Matrix Suction Instrumentation of a Vertical Moisture Barrier

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The rehabilitation of a section of Interstate 37 in San Antonio, Texas, was undertaken to correct a chronic problem of expansive clay roughness. A vertical moisture barrier was placed down to a depth of 8 ft (2.4 m) along the outside shoulders of the northbound and southbound lanes. Several concurrent measurements, including the measurement of matrix suction at both sides of the membrane at several depths, were made in the laboratory and in the field to evaluate the effectiveness of the moisture barrier. The calibration of the thermal moisture sensors that are used to measure suction, the difficulties encountered in the calibration process and how they were overcome, and the installation of the sensors in boreholes on each side of the moisture barrier are described in this paper. The devices are sensitive and accurate in measuring suctions above -1 bar but lose sensitivity below that level of suction. The sensors are expected to provide stable readings for several years. The site and soil conditions, the placement and cost of installing the vertical moisture barrier, and subsequent indications of moisture changes inside and outside of the barrier are also described.

The rehabilitation of a section of I-37 in San Antonio was undertaken to correct a chronic problem of expansive clay roughness. A vertical moisture barrier was placed down to a depth of 8 ft (2.4 m) along the outside shoulders of the northbound and southbound lanes. Several types of measurements have since been made to evaluate the effectiveness of the moisture barrier. These measurements include (a) periodic measurements of the matrix suction with devices that are the subject of this paper, (b) pavement surface profile measurements with the GM profilometer, and (c) a variety of laboratory tests on the soil from the site to determine its engineering, chemical, and mineralogical characteristics. The site location and existing subsurface conditions, the installation of the moisture barrier, and the calibration and installation of the moisture sensors are outlined in this paper. Some of the preliminary results of the study are presented and interpreted.

SITE LOCATION

Figure 1 shows a location map of the project site within the city of San Antonio on I-37. Where the deep, vertical, fabric moisture barrier was placed I-37 is an eight-lane divided highway (see Figure 2). The main lanes were separated by a sodded median, 28 to 36 ft (8.5 to 11.0 m) wide that had a concrete median ditch 3 ft (0.9 m) wide and a steel medium barrier guardrail. Each of the travel lanes was 12 ft (3.66 m) wide, with a 10-ft (3.05-m) outside shoulder and a 6-ft (1.8-m) inside shoulder. The main lanes were constructed on 6 in. (15 cm) of lime-treated subgrade, 6 in. (15 cm) of lime-stabilized base, and 8 in. (20 cm) of concrete pavement.

The rehabilitation contract included a rubberized asphalt seal coat, an asphaltic concrete level-up, and a finish course. Reconstruction of the median provided positive drainage from a built-up section with a concrete Jersey-type median barrier on base, which was sealed with asphalt (see Figure 3). A moisture barrier was placed 8 ft (2.4 m) deep along the outside shoulders of the northbound and southbound lanes. A perforated underdrain pipe 6 in. (15 cm) in diameter was placed in some areas outside the fabric. The fabric's trench was backfilled with gravel and the top 3 ft (0.9 m) were cement stabilized. Project contract quantities called for placement of 23,750 yd² (19 860 m²) of the fabric. The work extended from South Hackberry Street on I-37 to south of Pecan Valley Drive, a distance of more than 2 miles (3.2 km).

The depth of the barrier was selected on the basis of the monitoring records (1,2) of heave and moisture changes in a nearby, similar site. The heave records indicated that most of the heave took place above the 8-ft depth. Below 8 ft (2.4 m), the moisture content versus depth curves remained approximately parallel during the whole monitoring period, which indicates that moisture content below this depth is not affected by seasonal changes.

SUBSURFACE CONDITIONS

Subsurface conditions were investigated by drilling eight borings with a hand auger to a depth of 3 ft (0.9 m). For the field installation of the matrix

Figure 1. Location map.

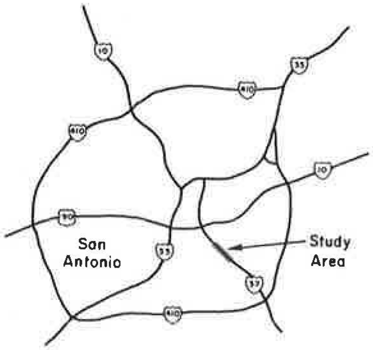


Figure 2. Cross section of existing pavement.

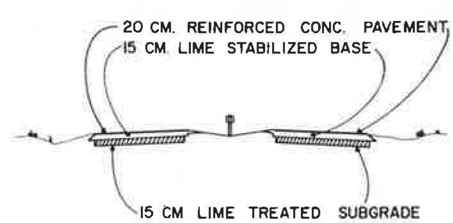
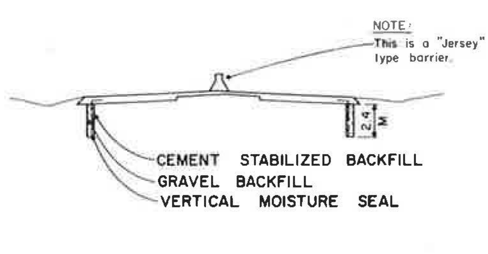
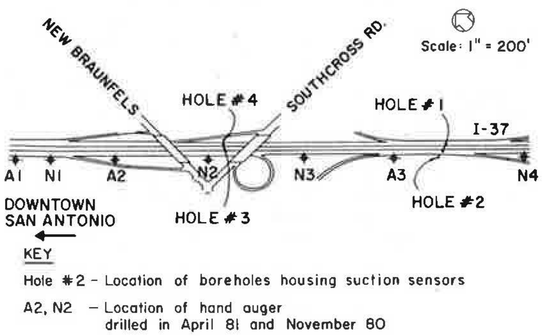


Figure 3. Cross section of rehabilitated pavement showing vertical moisture barriers.



suction sensors four mechanical borings were also drilled to a depth of 9 ft (2.7 m). The approximate locations of these borings are shown in Figure 4.

Figure 4. Site plan of sensor installations.



The hand-auger borings were drilled at two different times, the first half in November 1980 and the second half in April 1981. The deeper borings were drilled in October 1981.

Throughout the depth investigated, the subsoil consisted of highly weathered claystone. The soil is a highly plastic silty clay (CH), light gray mottled yellow and brown, with some sand and fine gravel. The grain-size distribution was investigated by sieving through No. 200 sieve, complemented by a hydrometer determination of the colloid content. The sand fraction represented less than 5 percent of the majority of the samples, the silt fraction amounted to from 35 to 45 percent, and the clay size particles made up from 50 to 65 percent of the total dry weight.

The liquid limit oscillated between 70 and 85 percent, and the plasticity index ranged from 40 to 50 percent. The general trend was for plasticity to increase with depth within the upper 3 ft (0.9 m). The activity (3) of these soils averaged about 0.85, which corresponds to that of a normally active clay.

The moisture contents of the soil samples obtained in the first hand-auger borings showed a marked increase with depth. The average moisture content of the soils was only 83 percent of their plastic limits in the first foot (0.3 m), but it was 91 percent in the second foot (0.6 m). The moisture content in the third foot (0.9 m) was higher than that of the plastic limit. Therefore, moisture contents that were higher than the plastic limit could be expected within the 8 ft (2.4 m) of membrane penetration. Furthermore, before the sampling in the summer of 1980 the weather was extremely hot and there was a long period of drought; as a result the samples taken in October 1981 had low moisture contents, probably the lowest to be encountered during the entire monitoring period.

To determine the mineralogical composition the soil was fractionated into sand, silt, coarse clay, and fine clay. Both clay fractions were dialyzed and freeze-dried. The minerals in each clay fraction were identified in subsamples, previously saturated with the appropriate cations, by X-ray diffraction, infrared spectroscopy, and electron microscopy. Quantitative analysis using analytic procedures was attempted. Smectite and vermiculite percentages were determined by the methods of Alexiades and Jackson (4,5). Micas were determined through the total potassium content (6). The predominant mineral was montmorillonite, which made up 27 percent of the total soil dry weight. Other minerals were muscovite (13 percent), kaolinite (8 percent), and vermiculite (2 percent).

PLACEMENT OF VERTICAL MOISTURE BARRIER

The contractor engaged a subcontractor for the fabric placement. The subcontractor used a Parson's 500 trenching machine with a special attachment that loaded the excavated material directly onto a dump truck. The trenching machine boom was fitted with a sliding shoring to hold the Typar roll vertically in the excavation, unroll it as the machine progressed, and prevent collapse of the earth wall. A portable paving machine batched the one-sack cement-stabilized base that topped the trench gravel backfill.

The subcontractor began placing the fabric on February 4, 1980, and completed the work on May 21. On the most successful day 485 ft (147.7 m) of the fabric were placed. The daily average was 350 ft (106.6 m). The subcontractor said that if the specification had been less rigid for the backfill the work would have been done for $16 per foot rather than the bid price of $21 per foot.

MATRIX SUCTION SENSORS

Suction is the energy per unit weight of water with which the water is held within the soil. The most common types of field sensors of soil suction include porous blocks (resistivity or thermal blocks) and psychrometers. The selection of sensor type was based primarily on two criteria, the proposed length of the monitoring period and the range of the suctions expected.

Because the site response would be monitored for several years, stable equipment was required. The long-range stability of thermal blocks is dramatically higher than that of resistivity blocks, and thermal blocks are less susceptibile to contamination or corrosion than are psychrometers, which are sensitive to corrosion of the thermocouple.

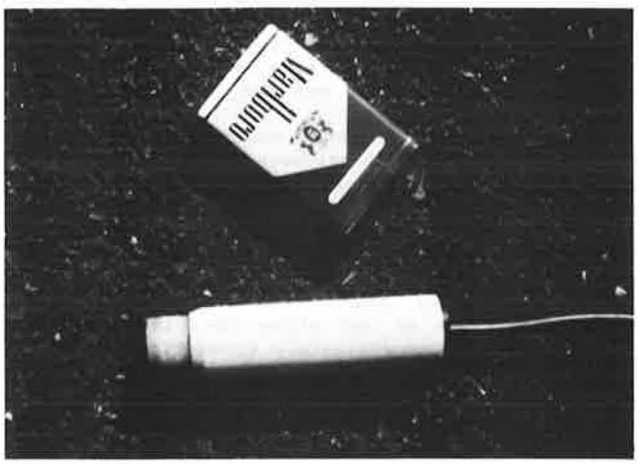
The preliminary site reconnaissance indicated moisture contents at and above the plastic limit, which corresponds approximately to suctions above -3 bars. Therefore, most of the time the measurements were expected to lie in the range of 0 to -1 bar, and only occasionally were they expected to become more negative. In this range the sensitivity of suction with respect to changes in relative humidity is drastic, and so is its dependence on temperature. This sensitivity and dependence greatly reduce the accuracy of suction measurements by psychrometers. Thermal blocks are accurate in this suction range, and their sensitivity drops off only at somewhat more negative suction levels.

Thermal blocks were selected as the best alternative, and a commercially available portable data acquisition system, the MCS 6000 of Moisture Control Systems, Inc., was selected. Each sensor consists of two modules housed in cylindrical polyvinylchloride (PVC) containers and connected in-line (see Figures 5 and 6). The first module has a porous ceramic tip in which are embedded a miniature heater and temperature sensing devices. The second module contains the rest of the circuitry, including amplification and timing devices. The sensors are connected to the data display by airtight and waterproof leads and connectors.

The measurement technique consists of sensing the rate of heat dissipation in a porous material of low heat conductivity compared with that of water (7). The operation requires that a precisely controlled amount of heat be released at a fixed rate. The release takes place at the center of the block, and the temperature rise after a fixed time is then measured. The temperature rise is inversely related to the moisture content in the porous block, and moisture content is, in turn, related to the matrix suction in the block.

Figure 5. Moisture sensor timing and amplification module (top) and sensing module (bottom).

Figure 6. Sensing module ready for installation.



The porous block is designed to achieve two main objectives:

1. The pore size distribution has to be such as to prevent complete desaturation within the range of matrix suctions to be measured, and
2. The size of the block has to be sufficient to prevent the heat pulse from affecting the temperature of the pore water in the surrounding soil (8). (The heat pulse must be contained within the block to avoid the need to calibrate the sensor for each specific soil.)

The sensor's output is not affected by the conductivity of the soil solution (9). The only environmental changes, other than matrix suction changes, that can affect the sensor's output are temperature changes. Temperature changes can cause changes in the thermal conductivity of the soil solution and in the output of the temperature sensing devices. This dependence has been found (9) to be small for higher suctions, but below -10 bar it can become significant. Nevertheless, the MCS sensors (7) are temperature compensated. The induced changes can be neglected provided that the rate of temperature change is less than 0.1°C per minute.

Two major uncertainties are associated with measurements with thermal blocks: (a) the nonunique suction-moisture content relationship of the block and (b) whether the measurement is purely matrix suction or is intermediate between this and the free energy of the soil solution.

Characterization of the hysteresis of the MCS thermal blocks was not attempted. However, reported typical errors due to hysteresis (10, p. 128) are ±0.25 pF. Because the expected suction range falls in the upper (less negative) suctions, any error due to hysteresis will be small and can be neglected.

The second uncertainty occurs because the boundary between the porous block and the clay will behave as a Donan membrane (11), which will allow the passage of water and ions but will prevent the passage of clay particles. This will cause a Donan potential across the boundary, and, consequently, the pore solution in the block will be somewhat different from the soil solution. Therefore, the sensor reading will include, to some undetermined extent, part of the osmotic suction of the soil solution.

SENSOR CALIBRATION

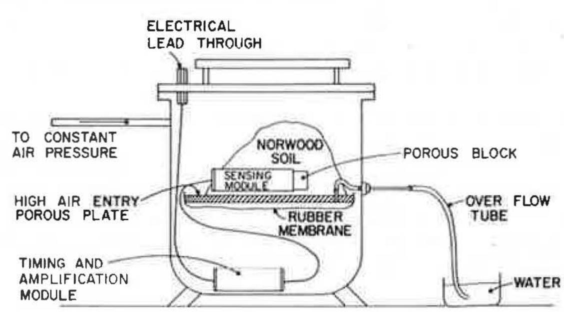
The sensors were calibrated using pressure-plate extractors. The sensor was placed within a soil clod on a high-air-entry porous plate. The plate, the soil, and the sensor were then enclosed in a pressure-plate extractor. The desired suction level was achieved by increasing the air pressure in the pressure chamber and letting the pore water be in contact with water at atmospheric pressure through a high-air-entry porous plate (see Figure 7).

The porous block of the sensor had to be saturated before attempting to calibrate the sensor. This was accomplished through four cycles of vacuum-assisted saturation and desaturation by air drying. After the fourth saturation cycle the sensors were kept underwater until their installation in the field.

In this calibration technique hydraulic contact must be maintained between the pore water within the block and in the pressure plate interstices. The selection of the soil type to achieve this is critical. The water-holding capacity of the soil has to be high enough to prevent complete desaturation at the maximum suction level to be achieved, and the shrinking potential of the soil has to be low enough to prevent excessive cracking or drying of the soil mass. The soil selected for this study was Norwood silty loam, a silty clay of low plasticity.

The soil was brought to approximately the saturation percentage, and then a 1-in.-thick layer was spread over three-fourths of the surface area of the pressure plate. The sensor was placed horizontally on the soil and pushed in, leaving the porous block side approximately 0.5 in. from the plate. More soil was then piled on the porous block. The total amount of soil used was about 3 or 4 lb. Much attention was paid to obtaining a good contact between

Figure 7. Cross section of calibration set-up.



the soil and the porous block, as well as to preventing air bubbles from becoming trapped in the soil mass. The sensor was connected to an electrical lead through the wall of the pressure chamber and the connections were protected by silicone cement and impermeable tape. The soil and plate were wetted by leaving 0.5 in. of water standing on the pressure plate overnight.

The pressure chamber was closed and the air pressure was increased gradually to the desired value. Thereafter the discharge end of the outflow tube was kept underwater at all times. The assembly was maintained under constant air pressure for about 2 weeks. Then the sensors were read for several consecutive days until the reading stabilized. The air pressure was then increased to the next desired calibration value. The outflow tube was inspected periodically to detect any excessive air bubbling, which would indicate faulty behavior of the system.

The high air pressure in the chamber has little effect on the thermal conductivity of the pore air; however, it has been reported (9) to have an appreciable effect on the output of the temperature-sensing units. This effect results in an erroneous sensor reading. To eliminate this error the sensor reading is taken after the air pressure is released from the chamber (12). The first step in reading the sensor is to clamp the outflow tube to reduce the backflow of water from the drainage line when the air pressure is released. The pressure release causes adiabatic cooling within the pressure chamber, which results in temperature gradients that can cause an erroneous reading. To eliminate the latter source of error the system is allowed to come to a uniform temperature for 15 min before reading the sensor. No attempt was made to evacuate the outflow tube; the large amount of soil used on the plates renders negligible any changes of moisture content due to backflow of the water.

The major difficulties encountered were loss of contact between the soil and the plate or between the soil and the sensor, waterproofing the electrical connections, and stopping air leaks out of the system. Most of the time the loss of contact was caused by upward bending on the perimeter of the soil clod that separated from the pressure plate. A partly successful corrective measure was to load the soil clod with a 2-lb porous stone. This was successful for air pressures below 1 bar, but above 1 bar it was not consistently successful. Loss of contact between the soil and the plate was checked for when the pressure chamber was opened.

The high air pressures in the chamber cause high partial pressures of water vapor. The excess vapor left by releasing the air pressure is partly expelled with the air and partly condensed within the pressure chamber. Condensation on the soil clod will result in the alteration of its moisture content, an effect that is minimized by using a large amount of soil. A more difficult problem is created by condensation on the electrical connections of the sensor. Connections must be airtight under several atmospheres of pressure differential between the interior of the connection and the outside of the waterproofing. Waterproofing with silicone cement and impermeable tape was used in this study, but the technique was not consistently successful.

Minor air leaks from the system can be difficult to detect but can induce excessive drying of the plate due to loss of vapor. In the short run this will alter the matrix suction within the chamber and will cause a defective calibration; however, after a somewhat longer time the air leaks will desaturate the porous plate. This is evidenced as frequent bubbling through the outflow tube. The sensor readings provide another indication--the readings will not stabilize but will continue to increase constantly. As an attempt to minimize these effects equilibration time was extended and the sensors were read several days after they appeared to have stabilized.

The sensors had been calibrated by the manufacturer with pressure-plate extractors at suction levels of -0.3 and -0.6 bar. In this investigation they were calibrated at approximately -0.6 and -1.0 bar using a 1-bar pressure-plate extractor, and at -2.0 and -4.0 bar using a 15-bar pressure-plate extractor. All of the calibration data available are shown in Figure 8. The broad band of scatter of the results is a clear indication of the variability of porous blocks.

The manufacturer describes a procedure to extrapolate the calibration curve based on the -0.6 bar calibration point. This curve for one of the sensors is presented in Figure 9. The calibration data

Figure 8. Calibration results.

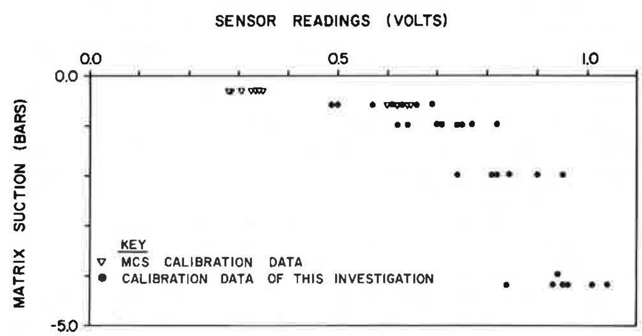
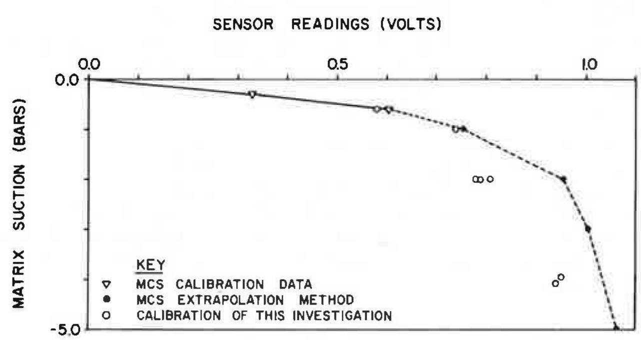


Figure 9. Comparison of typical calibration results.



obtained by the manufacturer match those obtained in this study; however, the extrapolated curve does not provide an acceptable approximation to the calibration points below -0.6 bar. The errors that can occur when using this approximate method are so great that they render the method questionable. The stabilization of readings was good and they repeated fairly well, except when there was condensation on the electrical connections.

All of the results indicate that the sensors are sensitive down to about -0.6 bar. Below this suction level sensitivity is progressively lost. Sensitivity below -2.0 bar is so low that the readings are considered questionable beyond this point. The wide scatter of the calibration points is an indication that the average or typical calibration curves should not be used and that a particular calibration curve is needed for each sensor.

FIELD INSTALLATION OF SENSORS

Ten sensors were installed in four boreholes in two areas: boreholes 1 and 2 were drilled in the south end-west side of the highway section, and boreholes 3 and 4 were drilled in the north end-east side of the highway section. Boreholes 1 and 3 were drilled inside the moisture barrier, and 2 and 4 were drilled outside. In both areas the two borings were located approximately 3 ft (0.9 m) from one another. The relative location of the two areas is shown in Figure 4.

At the south end-west side location three sensors were installed in each borehole at depths of 3 ft (0.9 m), 6 ft (1.8 m), and 9 ft (2.7 m) from the paved surface. At the north end-east side only two sensors per boring were installed at 4 ft (1.2 m) and 9 ft (2.7 m). The relative location of the sensors, the barrier, and the paved surface is shown in Figure 4.

The main concern in the field installation was to achieve good hydraulic contact between the porous block and the in situ soil. This is especially crucial for soils that have a high potential for shrinkage. If the contact between the porous block and the surrounding soil is lost, the water transfer will take place only in the vapor phase (10). This will cause a dramatic increase in equilibration time, and when equilibrium is reached the suction in the porous block will be the total suction of the surrounding soil instead of that of the matrix suction. To minimize the risk of losing contact between the block and the surrounding soil the sensors were embedded in a layer of Norwood soil identical to that use in the laboratory calibration of the sensors. The borings were 8 in. (20 cm) in diameter and 9 ft (2.7 m) deep. The bottom of the boring was tamped and a layer of Norwood soil was placed. The sensor was laid horizontally with the porous block located close to the wall of the boring. More Norwood soil was added to cover the sensor and then lightly tamped. The borehole was backfilled to the next installation level with the soil extracted during drilling. The soil was backfilled in lifts 1 ft (30.5 cm) thick. Between lifts the soil was tamped to achieve a good seal at the side of the borehole. The electrical connections were run up the borehole walls. Boreholes 1 and 3, which were drilled within the barrier, were also covered with asphalt concrete when the backfilling operation was completed in order to restore the original pavement surface and prevent any extraneous water infiltration.

PRELIMINARY RESULTS OF MEASUREMENTS

The sensors were installed in October 1981. At the time of installation the porous blocks were saturated, but the Norwood soil was in an air-dry condition. Therefore, the surrounding soil had to give water to the Norwood soil to reach equilibrium. This is believed to have imposed a long but undetermined equilibration time.

At present, records are available for only 1 year, and it is thought that longer records are needed before appropriate conclusions can be formulated about the trends and the performance of the vertical moisture barrier. The available readings of three pairs of sensors are presented in Figure 10. The two sensors of the left part of Figure 10 are installed in boreholes 3 and 4 at a depth of 4 ft (1.2 m). The two sensors of the center part of the figure are installed in boreholes 1 and 2 at a depth of 6 ft (1.8 m). The two sensors of the right part of the figure are installed in boreholes 3 and 4 at a depth of 9 ft (2.7 m). In each case the readings of the pairs of sensors reflect the suction change across the vertical moisture barrier. Two readings of the sensor at 9 ft inside the barrier are thought to be in error; both readings were out of the range of the sensor. In both cases the faulty reading is attributed to malfunction of the sensor, probably caused by water leaks that affected the electrical circuitry.

The purpose of a vertical moisture barrier is to protect the soil mass inside from extreme fluctuations of water content. This is accomplished by increasing the distance water must travel to get into or out of the soil. A very deep barrier would eventually reduce to zero the fluctuations of water content on the inside. However, from a practical standpoint, the depth of the barrier has to represent a compromise between the cost of installation and an acceptable level of moisture content oscillations of the foundation soil. With the 9-ft barrier depth selected for this study, it was expected that the soil suction inside the barrier would follow the outside trend to some extent but that the oscillations would be considerably damped out. The measurements to date clearly show that this is the case.

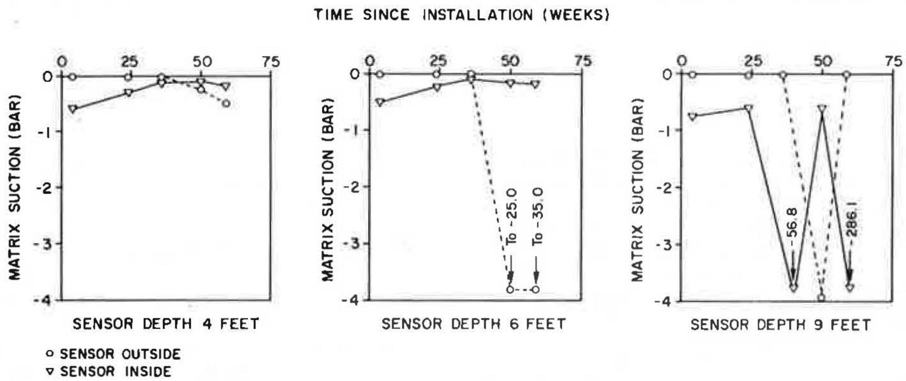
During the first half of the monitoring period the soils outside the barrier showed suctions close to zero, which indicates that the soils are almost saturated. The soils inside the barrier were not saturated to start with, but they gradually wetted up as indicated by their suctions that approach zero. However, it took soils inside the barrier about 35 weeks to reach suction levels similar to those of soils outside the barrier. The unusually wet conditions outside the barrier were caused by the long rainy season that occurred during the autumn and winter months of 1981 and 1982. During the second half of the monitoring period, the soils inside the barrier have shown almost no variation in suction level; however, the soils outside have dried out to significant negative suction levels that correspond to the dry conditions during the summer of 1982.

Other measurements are being made. In the laboratory suction-moisture content relations are being determined for soils from various depths. Other fundamental characteristics of the soil, such as cation exchange capacity and exchange sodium percentage, are also being measured. In the field periodic profile measurements are being made with the GM digital profilometer and changing roughness patterns are being analyzed. It is too early in the life of the rehabilitated pavement to expect any significant increase in roughness or other distress, and none has been observed.

SUMMARY AND CONCLUSIONS

A vertical moisture barrier was installed on I-37 in San Antonio and has been in service for more than 2 years. Precise matrix suction sensors were placed on both sides of the moisture barrier at various depths below the surface to monitor the changes of moisture and suction as they are affected by ambient conditions. The sensors are sensitive and accurate in their readings of suction above -1 bar and are expected to provide stable readings for several years. Calibration of the sensors required the use of a pressure-plate extractor in which the sensors were surrounded by a soil (Norwood silty loam) that has a known suction-moisture relation and low plasticity that helps to keep it in good hydraulic contact with the water films in the ceramic disk on which it rests during calibration. There is enough variation in the characteristic slope of the calibration curve of these thermal moisture sensors to

Figure 10. Readings of sensors at various depths.



necessitate the separate calibration of each sensor instead of the use of an average curve supplied by the manufacturer. At suctions below -1 bar the devices lose sensitivity and large variations occur in the calibration curves.

The sensors were installed in boreholes surrounded by the same soil (Norwood silty loam) in which they were calibrated and placed close to the wall of the borehole to reduce the time before they would begin to sense the suction in the surrounding soil. Subsequent readings indicate that the soil on the inside of the vertical moisture barrier has remained at a relatively stable suction level whereas the soil on the outside of the moisture barrier has had significant suction changes following seasonal climatic changes. To date, the sensors have performed as expected and have proven to be sensitive devices for measuring suctions above -1 bar.

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Publication of this paper sponsored by Committee on Environmental Factors Except Frost and Committee on Soils and Rock Instrumentation.