configuration, and the distribution of crack depths are imposed by the type of vegetative cover and the predominant environmental conditions. A shrinkage crack depth distribution that is believed to be representative of roadside conditions in Texas corresponds to the site GRF in the experimental data published by El Abedine and Robinson *(26)*.

To estimate the maximum crack depth, it is necessary to study the behavior of a soil region extending between two consecutive major cracks. A typical spacing between major cracks is 16 ft (488 cm) *(2)*. The linear shrinkage that occurs at each depth translates into displacements imposed on the crack faces of all shrinkage cracks reaching each depth. Therefore, only part of the total shrinkage at each depth goes into increasing the width of the two major cracks. This part of shrinkage is estimated from the average crack spacing at each depth assuming that all cracks are evenly spaced. The distribution of crack depths used is shown in Figure 5. The analysis forces the distribution of cracks always to follow the relationship shown in Figure 5 independently of the size of the maximum crack depth. The average spacing is obtained by dividing the 16-

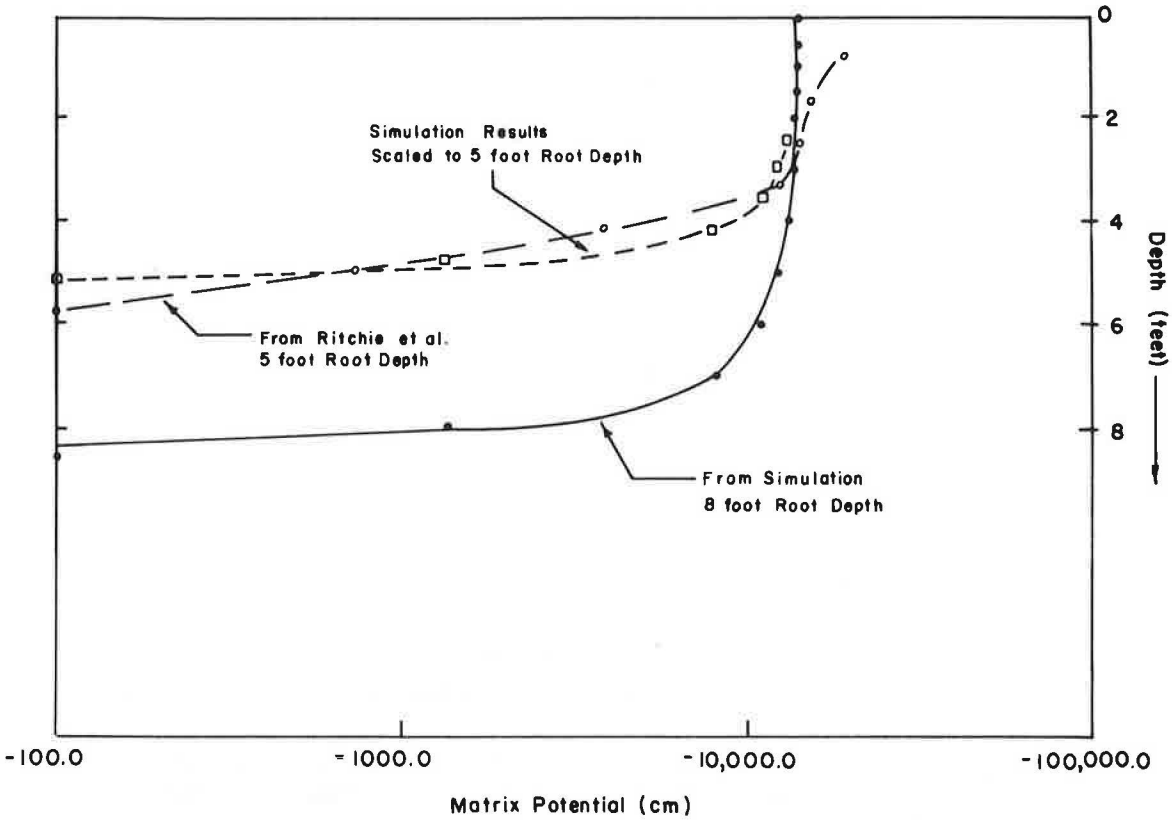

FIGURE 3 Water potential versus depth at the wilting point.

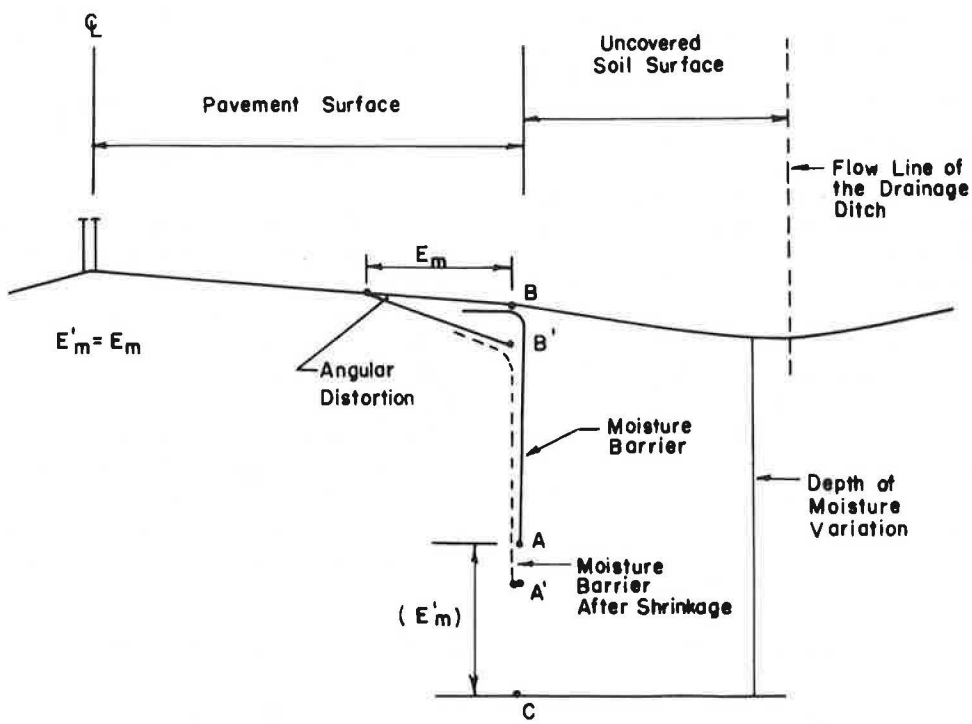

FIGURE 4 Illustration of the differential drying conditions under the pavement edge.

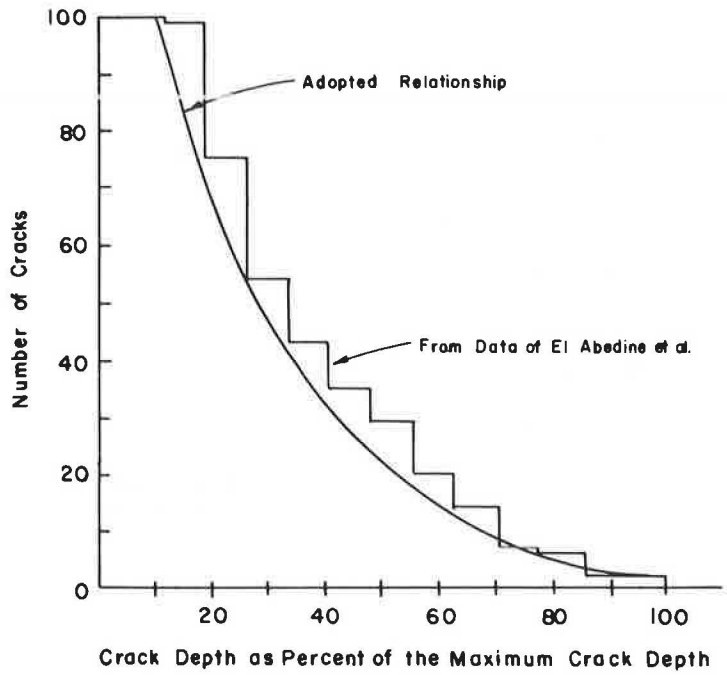

FIGURE 5 Distribution of number of cracks with depth.

ft (488-cm) spacing between major cracks into the number of cracks (n_c) minus 1 that reach the depth in question. Because the depth included in Figure 5 is relative to the maximum crack depth, n_c is found at each depth by trial and error. Because each soil column is bounded by two shrinkage cracks, this implies that the displacement (d_i) imposed on each crack face is the result of the linear shrinkage (ε_i) acting only on one-half of the average crack spacing.

Neglecting the Poisson's effect, the shrinkage crack must extend at least to the deepest point in the profile that will experience any volumetric strains in the change from the wettest to the driest profile. The question is how much the crack will propagate beyond this point imposed by the displacements that occur above this same point.

Besides the imposed displacements, the factor controlling this extra crack propagation is the predominant soil modulus in the area where the propagation takes place. The area into which the crack will extend will be essentially unaffected by the root extraction, as the change from wettest to driest conditions will not impose any volumetric strains at this level. Therefore, it is reasonable to assume that the soil in this area will behave very nearly as if it were saturated. Under these conditions, the extension of the crack may be analyzed assuming that the soil near the crack tip is elastic, with the elastic modulus being a function of the confining stress. The dependence of the elastic modulus on the confining stress is assumed to follow the model proposed by Janbu *(28)*. The material parameters of this model are adopted from typical values proposed for highly plastic soils *(29)*.

The effect of the soil modulus on the final crack depth is small. Therefore, it is believed that the crack depth for most expansive soils can be found, to a good approximation, using an elastic modulus of 1,400 psi (100 kg/cm^2) at 5 psi (0.3 kg/cm^2) confining pressure; that is, the crack depth can be found using the set of curves presented in Figure 6.

PROPOSED DESIGN PROCEDURE FOR DEPTH OF MOISTURE BARRIERS

The first step to determine the depth of a moisture barrier is to select the appropriate parameters for the particular site being considered. These include parameters related to the geometrical design of the cross section and others related to site conditions. The rainfall multiplying factor (RMF) is in the first category. The second category includes the rooting depth and the maximum water capacity of the soil profile.

The next step is to use these data and the design life chosen for the pavement to determine the minimum water depth associated with the design event as described elsewhere *(5)*. From this minimum, the driest matrix potential profile to be expected is defined. The driest and wettest profiles determine the total linear shrinkage that can take place at each depth within the root zone.

The total shrinkage at each depth is modified to take into account the presence of multiple shrinkage cracks. The maximum crack depth is obtained by trial and error. The criterion to prevent the development of pavement roughness is based on the maximum crack depth. The criterion to prevent excessive edge drying is derived from the expected profile of total shrinkage.

The evaluation of these parameters and a summary of all of the steps for the design are discussed in detail in the rest of this section. The design procedure is illustrated for a section of I-37 in San Antonio, Texas. The site investigation and the monitoring of this section have been described elsewhere *(30)*.

Rainfall Multiplying Factor (RMF)

The RMF embodies the effects of several phenomena that modify the availability of water to a soil profile adjacent to an

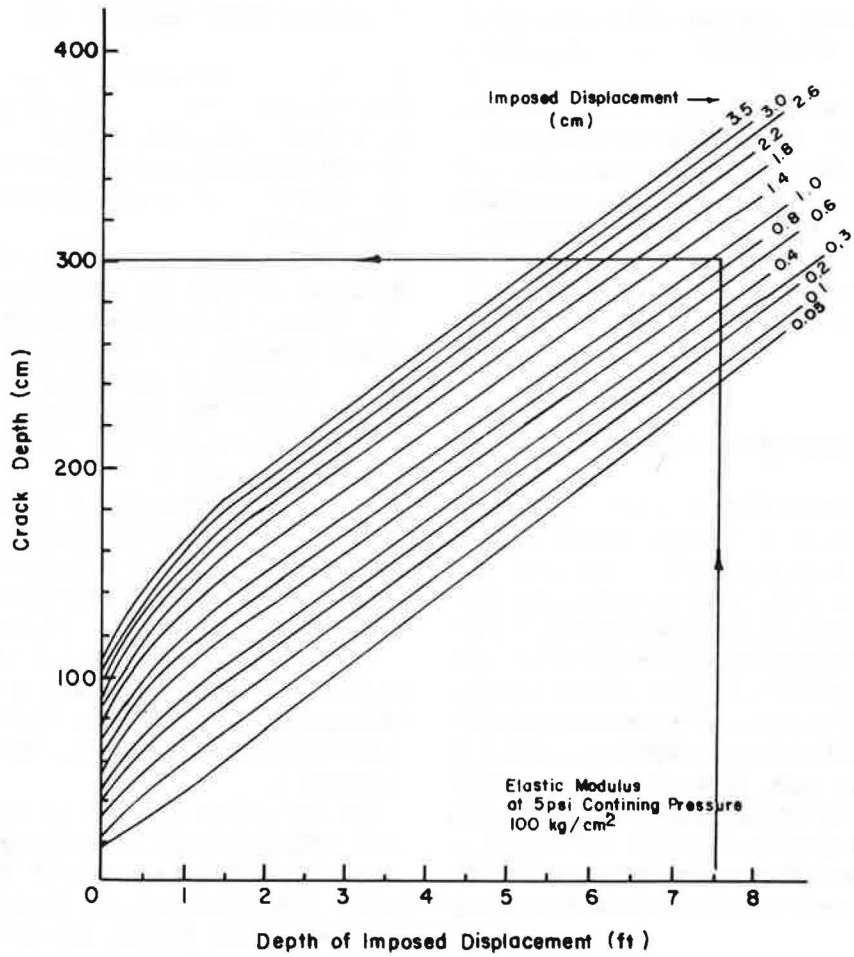

FIGURE 6 Design curves of crack depth versus imposed displacement and depth of imposed displacement for an elastic modulus of 100 kg/cm^2.

impermeable structure like a pavement. The first of these effects is due to the runoff from the pavement if it drains toward the side drainage ditch. This runoff is an extra supply of water for these soils above the normal rainfall for the area. The second effect is due to the shape of the general ground surface surrounding the pavement. If the ground surface slopes down away from the pavement, the free water within the crack fabric might flow away from the structure; by way of contrast, if the highway is in a cut, part of the rainfall on the slope will flow toward the drainage ditch and will provide an extra supply of water for the soils adjacent to the pavement. Thus, the depth of the moisture barrier may not be uniform within a section. The depth of the barrier must be defined for the conditions prevailing at the edge of the pavement where it is to be installed.

The RMF is equal to 1 when the pavement edge does not receive any runoff. When there is runoff from the pavement, the effect is estimated assuming that all the rainfall on the pavement is available to the edge soils. The total water available is obtained by multiplying the rainfall by the ratio of the width of the pavement draining to the side plus the width of the edge soils over the width of the edge soils. This relative width ratio is believed to be a reasonable estimate of the RMF for the case of a highway on flat ground; however, this value must be modified somewhat if the section runs in a cut or an embankment. When the highway is in a cut, the RMF is expected to be somewhat larger than the relative width. Similarly, it is expected that the RMF is smaller than the relative width ratio in the case of an embankment.

The section of I-37 that is used in the example runs in a cut about 15 ft deep. The roadway has three lanes with a shoulder in each direction separated by an impermeable median. The cross section is symmetrical with respect to the median, and, therefore, the moisture barriers on both edges of the pavement may be designed for identical conditions. The total width of each roadway is about 65 ft; the width of the exposed soil surface at the edge of the pavement is from 5 to 15 ft. Therefore, the relative width ratio is at least 5, even without including any contribution of water from the cut slope surface. In this case, an RMF of 5 seems reasonable.

Rooting Depth

There is ample agreement in the literature that the root system of native and sod grasses extends to maximum depths of 6 ft (180 cm) to 8 ft (240 cm). A root depth of 8 ft (240 cm) means that the barrier will be designed for the worst possible case. This assumption appears reasonable for the case of a well-developed homogeneous soil profile. However, under many conditions root development is impaired and the above assumption may be excessively conservative. Root growth is

controlled by water availability, soil compaction, and the availability of oxygen. But the main factor that limits root growth is oxygen availability *(27)*.

If the soil is depleted of water frequently, it seems reasonable to expect root depths of 8 ft (240 cm). However, if the profile is rarely emptied of water, the lower part of the root system will remain in anaerobic conditions most of the time, and therefore it will progressively die. If the root system is confined to shallower depths, the effect on the design can be very important. However, at the present time, until this aspect can be confirmed, the conservative approach is to use a root depth of 8 ft (240 cm).

Determination of the Driest Matrix Potential Profile

The root depth selected for the site is used to scale the design matrix potential profiles shown in Figure 2. The next step is to determine the minimum water depth for the design event. This is accomplished using the results of the statistical analysis *(5)* with the maximum soil capacity, life of the pavement, and the RMF. For I-37, a profile capacity of 22 in. (56 cm) of water, an RMF of 5, and a design life of 25 years indicate a design minimum water depth of 35 percent of the maximum capacity.

This percentage is used to identify which intermediate drying step yields a stored water depth closest to the design minimum. This is done by calculating the water depth stored for each step and then choosing the profile that contains a stored water depth closest to the design minimum. For I-37, the driest potential profile matrix possible corresponds to drying step No. 6.

Calculation of Shrinkage and Crack Depth

The first step is to calculate the linear shrinkage associated from saturation to the driest possible profile. Then the experimental crack distribution of Figure 5 is used to estimate the imposed displacements on the potential crack face. This process can be arranged in a table as illustrated for the pavement of I-37 in Table 1.

The final matrix potential at each node shown in column 3 is the drying step No. 6. The vertical stresses shown in column 4 are calculated with the unit weight of the soils at I-37. The soil parameters used are $\gamma_h = 0.08$ and γ_σ 0.10 and thresholds of –50 cm for the matrix potentials and 0.097 kg/cm^2 for the octahedral stresses. The linear shrinkage at each node is calculated by substituting the final potentials in column 3 and stress, column 4, into Equation 2.

From the linear shrinkage, the crack depth is calculated by trial and error. In Table 1, the first guess is a maximum crack depth of 9 ft (270 cm). The relative depth is found by dividing each node depth, column 2, into the 9 ft (270 cm). The number of shrinkage cracks that reach each node is read from Figure 5 as the ordinate of the continuous curve corresponding to the depth of the node. The number of cracks and the linear shrinkage are used in Equation 3 to determine the displacements imposed on the crack's face. These are listed under Trial 1, column 7.

The depth of the node and the imposed displacement are used in Figure 6 to read the corresponding crack depth, which is listed under Trial 1 of column 8. The largest value in this column is the maximum crack depth. In this case, the largest value is 325 cm. Because this crack depth is noticeably

TABLE 1 SAMPLE OF CALCULATION OF CRACK DEPTH FOR I-37 IN SAN ANTONIO, TEXAS

Mode No.	Depth (cm)	Matrix Potential (cm)	Vertical Stress (kg/cm)	Linear Shrinkage (%)	Angular Deflection	Imposed Displacement (cm) Trial 1	Trial 2	Trial 3	Imposed Crack Depth (cm) Trial 1	Trial 2	Trial 3
1	0	3256	*	*	*						
2	15	3242	0.073	4.83	0.034						
3	30	3216	0.047	4.82	0.033						
4	45	3185	0.093	4.81	0.032						
5	60	3158	0.100	4.76	0.031						
6	76	3123	0.130	4.36	0.029						
7	91	3085	0.160	4.05	0.028						
8	106	3049	0.190	3.79	0.027						
9	121	3008	0.223	3.54	0.025						
10	137	2919	0.260	3.28	0.024						
11	152	2848	0.290	3.10	0.023						
12	167	2769	0.320	2.92	0.021	0.594					
13	182	2663	0.353	2.73	0.020	0.740					
14	198	2377	0.387	2.47	0.018	0.927	0.603				
15	213	2085	0.420	2.20	0.016	1.193	0.716		275	261	
16	228	1750	0.453	1.89	0.013	1.537	0.838		298	288	
17	243	677	0.481	0.68	0.007	0.830	0.415		325	300	
18	258	131	0.513	0.00	0.000	0.000	0.000		312	292	
						Assumed Crack Depth			Resulting Crack Depth		
						270	300		325	300	

different from the initially assumed crack depth (270 cm), a new trial is necessary. The new guess is 10 ft (300 cm), which is the average of the two crack depths of the previous iteration.

The same process is repeated for the second guess. Now the resulting crack depth at the end of the iteration is 10 ft (300 cm), which is the same value as was assumed. Therefore, the maximum crack depth at I-37 for a 25-yr return period is 10 ft (300 cm).

The angular deflections shown in column 6 are intended to provide the basis on which to choose the criteria to prevent excessive edge drying. This column has been calculated assuming that the linear shrinkage obtained for each node is a representative average for a one-half-foot slice centered on the node. The settlement at the edge of the pavement is assumed to be the accumulated shrinkage of the soils deeper than the tip of the barrier. The angular deflection is estimated by dividing the edge settlement into the distance from the tip of the barrier to the first node with no shrinkage. The angular deflections shown in column 6 are the results for the depths of different barriers. The depth of the barrier that corresponds to a specific value of angular deflection, column 6, is the midpoint between the corresponding node and the node above it.

Design Criteria

When the moisture barrier is intended to prevent the development of pavement roughness, the barrier should extend to the maximum crack depth expected with the hydrologic regime imposed by the pavement, or to the crack depth existing at the time of construction, whichever is larger. For the case of I-37, this criterion would require a barrier 10 ft (300 cm) deep.

The second function of the moisture barrier is to prevent excessive drying of the soils under the pavement edges in order to prevent the formation of longitudinal cracks along the edges of the pavement. The size of the deformation that would cause the pavement to crack depends on the pavement itself. A concrete pavement would be expected to crack when the angular deflection exceeds 1/360. The asphalt concrete in a flexible pavement can take larger angular deflections. However, as the asphalt ages, the material becomes brittle. Because this aging process is very fast compared with the design life of the pavement, it is probably reasonable to use the same criteria for asphalt as for concrete.

For the case of I-37, to find the barrier depth that reduces the angular deflection to 1/360, it is necessary to interpolate the angular deflection data included in column 6. The interpolation was done assuming that the variation is linear. The resulting barrier depth is found to be 8 ft (240 cm).

The two criteria require barrier depths that differ by about 2 ft (60 cm) in the case of I-37. The question now is which of the two criteria should be used. The selection should be made on a case-by-case basis and should be based mainly on the initial status of the soil mass under the pavement. A vertical barrier for a new pavement would usually be designed to prevent the development of roughness. However, if there is evidence that the soil beneath the new pavement is not cracked, there is no need to design for this condition. It would be enough to design the barrier to prevent longitudinal cracking.

When a vertical barrier is to be placed at the time of repairing an old pavement, it is not clear which of the two alternatives should be used. The choice should be made depending on whether the subsoil under the old pavement has already reached the equilibrium profile. If this is the case, the barrier should be designed to prevent longitudinal cracking. Otherwise, it seems that the wise choice is to design the barrier to prevent the development of roughness.

In the case of I-37, a vertical moisture barrier was installed at a time of a major rehabilitation of that pavement section. The old pavement had been in place for more than 10 years at the time of the rehabilitation. This appears to be enough time for the soils under the old pavement to have reached their equilibrium profile. Thus, the existence of a shrinkage crack network in the soils beneath the pavement is unlikely. Therefore, the barrier depth at this site should be selected to prevent longitudinal cracking; that is, the barrier depth should be 8 ft (240 cm).

Sensitivity of Design Criteria to the Site Conditions

This section presents a comparison of the required barrier depths for a range of design events and different material parameters of the soil profile. This is intended to provide a basis on which to determine the accuracy required in evaluating the design parameters for a particular site. This comparison has been worked out for the section of I-37 in San Antonio.

The extreme design events possible for the San Antonio area are 100 percent depletion of soil water (i.e., the drying step No. 10), and the least demanding corresponds to a 65 percent soil water deficit (i.e., the drying step No. 6) *(5)*. The most relevant material property is the swelling coefficient. The comparisons were based on two extreme values of the swelling coefficient: one for a high swell material ($\gamma_h = 0.08$) and the other a typical swelling coefficient for a medium swelling soil ($\gamma_h = 0.04$). In both cases, the compressibility coefficient was assumed to be 20 percent larger than the corresponding swelling coefficient. The third parameter considered is related to the wettest condition that is reasonable to expect at a site. The two extremes considered are the matrix potential threshold −50 cm and the lowest limit usually accepted as the field wettest condition at a matrix potential of −1000 cm.

The effect of the change of these parameters on the required barrier depth is described in detail elsewhere *(5)*. For the longitudinal cracking criterion, the maximum difference in barrier depth for the two extreme combinations of the above parameters is only a few inches. Considering the accuracy of this simulation, it is believed that this difference is not significant. In summary, neither the design event nor the material properties have any significant bearing on the depth of the barrier required to prevent longitudinal cracking. In this case, the barrier must be placed to the depth of the root zone, independently of the design event or the properties of the subsurface soils.

The barrier depths required by the roughness criterion are always about 2 ft (61 cm) deeper than the depth required by the longitudinal cracking criterion. For the roughness criterion, the maximum difference in barrier depth for the two extreme combinations of parameters is about 1½ ft (45 cm). Although the effect is larger than for the other criterion, the effect of the design event and the material properties remains quite moderate.

In summary, the effect of the material properties and the design event on the required barrier depth seems to be very

small. The dominant factor by far is the depth of the root zone that the native vegetation will establish in the soil profile in question. As was discussed earlier, there is not enough information to determine whether the design event (or maybe the annual minimum water depth in an average year) has an effect on the root system that the plants establish in the soil. If this is so, the design event has an indirect effect on the barrier depth through the changes it might impose on the root depth or root distribution.

CONCLUSIONS AND RECOMMENDATIONS

The placement of a vertical moisture barrier enclosing the soils around an impermeable structure has as its main purpose the isolation of the subsoils from the climatic changes in the area. The barrier performs different roles depending on the initial state of the subsoil at the time of the installation. If the soil profile is at an advanced stage of desiccation, the role of the moisture barrier is to prevent the access of free water to the shrinkage crack fabric. If the subsoil is initially very wet, the role of the moisture barrier is to prevent excessive drying of the soil under the edges of the pavements.

From both points of view, the worst condition that governs the design is associated with the worst drought intensity that seems possible at the site. Drought severity is characterized based on the water deficit caused in the subsoil. This is evaluated by formulating the daily water balance using approximate methods to estimate the water going in and coming out of the soil as dictated by the meteorological conditions. The water that replenishes the subsoil originates from direct rainfall and runoff from the pavement. The extra supply of water because of runoff is included in the analysis by multiplying the rainfall by the RMF.

Drought severity is then related to the direct matrix potential profile. This relationship is obtained by numerical simulation of the water flow. This is assumed to conform to the extension of Darcy's law for unsaturated flow. The water extracted through the roots of the native vegetation is included in a sink term in the flow equation.

The analyses of the maximum crack depth of the maximum shrinkage that occurs at the edge of the pavement are found from the change of matrix potential from field capacity to the driest potential profile imposed by the design event. The shrinkage at any depth is found by accumulating all linear strains that occur below it. To find the depth of the crack, the strains imposed are modified to account for the presence of multiple cracks.

The displacement imposed at several depths within the root zone causes the propagation of the crack beyond it. Because this propagation takes place within a soil mass in which matrix potential changes are small, the soil behavior is assumed to be linearly elastic with moduli corresponding to a nearly saturated soil. The crack extension is determined with finite elements by imposing the set of displacements at each node of the root zone. The crack tip is chosen as the first node that is in compression when all the nodes above have two displacement freedoms.

A sensitivity analysis of the design parameters indicates that the edge shrinkage criterion is quite insensitive to any of the variables, whether the design event or the soil properties. The conclusion is that when a barrier is used to prevent excessive drying under the edge of the pavement, the barrier should reach the root depth. The barrier required by the roughness criterion is more affected by the variables considered. Nevertheless, the most extreme combinations of variables resulted in a 15 percent change in barrier depth. The barrier depth required by this criterion is about 25 percent larger than the root depth.

The parameter that is believed to have the most effect on the barrier depth is the rooting depth of the vegetation. A conservative rooting depth is 8 ft (240 cm). One potentially important aspect is the effect that the extra availability of water might have on the root system developed by the roadside vegetation. To determine the influence of this factor on the rooting depth, more research would be needed to clarify the rooting habits of native vegetation at roadsides, and how they are influenced by the runoff from the pavement.

It appears likely that this information could be developed with field studies that include the determination of root distribution in soil profiles taken from roadsides. The sites to study should be selected in several climatic regions and should also include several pavement widths. The need for more research in other aspects is contingent upon the results of the recommended research on root depth and root distribution. In this sense, if the native grasses develop root depths of about 8 ft (240 cm) under all circumstances, further research in other aspects is not warranted. However, if the root system established by the vegetation is dependent on the water availability, the influence of the design water depths will no longer be negligible and a better definition of the design event can result in significant savings in barrier depth.

REFERENCES

1. M. L. Steinberg. Deep Vertical Fabric Moisture Seals. *Proc., Fourth International Conference on Expansive Soils,* Denver, Colo., ASCE, pp. 383–400, 1980.
2. R. L. Lytton, R. L. Boggess, and J. W. Spotts. Characteristics of Expansive Clay Roughness of Pavements. In *Transportation Research Record 568,* TRB, National Research Council, Washington, D.C., 1976, pp. 9–23.
3. M. Dagg and K. Russam. The Relations Between Soil Shrinkage and the Development of Surface Cracks in an Experimental Road in Kenya. *African Soils 13,* 1968, pp. 5–25.
4. M. Picornell, R. L. Lytton, and M. Steinberg. Matrix Suction Instrumentation of a Vertical Moisture Barrier. In *Transportation Research Record 945,* TRB, National Research Council, Washington, D.C., 1983, pp. 16–21.
5. M. Picornell. *The Development of Design Criteria to Select the Depths of a Vertical Moisture Barrier.* Ph.D. dissertation, Texas A&M University, College Station, Dec. 1985.
6. J. L. Ritchie and J. E. Adams. Field Measurements of Evaporation from Soil Shrinkage Cracks. *Proc., Soil Science Society of America,* Madison, Wis., Vol. 38, 1974, pp. 131–134.
7. C. M. A. de Bruijin. Moisture Redistribution in Southern African Soils. *Proc., Eighth International Conference on Soil Mechanics,* Moscow, USSR, Vol. 2, 1973, pp. 37–44.
8. J. T. Ritchie, E. Burnett, and R. C. Henderson. Dryland Evaporative Flux in a Subhumid Climate: Soil Water Influence. *Agronomy Journal,* Vol. 64, March–April 1972, pp. 168–173.
9. B. G. Richards. Moisture Flow and Equilbria in Unsaturated Soils for Shallow Foundations. *Permeability and Capillarity of Soils,* ASTM STP 417, American Society for Testing and Materials, 1967, pp. 4–34.
10. A. A. B. Williams and J. T. Pidgeon. Evapo-Transpiration and Heaving Clays in South Africa. *Geotechnique,* Vol. 23, No. 2, 1983, pp. 141–150.

11. I. Ravina. The Influence of Vegetation on Moisture and Volume Changes. *Geotechnique,* Vol. XXXIII, No. 2, 1983, pp. 151–157.
12. J. E. Adams and R. J. Hanks. Evaporation From Soil Shrinkage Cracks. *Proc., Soil Science Society of America,* Madison, Wis., Vol. 28, 1964, pp. 281–284.
13. J. R. Johnson and H. O. Hill. A Study of the Shrinking and Swelling Properties of Rendzina Soils. *Proc., Soil Science Society of America,* Madison, Wis., Vol. 9, 1944, pp. 24–29.
14. L. A. Richards. Capillary Conduction of Liquids Through Porous Systems. *Physics 1,* 1931, pp. 318–333.
15. F. J. Molz, I. Remson, A. A. Fungaroli, and R. L. Drake. Soil Moisture Availability for Transpiration. *Water Resources Research,* Vol. 4, No. 6, 1968, pp. 1161–1169.
16. M. N. Nimah and R. J. Hanks. Model for Estimating Soil Water, Plant, and Atmospheric Interrelations: I. Description and Sensitivity. *Proc., Soil Science Society of America,* Madison, Wis., Vol. 37, 1973, pp. 522–527.
17. M. N. Nimah and R. J. Hanks. Model for Estimating Soil Water, Plant, and Atmospheric Interrelations: II. Field Test of Model. *Proc., Soil Science Society of America,* Madison, Wis., Vol. 37, 1973, pp. 528–532.
18. A. S. Laird. *A Study of the Root Systems of Some Important Sod Forming Grasses.* Florida Agricultural Experiment Station, Bulletin 211, 1930.
19. R. Driscoll. The Influence of Vegetation on the Swelling and Shrinking of Clay Soils in Britain. *Geotechnique,* Vol. 33, No. 2, 1983, pp. 93–105.
20. J. E. Weaver and R. W. Darland. Soil-Root Relationships of Certain Native Grasses in Various Soil Types. Ecology Monographs 19, 1949, pp. 303–338.
21. F. J. Molz and I. Remson. Extraction Term Models of Soil Moisture Use by Transpiring Plants. *Water Resources Research,* Vol. 6, No. 5, 1970, pp. 1346–1356.
22. J. L. Nieber. Simulation of Infiltration Into Cracked Soils. Presented at the 1981 Summer Meeting American Society of Agricultural Engineers, Orlando, Fla., June 21–24, 1981.
23. R. L. Lytton. The Characterization of Expansive Soils in Engineering. Presentation at the Symposium on Water Movements and Equilibria in Swelling Soils, American Geophysical Union, San Francisco, Calif., 1977.
24. M. Picornell and R. L. Lytton. Modeling the Heave of a Heavily Loaded Foundation. *Proc., Fifth International Conference on Expansive Soils,* Adelaide, Australia, 1984.
25. R. G. McKeen. Field Studies of Airport Pavements on Expansive Clays. *Proc., Fourth International Conference on Expansive Soils,* Denver Colo., ASCE, Vol. 1, 1980, pp. 242–261.
26. A. Z. El Abedine and G. H. Robinson. A Study on Cracking in Some Vertisols of the Sudan. *Geoderma 5,* 1971, pp. 229–241.
27. S. A. Taylor and G. L. Ashcroft. *Physical Edaphology.* W. H. Freeman & Co., San Francisco, Calif., 1972, pp. 355–356.
28. N. Janbu. Soil Compressibility as Determined by Odometer and Triaxial Tests. *Proc., European Conference on Soil Mechanics and Foundation Engineering,* Wiesbaden, Federal Republic of Germany, Vol. 1, 1963, pp. 19–25.
29. J. M. Duncan, P. Bryne, K. S. Wong, and P. Mabry. *Strength, Stress-Strain, and Bulk Modulus Parameters for Finite Element Analyses of Stresses and Movements in Soil Masses.* Report UBC/GT/80-01, University of California, Berkeley, Aug. 1980.
30. M. Picornell, R. L. Lytton, and M. L. Steinberg. Assessment of the Effectiveness of a Vertical Moisture Barrier. *Proc., Fifth International Conference on Expansive Soils,* Adelaide, South Australia, May 1984.

Publication of this paper sponsored by Committee on Environmental Factors Except Frost.