# Field and Laboratory Studies of the Effect of Subbase Type on the Development of D-Cracking

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Field and laboratory observations of numerous pavements have indicated that the development of D-cracking depends on the nature of the coarse aggregate used in the concrete and the facility with which moisture can be transported away from the subbase and pavement slab. It has been found necessary to install longitudinal tile subdrains in the shoulder areas to prevent the development of D-cracking associated with numerous coarse aggregates. Varying the type of subbase material also has been found to affect the rate of development of deterioration. Based on these observations, a series of simulated pavement slabs was cast in the PCA outdoor test plot to study the effect of granular, clay, cement-treated, and granular + vapor barrier subbases on moisture movements and the development of distress in the concrete slabs. Three coarse aggregates known to cause D-cracking were used. Moisture changes were based on weight measurements of 1-in. thick by 5½-in. diameter concrete discs tightly secured and inserted into precast cylindrical holes of similar size in each slab. Results after two freeze-thaw seasons showed that the level of saturation in all slabs had increased and, based on the examination of crack patterns in cores taken from the slab, certain particles of coarse aggregate had become critically saturated prior to freezing. It was also found necessary to take into consideration certain factors unique to the test procedure in the interpretation of the test results.

•DURING the past several years, field studies of a large number of pavements have revealed the widespread occurrence of a type of deterioration known as D-cracking, in which distress develops along joints, structural cracks, and the outside edges of pavement slabs (Fig. 1). Further observations revealed that deterioration was initiated in the lower levels of the pavement slab (Fig. 2). These observations and associated laboratory studies indicated that distress was due to the freeze-thaw failure of coarse aggregate particles (Fig. 3), and that pavement design, or the environment into which the concrete was placed, was a decisive factor in the durability of the pavement (1). Recognition of this fact led to studies at the PCA laboratories in which various combinations of subbases and concrete slabs were placed in an outdoor test plot to simulate pavement exposures in a freeze-thaw climate. It was anticipated that the findings in this study would indicate the need for durability as well as other considerations in pavement design. Additional information from the field observations, together with interim results from the laboratory tests, are discussed.

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Paper sponsored by Committee on Performance of Concrete–Physical Aspects and presented at the 49th Annual Meeting.

Figure 1. D-cracking along transverse joint of pavement.

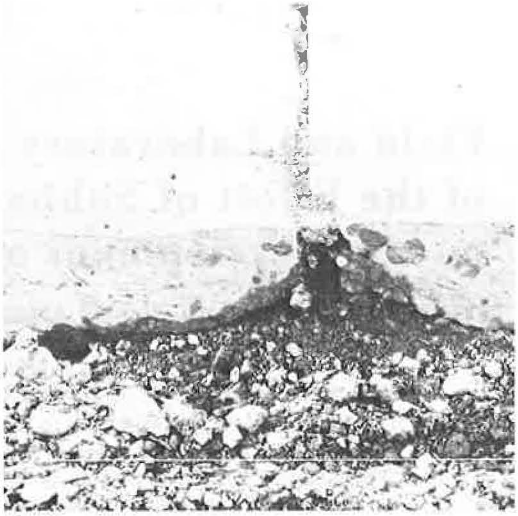

Figure 2. Transverse cross section of pavement in which severe D-cracking has developed. White line shows original bottom of pavement slab, lower half completely deteriorated.

## FIELD OBSERVATIONS

The field observations were based on performance of more than 50 pavements located in Illinois, Iowa, Kansas, Minnesota, Missouri, Ohio, and Manitoba. Aside from inherent differences in durability of the coarse aggregates used, the findings underscored the importance of moisture availability and subbase drainage in the development of D-cracking. To cite an extreme comparison, bridge deck concrete that contained coarse aggregate from the same source as that used in the abutting pavement and in other pavements where D-cracking was extensively developed did not display similar evidence of aggregate failures. This may be explained by the fact that the underside of a bridge slab is not regularly exposed to free water or relative humidities of 100 percent, and thus the concrete is permitted to dry periodically and the aggregate to remain at a safe level of saturation.

Differences in subbase materials were found to affect the rate of development of D-cracking. In one section of Interstate pavement, D-cracking developed within 3 years where the concrete was placed on a granular subbase covered with a 1-mil

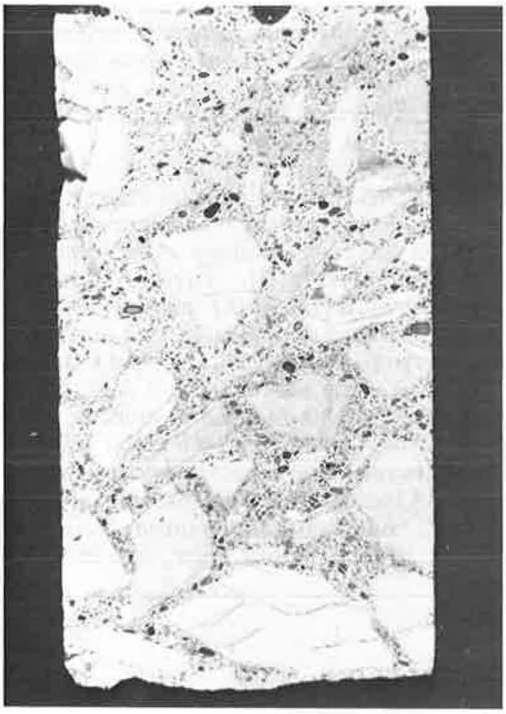

Figure 3. Vertical section of core taken through D-cracked pavement slab. Severe cracking in coarse aggregate particles extends into surrounding mortar.

thick polyethylene vapor barrier. In a nearby secondary pavement, in which the concrete was made with coarse aggregate from the same source but placed directly on a clay subgrade, only minor D-cracking appeared at a few transverse-longitudinal joint intersections after 7 years of service.

The importance of early moisture accumulation in base material was evident on a section of pavement built in 1950. After approximately 15 years of service, D-cracking had developed only in the southbound lane, which was placed directly on a rutted and water-filled clay subgrade immediately after a prolonged steady rainfall. In contrast, the northbound lane was placed at about the same time but on a relatively dry subgrade and showed no evidence of D-cracking.

The use of drainage facilities has been found, in some cases, to delay and possibly eliminate the development of D-cracking of the type that has been widely observed in pavements placed on granular subbases—both trenched in and carried through the shoulders. Schematic diagrams of the various pavement designs are shown in Figure 4. Figures 4a and 4b show widely used designs where there are no facilities provided to drain the subbase. D-cracking has developed with these designs at an early age in pavements containing susceptible aggregates. In these cases, moisture accumulated in the subbase more rapidly than it was able to drain away through the denser subgrade material; therefore, an environment was created where the lower levels of the pavement slab became critically saturated.

Three pavement designs with drainage facilities are shown in Figures 4c through 4e. In Figure 4c, longitudinal tile subdrains are contained in trenches backfilled with open-graded material to the bottom of the subbase. After less than 2 years, lateral drains extending from the longitudinal drains were found to be inoperative. Within 5 years, severe D-cracking had appeared at the pavement wearing surface.

Figure 4d shows a design where the trench was backfilled through the subbase. In this case, lateral drains were operating after 6 years and there was no evidence of D-cracking at the wearing surface where coarse aggregate was used from the same source as that in Figures 4b and 4c.

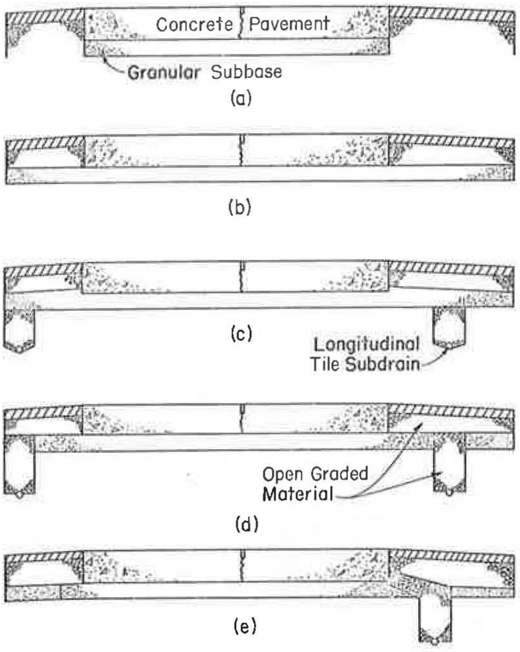

Figure 4. Pavement designs investigated in field studies.

Figure 4e shows a later design where a positive drainage connector was installed between the trench and the pavement slab. After 3 years, lateral drains were functioning and there was no evidence of D-cracking at the wearing surface. However, it is too early to determine if this design is a durability improvement on the design in Figure 4d.

## CONTROLLED FIELD STUDIES

In view of these observations, a series of 4- by 5-ft by 6-in. thick concrete slabs containing coarse aggregates known to cause D-cracking were cast on subbases of various types in the outdoor test plot at the PCA laboratories. The primary purpose of these tests was to determine the effect of subbase type on moisture accumulation in the concrete slab. In view of the small scale on which these tests were to be made, it was considered impossible to install drainage facilities with the expectation of having them function in a manner similar to those used in highway construction.

### Subbase Type and Construction

Four types of subbases were used in this study: granular, granular + 4-mil polyethylene sheeting between the base and the slab, cement-treated, and clay. Details for these materials are given in Table 1. For the granular materials used for the cement-treated base, the cement content was 6.0 percent by weight and the water content was 7.8 percent by weight. The materials used for the clay subbase had the following characteristics: liquid limit, 29; plastic limit, 15; and plasticity index, 14. Subbases for each slab were carried 2 to 2½ ft beyond the test slab. The granular base material was used as it already existed in the test plot and was maintained at a nominal 6-in. thickness resting on existing clay loam soil. The clay subbase was placed directly on similar clay material underlying the clay loam, and was compacted in 8-in. layers and brought to the same grade as the granular material. The cement-treated base was compacted in 2 layers to a 6-in. thickness and covered with polyethylene until the test slabs were cast.

TABLE 1

GRADATION OF GRANULAR SUBBASE MATERIAL

| Subbase | Sieve | Cumulative Percent Passing |
|---|---|---|
| Granular | 1½ in. | 100 |
| | ¾ in. | 93.4 |
| | No. 4 | 81.6 |
| | No. 8 | 75.7 |
| | No. 30 | 58.4 |
| | No. 200 | 4.0 |
| Cement-treated | 1 in. | 100 |
| | ¾ in. | 92.5 |
| | ¼ in. | 64.0 |
| | No. 4 | 58.5 |
| | No. 8 | 50.8 |
| | No. 16 | 43.0 |
| | No. 30 | 30.7 |
| | No. 50 | 7.5 |
| | No. 100 | 2.5 |
| | No. 200 | 1.2 |

## Concrete Slab Construction

Three coarse aggregates known to cause D-cracking were used in this study. These materials were obtained from limestone sources in Bethany Falls, Coralville, and Ervine Creek. Each of the aggregates was obtained from the stockpiles used for paving. Gradations and absorptions for these materials are given in Table 2. All slabs were cast in the fall of 1967. Before their use, the coarse aggregates were stockpiled and repeatedly hosed down and covered with burlap for 10 days. The sand used was obtained from Elgin, Illinois, whereas the cement was a laboratory blend of three commercial ASTM Type I cements produced in the Chicago area.

The mix design called for 6.8 bags of cement/cu yd and a water-cement ratio of 5 gal/bag. The air content was held at 6.0 ± 0.2 percent and the slump at 2 to 3 in. Following the initial floating, full-length, Y-shaped steel forms were vibrated into the slabs to a depth of 2 in. in order to procude "longitudinal" and "transverse" joints (Fig. 5). After the final finish, the slabs were covered with polyethylene. The following day the forms were stripped and vertical cracks were produced as extensions of the formed joints. For this work, numerous small, low-angle wedges were placed in the Y-shaped forms and driven downward until cracks could be observed on the vertical surfaces of the slabs. The forms were

TABLE 2

SUMMARY OF DATA FOR COARSE AGGREGATE

| Coarse Aggregate Source | Gradation of Coarse Aggregate | | Percent Absorption During 24 Hours |
|---|---|---|---|
| | Sieve | Cumulative Percent Passing | |
| Bethany Falls | 1½ in. | 100 | 1.74 |
| | ¾ in. | 95 | |
| | ⅜ in. | 37 | |
| | No. 4 | 0 | |
| Coralville | 1½ in. | 100 | 3.55 |
| | ¾ in. | 77 | |
| | ⅜ in. | 22 | |
| | No. 4 | 0 | |
| Ervine Creek | 1½ in. | 100 | 2.84 |
| | ¾ in. | 60 | |
| | ⅜ in. | 2 | |
| | No. 4 | 0.8 | |

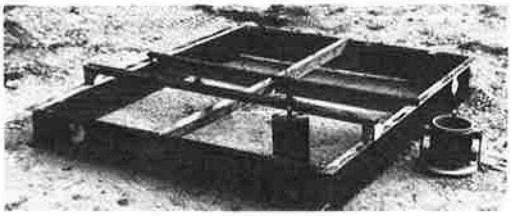

Figure 5. Form for casting test slabs and Y-shaped forms for making joints and cylinder mold used for concrete to be placed into cylindrical hole cast into slab.

removed, the joints were left unsealed, and granular material was compacted around the slabs, which were covered for curing with polyethylene for an additional 13 days.

### Moisture Measurements

In order to monitor moisture movements in the test slabs, a method initially reported by the California Division of Highways was used (2). Cylindrical steel molds, machined to an outside diameter of 5.550 in., were positioned at centers 12 and 15 in. from the outside edges of the slabs (Fig. 5). These were removed from the slabs after approximately 6 hours. The concrete cylinders to be inserted into the holes thus formed were cast in steel molds machined to an inside diameter of 5.500 in. and equipped with centrally located 0.500-in. diameter steel rods, which were required to form a hole through which another rod could later be inserted to clamp the discs together. Concrete was taken from each batch for the appropriate slab and externally vibrated into the mold. After 1 day, the concrete cylinder was removed from the mold, placed in a plastic bag, and cured under polyethylene with the slab for 13 days. Companion reference cylinders were made each day of casting and cured in a similar manner.

Following the curing period, the cylinders were sectioned horizontally into six 1-in. thick discs whose sawed surfaces were finally lapped in water to permit intimate contact during the test exposure. A 0.500-in. diameter aluminum rod was then inserted into the centrally located hole and a 1-in. diameter rubber gasket and aluminum washer were fitted between the concrete and a steel nut to provide a tightly secured stack of discs. After insertion into the slab, the annular space in the hole was sealed with caulking material at the exposed surface. Weight measurements of each disc were made in the late fall and early spring to determine moisture changes just before and after the freezing season. After the 14-day cure, the companion cylinders were sliced and weighed. After moist-curing for an additional 2 to 3 months at 73 F, the slices were again weighed, and then oven-dried at 230 F to constant weight to determine the amount of evaporable water the concrete would hold under conditions of 100 percent relative humidity. Little or no weight change was recorded between the measurements at 14 days and at 3 months. Comparisons were then made between these measurements and those obtained from the test specimens.

Figure 6 summarizes the results of measurements according to subbase type after exposure to 2 freeze-thaw seasons. Each curve represents the average for the full depth of slabs made with 3 different coarse aggregates. It should be pointed out that the curves were derived from data obtained only during the months specifically indicated on the abscissa, and do not include the extreme effects of summer drying. An initial moisture increase of 3.7 to 6.3 percent was recorded after a 1-month, late fall exposure. The greatest average increase occurred in concrete placed on the clay subgrade. By April following the first freeze-thaw season, moisture contents had dropped 2 to 5 percentage points for concrete placed on the clay, cement-treated, and granular + vapor barrier bases but still remained above that immediately following an initial curing period. Moisture contents of concrete placed on the granular subbase dropped more than 4 percentage points to a level somewhat below that immediately following the initial curing period. Average moisture contents were nearly the same for the spring and fall measurements but then increased greatly during the fall season. The greatest increase was recorded for concrete placed on the cement-treated base. By December preceding the second freeze-thaw season, moisture contents were higher than the previous December only for concrete placed on the cement-treated and granular + vapor barrier subbases. During the second freeze-thaw season, moisture contents increased for concrete placed on the granular and clay subbases and remained constant or decreased for the other concretes. Following the most recent summer season, moisture contents were at higher levels than at any previous time.

Data for the bottom half of the concrete slabs are shown in Figure 7. It is seen that similar but less pronounced trends occur here compared with those for the full depth of the slab, except during the first month's exposure following the initial curing period. During this period, moisture increases were greater, as might be expected, because there was no direct exposure to atmospheric drying. Also, there was a slight change in the relative positions of the curves after 22 months' exposure. Comparison of the

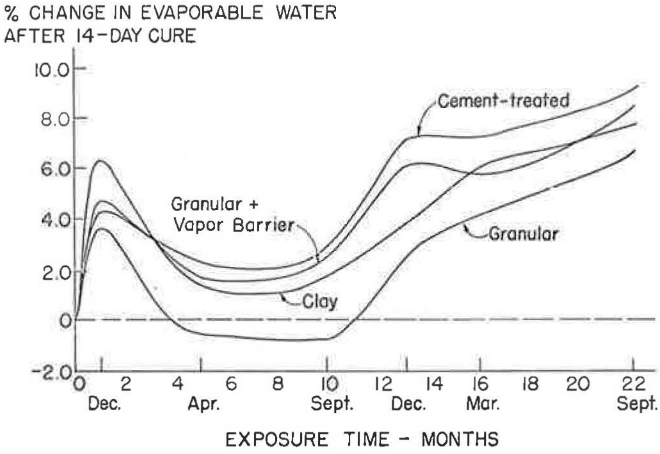

Figure 6. Moisture measurements for full depth of slabs on 4 subbases.

curves in Figures 6 and 7 shows that the bottom half of the slabs placed on the cement-treated and granular + vapor barrier subbases had smaller increases in evaporable water content compared with the full depth of these slabs.

Comparison of data for the full depth and bottom halves of the slabs placed on granular and clay subbases is shown in Figure 8. These curves indicate that greater moisture increases in the bottom half of the slabs during the first month's exposure following the 14-day curing period were more than maintained at later test ages. For example, differences between the full depth and bottom half of the slabs for the granular and clay subbases were 2.3 and 0.9 percentage points respectively after 1-month exposure, and 3.7 and 2.3 percentage points after an exposure of nearly 2 years. Similar results were obtained for concrete placed on the other two subbases.

As stated earlier, 3 different coarse aggregates known to cause D-cracking were used in this test series. Comparison of changes in moisture contents for the concretes containing these aggregates is shown in Figure 9. The curves suggest that the porosity of the coarse aggregate was a factor in the changes in moisture content, be-

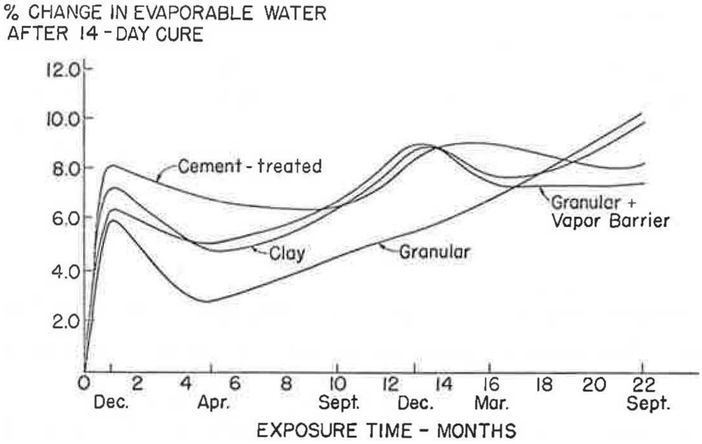

Figure 7. Moisture measurements for bottom half of slabs on 4 subbases.

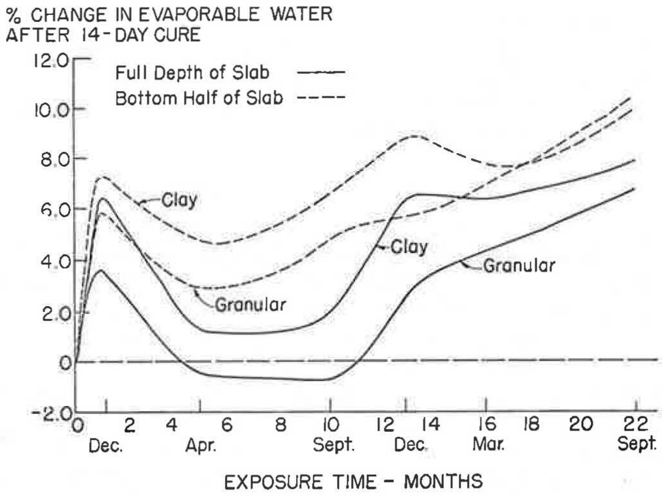

Figure 8. Moisture measurements for top and bottom halves of slabs placed on granular and clay subbases.

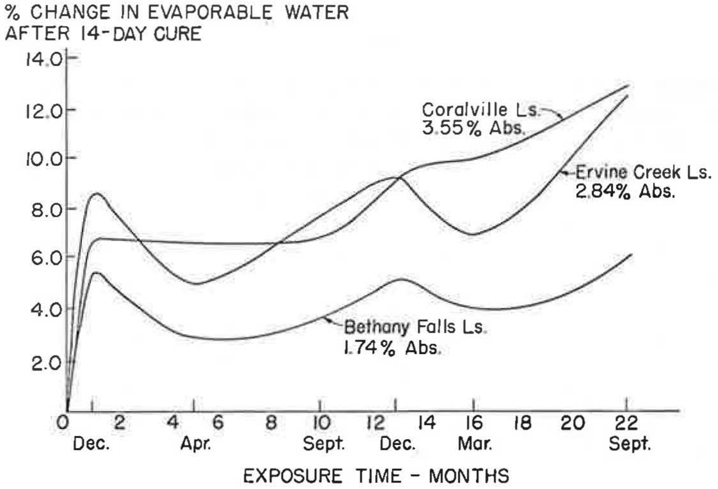

Figure 9. Moisture measurements for full depth of slabs made with 3 coarse aggregates.

cause the percent increase in evaporable water was lowest for concrete containing Bethany Falls limestone, which had the lowest vacuum absorption of 1.74 percent.

## Petrographic Examination of Concrete

At the exposure age of 16 months, immediately following the second freeze-thaw season, 2 cores were taken from each of the concrete slabs, sectioned, and lapped longitudinally to study the extent of cracking in the coarse aggregate. Results showed that between 5 and 12 percent of the particles above those containing cracks in the unused aggregate were fractured in the concrete. The least amount of cracking was found in slabs placed on the clay and cement-treated bases and greatest amount in slabs placed on the granular and granular + vapor barrier bases. In no instance was D-cracking apparent at the wearing surface. Apparently, moisture increases during the fall and winter seasons had been sufficient to critically saturate some of the coarse aggregate particles before freezing. However, the extent of cracking did not correlate with the percentage of moisture absorbed.

## DISCUSSION OF FINDINGS

Several apparent precautions or limitations that must be considered in the procedure for measuring the moisture changes by this technique require that the results be interpreted with caution. First, the absolute values are probably not totally representative because the relative roughness of the interfaces would, on a submicroscopic scale, create relatively large voids between the much smaller capillaries in the cement paste and aggregate on both sides of the interface. The capillary flow between discs would thereby be disrupted. Later laboratory tests, in fact, substantiated this effect. Also, for concrete discs placed on the cement-treated and granular + vapor barrier subbases, there is no bonded contact between the concrete and underlying material. Therefore, free water may collect at this interface that would not otherwise be present, or it may evaporate more rapidly if leaks had developed in the seal in the annular space at the wearing surface. In addition, because a continuous shoulder composed of open-graded granular material was used between slabs (4 percent passing the No. 200 sieve), some evaporation may occur that would tend to minimize larger moisture differentials among slabs placed on the four types of subbases.

## CONCLUSION

Although many precautions were taken in carrying out these tests, it is believed that the only conclusion that can be drawn from the moisture movement data is that a gradual increase in moisture content has occurred in these concrete slabs, regardless of the type of subbase. That these moisture increases were at one time sufficient to critically saturate certain coarse aggregate particles is indicated by the increase in the percentage fractured in the unused aggregate. Cracking of the type observed is similar to that which develops during the early stages of D-cracking in pavements.

Although field observations of pavements indicate that D-cracking can be delayed and possibly eliminated by the use of functional artificial drainage facilities, simulation and study of this factor have not yet been carried out under controlled laboratory conditions. However, studies of the D-cracking problem are continuing, and it is anticipated that work along these lines, together with tests to determine whether or not special drainage provisions would be beneficial with particular sources of coarse aggregate, will be conducted in the near future.

## REFERENCES

1. Stark, David, and Klieger, Paul. Field and Laboratory Investigation of D-Cracking in Concrete Pavements.
2. Tremper, Bailey, and Spellman, D. L. Tests for Freeze-Thaw Durability of Concrete Aggregates. HRB Bull. 305, 1961, pp. 28-50.

## *Discussion*

PHILIP D. CADY and ROGER E. CARRIER, Pennsylvania State University—In discussing the test method that he employed, the author voiced his concern regarding the discontinuity between the disc stack and the slab. If the annular area at the top of the slab is adequately sealed, the space between the discs and the slab should equilibrate at a relative humidity that will provide equal capillary filling in the discs and slab by the mechanism of capillary condensation. What appears to be of more concern to us is the fact that the moisture exchange surfaces (the hole in the slab and the peripheral surfaces of the discs) are cast surfaces. We believe that a cast or finished concrete surface will have a vastly different pore system than the interior of the concrete. For one thing, the effect of the aggregate in moisture transport will be considerably altered because no aggregate is exposed at formed surfaces. Because of this, in experiments similar to those described by Stark, we used disc stacks sliced from concrete cores, where the disc stacks were tested in the core holes from which they were originally taken. During February 1968 through July 1969, our experiments were carried out in a pavement slab at a rest area on I-80 in central Pennsylvania. A rain gage was installed at the site and the disc installations and rain gage were monitored monthly. Four-in. diameter cores were taken from the 10-in. thick pavement slab and were subsequently cut into 6 discs approximately $1\frac{1}{2}$ in. thick. A $\frac{3}{8}$-in. diameter hole was drilled through the center of each disc. A large hole, 1 in. in diameter, was drilled through the top disc and a brass insert (topnut) was cemented in the hole using a weather-resistant epoxy glue. The top surface of this topnut was flush with the road surface. The six discs were bolted together with a $\frac{3}{8}$-in. diameter brass bolt. O-shaped rubber gaskets were placed between the discs to cut off the annular space created by the core bit. The annular space at the top was sealed with an O-ring and caulking compound (Fig. 10).

Before insertion into the pavement, the discs were vacuum saturated ($1\frac{1}{2}$ hours of vacuum to 2 mm of Hg absolute with 24 hours of water submersion). Each disc was weighed (after damp drying the surface), and then oven-dried at 220 F to constant weight to establish the evaporable water content when saturated. They were then bolted together and inserted into the pavement. The two cores were placed 5 ft apart in 1 slab.

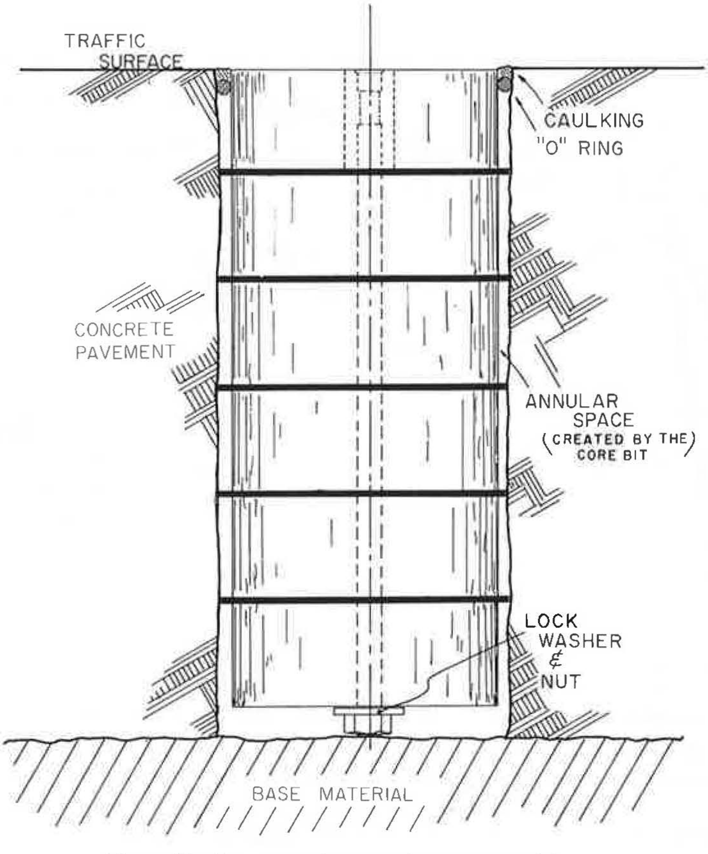

Figure 10. Test core placement in pavement slab.

The test slab was a part of a rest area on the eastbound lane of I-80, approximately 10 miles north of Clearfield, Pennsylvania. It is located on the southeastern slope of a hill, at an elevation of approximately 2,100 ft. The site lies over a thick-bedded, medium- to coarse-grained sandstone. The sandstone is well fractured and well drained. The 10-in. concrete slab is underlain by an 8-in. subbase (< 3-in. maximum crushed sandstone with a fairly uniform gradation) and 12 in. of granular material (essentially the same material). Because the test site lies on a sidehill location, little or no residual soil material lies between the granular material and the sandstone bedrock. In short, the pavement slab is well drained.

At the end of each month, the stacks of discs were removed. The surfaces were dried with a towel to a damp condition (SSD), and each disc was immediately weighed at the test site. After weighing, the stacks were reassembled, and inserted into the pavement. The O-ring was replaced and the annular space at the top was filled with caulking compound. To keep the top of the stack flush with the pavement, it was necessary to place a small layer of sand at the base of each core hole.

The nearby precipitation measuring stations could not offer valid data for rainfall at the test site because of the mountain topography that is atypical to this site. Thus, a rain gage with a 10-in. capacity was installed at the test site. It was placed in a cleared area to ensure proper exposure (lateral distance to nearest tall object was greater than twice that object's height, as recommended by rain gage manufacturer). Precipitation measurements were made on the last day of each month. Little evaporation occurred from the rain gage in the month period because of the small opening in the funnel in the top of the rain gage. In the winter months, the gage could not be read because the water had frozen and no thawing facilities were available at the test site.

The measured fluctuations in moisture content as well as the moisture distribution are shown in Figures 11 and 12. Results for December were not obtained because sev-

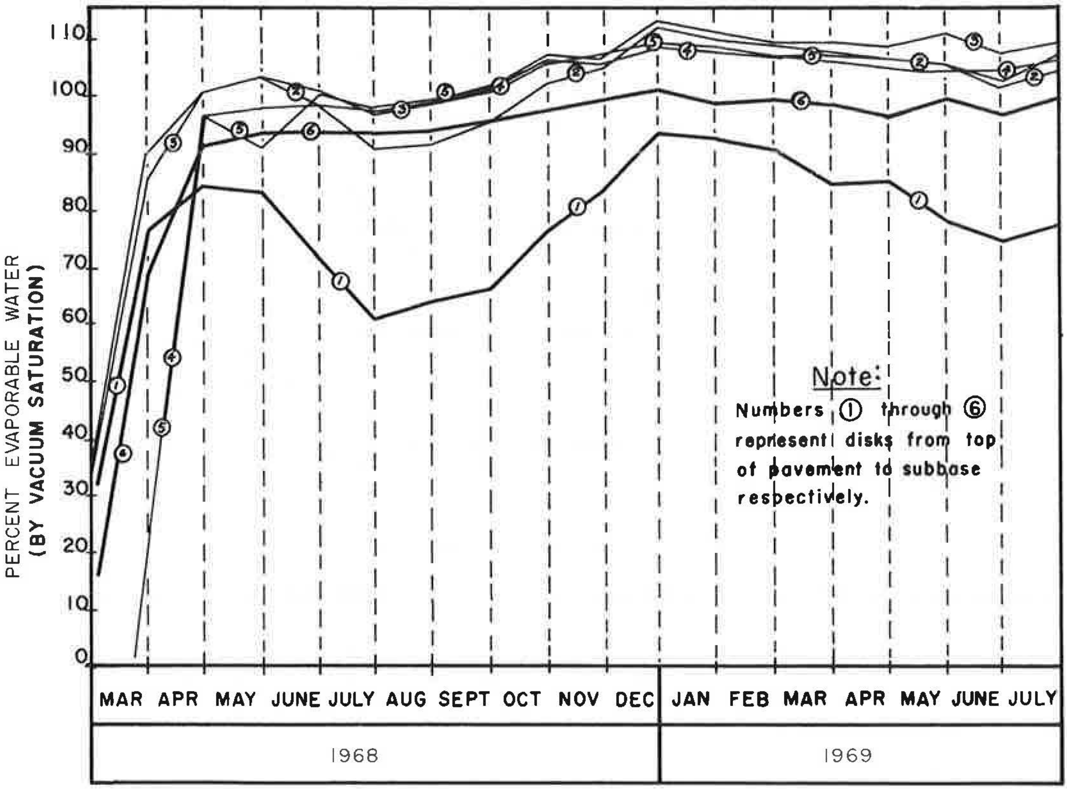

Figure 11. Moisture distribution in specimen A.

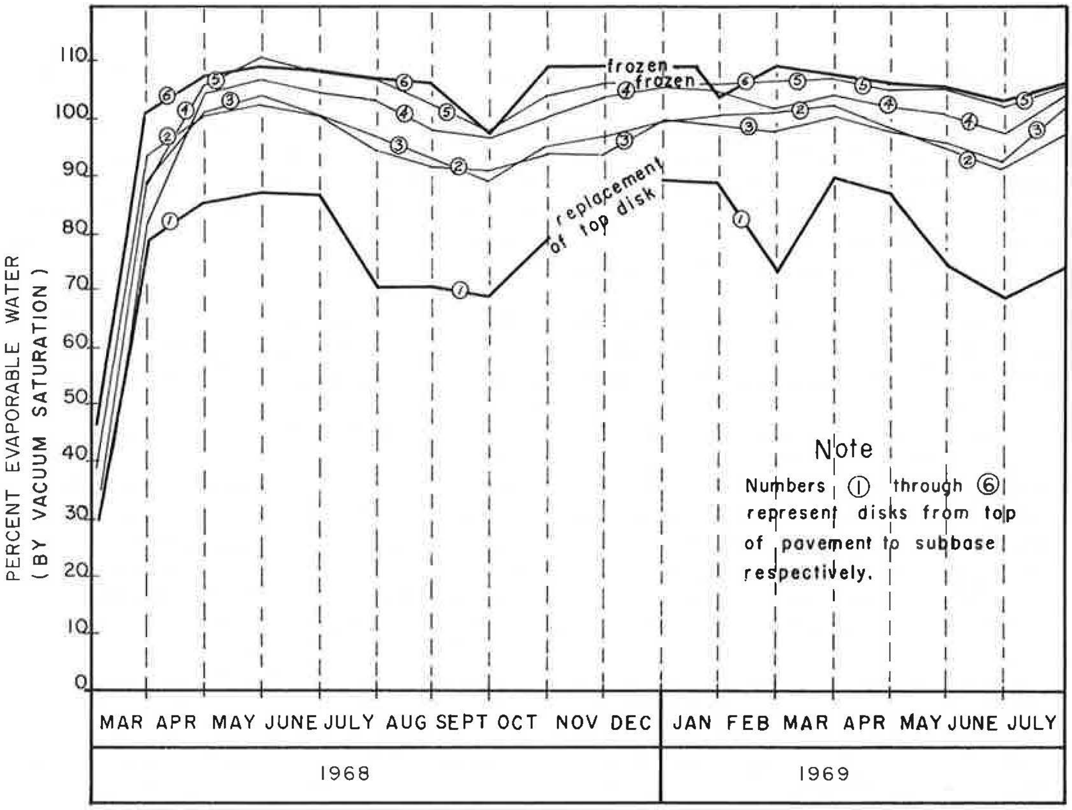

Figure 12. Moisture distribution in specimen B.

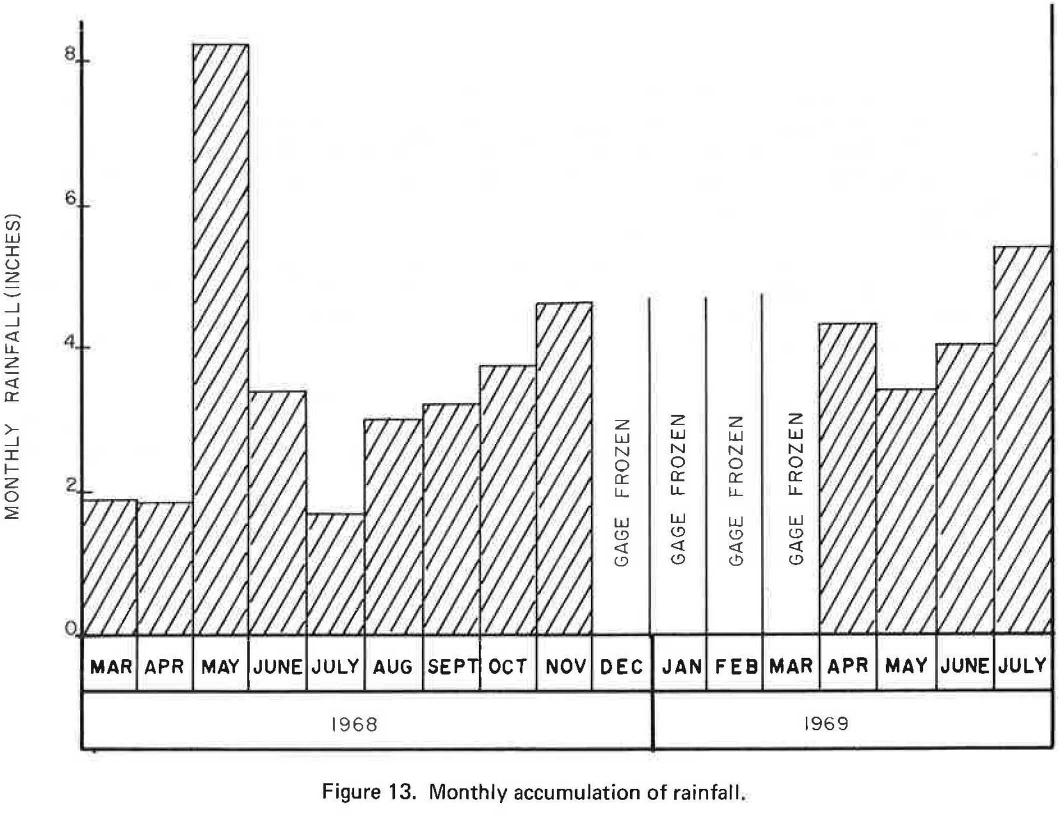

Figure 13. Monthly accumulation of rainfall.

eral of the discs became frozen fast in the slab. The rain gage data for the test period is shown in Figure 13.

As can be seen readily in Figures 11 and 12, the natural conditions allowed more water uptake than did the vacuum saturation; i.e., more than 100 percent of the evaporable water as here defined entered the discs when they were placed in the natural environment. Oven-dried specimens were placed in February 1968, and, for both cores, levels over 100 percent were reached by the end of April 1968. Those figures also show that, as might be expected, the lower discs always contained more moisture than the uppermost disc.

Traffic caused the top disc in specimen B to crack in November 1968 and it had to be replaced. It was discovered at the end of the test period that the epoxy bond in specimen A had failed sometime during the test, and it is felt that this caused the upper discs to become wetter than the lowest disc.

Note that in both cases, the upper 1½-in. thick disc seldom reached the critical 91.7 percent saturation level, the level above which freeze-thaw damage is probable. Note also that in both cases the lower discs seldom went below the 91.7 percent saturation level in the test period. There was evidence of slight flaking on the underside of some of the discs. Small flakes of mortar fell from these faces—especially from entrapped air pockets located on the undersides of these discs—to the top side of the next lower disc. These flakes appeared on the towel when the discs were toweled to the damp-dry condition. This occurred only in the winter months, but it never occurred on the top disc.

Note also from Figures 11 and 12 that the upper disc dries in the summer, as expected, but that the moisture content in the discs below that remains fairly constant. These discs are apparently not affected by seasonal changes in moisture.

We are currently carrying out similar experiments using disc stacks in concrete bridge decks. However, there is not enough data at this time to report on those installations.

DAVID C. STARK, Closure—In their discussion, Dr. Cady and Mr. Carrier point out another shortcoming in the reported procedure of using stacked discs to measure moisture contents; namely, the introduction of formed (cast) surfaces in the test material. They have apparently circumvented this problem by using concrete cores from which to construct the stacked discs.

The data in their discussion are interesting in that saturation levels greater than 100 percent (based on vacuum saturation) were reached within 1 year in the lower levels of the pavement slab. This finding supports our observations of D-cracking in pavements where deterioration in the form of fractures extending from coarse aggregate particles into the surrounding mortar have been noted in the lower levels of the slab after 1 year of exposure.

Although we are continuing to collect data of this sort in our outdoor test plot, we are presently exploring alternate methods of measuring moisture contents without having to cope with the type of precautions and uncertainties associated with this test procedure.