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One solution to pavement failures is the elimination of expansion joints and the spacing of contraction joints as far apart as possible. No practical method is available that will prevent moisture from accumulating beneath the pavement.

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Slab Warping Affects Pavement Joint Performance*

By F. N. HVEEM†

SYNOPSIS

An investigation of joint troubles and failure is discussed and a method of determining thermal and moisture expansion in thin concrete specimens described. Evidence of warping and curling of pavement slabs and the sequence of events leading to pumping and subsequent faulting of joints are considered. It was evident that curling was due to combined effects of temperature differential and moisture. Profilograph studies of pavement surfaces are described.

One solution to pavement failures is the elimination of expansion joints and the spacing of contraction joints as far apart as possible. No practical method is available that will prevent moisture from accumulating beneath the pavement.

INTRODUCTION

By 1944 highway engineers throughout the United States were becoming increasingly concerned over the evidences of distress in some portland cement concrete pavements, generally in the form of mud pumping or faulting at the joints. At this time the California Division of Highways began extensive field and laboratory studies to determine the causes for troubles at the joints in California concrete pavements. These studies, covering four years, included taking samples of subgrade soils through holes cut in the pavement by a core drill, inspection of the condition of dowels where faulting was in evidence, tabulation of construction data including design features and sources of materials and a scrutiny of any facts or data which might have a bearing upon the problem. As a result, certain remedial measures were put into effect to reduce the probability that similar types of distress would develop on future pavements.

Concrete pavements were constructed in California as early as 1914, and the use of concrete along with other materials has continued with periodical changes in design, including greater pavement width and thickness. Increasing attention has been given to the selection and compaction of materials in the supporting subgrade.

Prior to 1925 most concrete pavements were placed in continuous slabs without joints or with construction joints placed only at the end of each

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day's run. Frequent buckles or blowups in these early thin pavements directed attention to the expansive forces developed during hot weather.

To prevent accumulation of expansive movements in pavements, expansion joints were installed by most states, and to discipline the inevitable cracks into a uniform and more sightly pattern, contraction joints were introduced. In line with trends throughout the United States, the typical California pavement design from 1925 to 1940 included expansion joints at 60-ft intervals with two contraction or dummy joints placed between each expansion joint, thus providing a 20-ft slab.

The introduction of expansion and contraction joints led to concern over the weakness imparted to the pavement at these joints, and load transfer devices, generally in the form of dowels, were soon proposed. California adopted round dowels of hard-grade steel placed first at 28-in. intervals and later a greater number were used at 15-in. spacing. With the steady increase in traffic, engineers began to observe faulting or vertical offsets at expansion joints. Because of the attention focused on expansive properties of concrete, these vertical offsets or stepoffs were first attributed to careless construction, on the theory that the expansion joint materials had become canted or tipped from the vertical, thus providing an incline which resulted in an offset when the slabs were subjected to longitudinal thrusts. While this type of faulting does exist, investigation of California pavements indicated that it is relatively infrequent.

PROFILOGRAPH

With the increase of traffic and rapid multiplication of heavy trucks with three or more axles, faulting became more marked. To study the surface contour of pavement and to detect minute changes in riding qualities, a profilograph was constructed in the materials and research department.* The profilograph measures the intimate profile of a pavement and makes a direct record in the form of a graph on a dependably accurate scale. To check the accuracy of the instrument, profilograph records of pavement surfaces were compared to profiles obtained by scale measurement from a stretched piano wire. The relation between these two methods of measurement is shown in Fig. 1.

A few trial runs with the profilograph indicated that many concrete pavements were elevated or "turned up" at each joint or transverse crack; this was true even though the individual pavement had been known to be markedly smooth when constructed. To follow and chart the changes that characteristically occur in a concrete pavement after construction, a project under construction in 1944 was selected and profilograph records taken of the newly laid pavement as soon as the surface had hardened sufficiently. Fig. 2A shows the profilograph of a section placed June 8.

The newly finished pavement was very smooth; surface irregularities were so small as to be negligible (less than $\frac{1}{32}$ in. in 10 ft). This smooth condition

*California Highways and Public Works, March-April, 1944.

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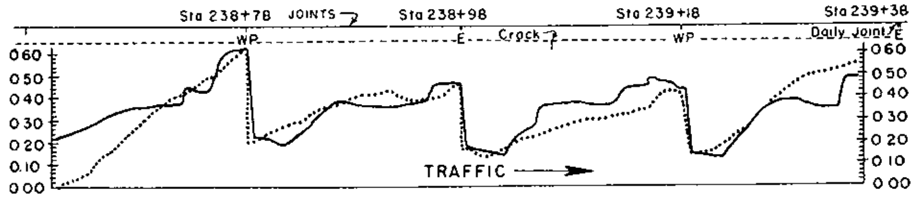

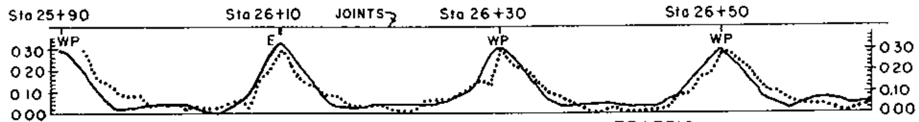

Fig. 1—Relative accuracy of profilograph records compared with profile obtained by stretching a piano wire and scaling offset to pavement surface. Bottom profile represents section of very smooth pavement constructed in 1937. Surrounding country was flooded early in 1938 and pavement curled soon after. At present, pavement has no cracks and is in excellent condition except for curl. Profiles taken 30 in. west of longitudinal joint

had not changed appreciably by the end of one week (Fig. 2C). However, the fourth profile (recorded in the early morning on July 10 when the pavement was 32 days old) shows a definite curling of all slabs.

It is evident that this curl must be due to the combined effects of temperature differential plus moisture. If the curl were due to temperature differences alone, then the fifth profile (Fig. 2E) taken in the afternoon of July 9 should show the slabs convex upward. As the slabs are flat and the surface virtually indistinguishable from the original profile, it is evident that for this pavement, expansion of the upper surface due to temperature only compensates for expansion of the underside caused by moisture.

Effect of soil conditions

Profilograph records can be used to study and analyze many aspects of pavement performance in relation to local conditions. For example, Fig. 3 illustrates types of roughness in relation to subgrade soil type. Fig. 3A shows the marked faulting which developed over a clean sand subgrade, while Fig. 3B and 3C illustrate sections of pavement on the same route where the subgrade is a clayey silt.

Fig. 3D is interesting as it shows a marked contrast in the condition of the pavement due apparently to a grove of trees along the roadside. A closely spaced windbreak of large eucalyptus trees is planted on the property line along the pavement represented by the profile (from the left edge of the sheet to the center, see note on profile). The moisture content of soil under the pavement adjacent to the trees was found to be only 53 percent of that required to fill the voids while the subgrade soil beyond the influence of the trees was 98 percent saturated. The roughness of the pavement is much more

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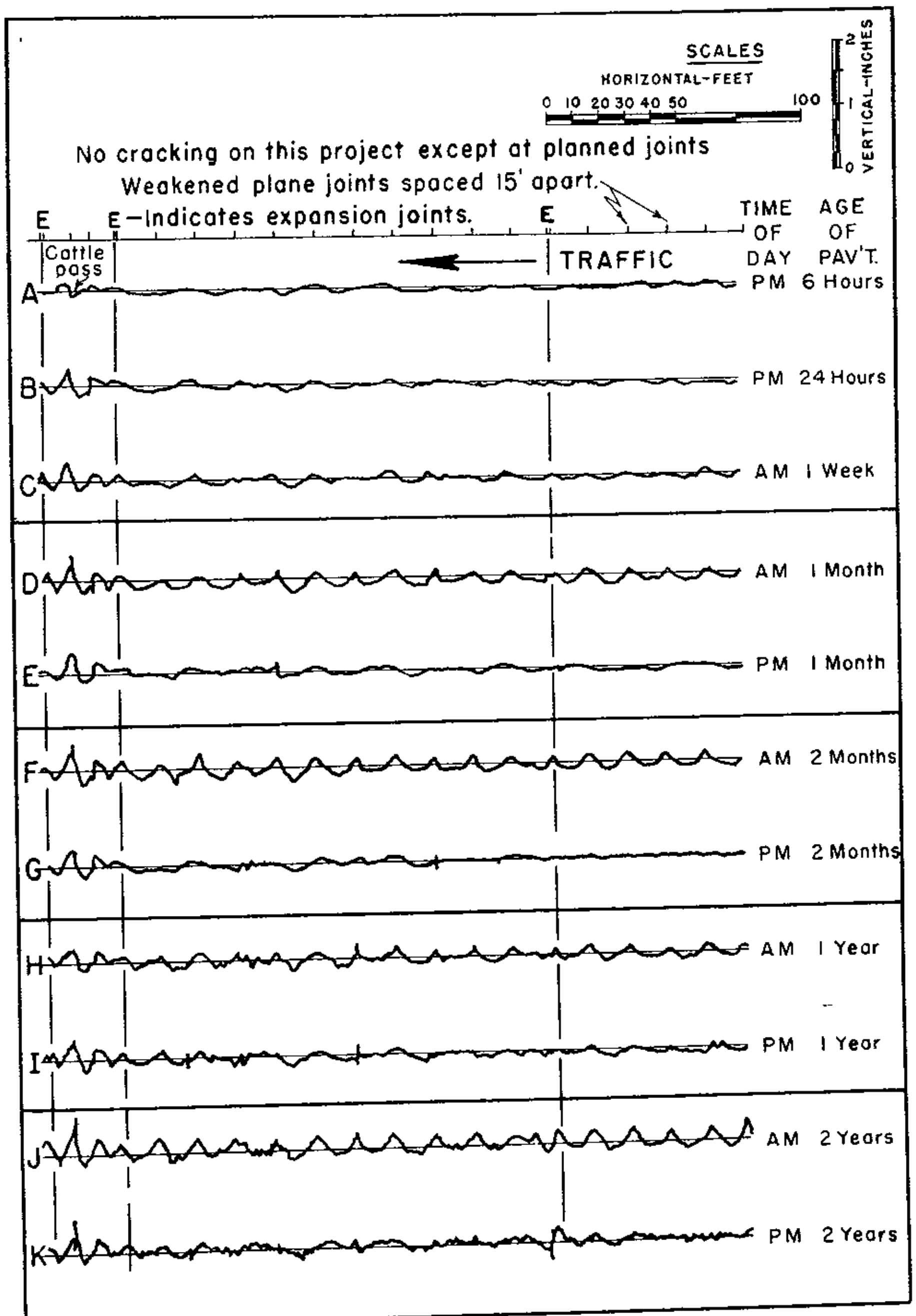

Fig. 2—Profilograms showing development of curling as pavement increases in age

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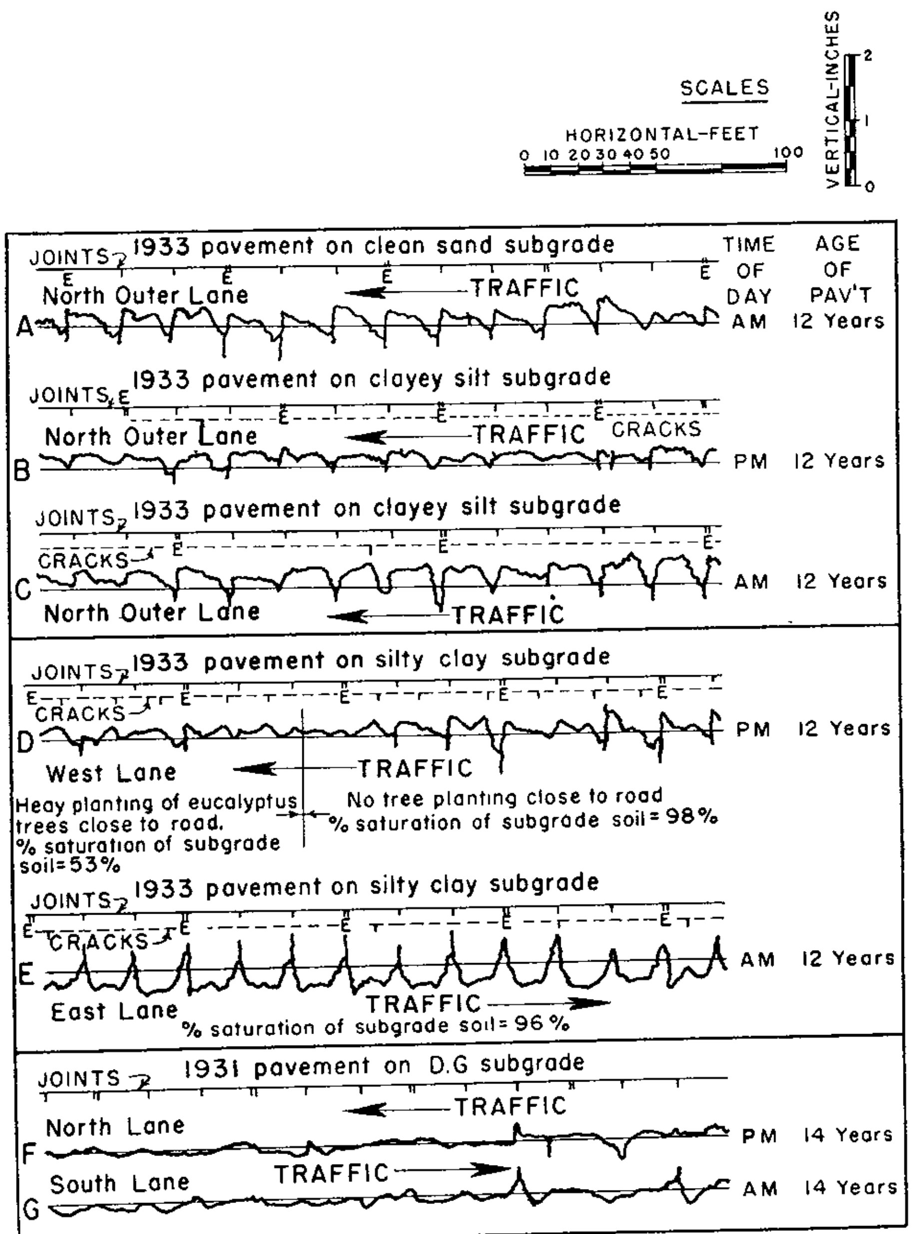

Fig. 3—Profilograms illustrating pavements placed on different types of subgrade soils. Weakened plane joints 20 ft apart. Expansion joints 60 ft apart, except north outer lane C where spacing is 100 ft

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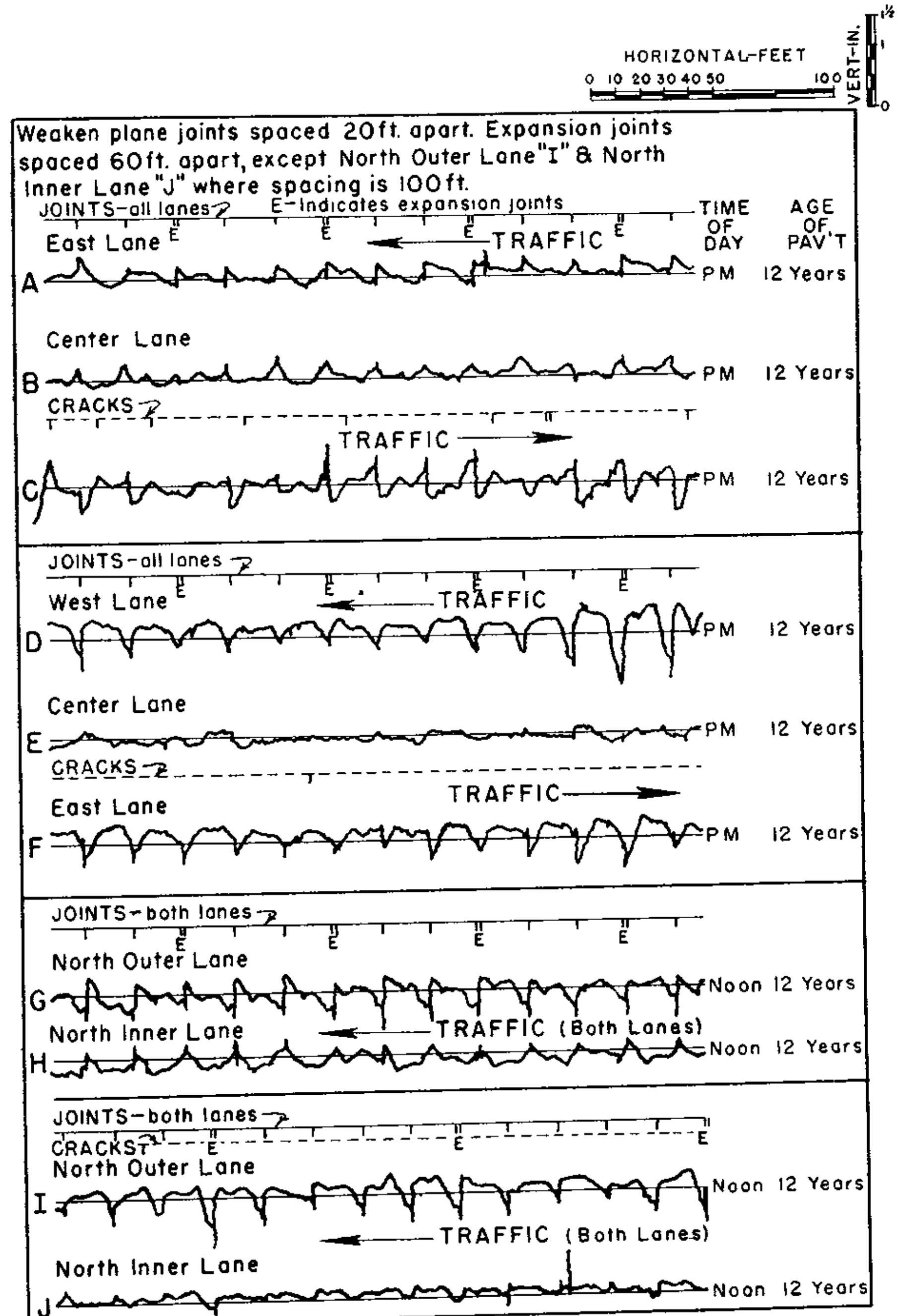

Fig. 4—Profilograms illustrating difference between inner and outer lanes

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marked and the faulting at the joints quite apparent where there were no tree roots to draw moisture from beneath the pavement.

Traffic

The effects of traffic are shown clearly by comparing the profilograph trace at inner and outer lanes on multiple lane highways. Fig. 4 shows the marked faulting on the outer lanes of two 3-lane pavements and on one section having four lanes. The lighter traveled inner lane on project Ora-60-A,B,C (Fig. 4B) shows definite evidence of the curled slabs that seem to be a characteristic forerunner to faulting.

This curled condition is not so apparent on LA-4-D (Fig. 4E), and this pavement is unique in California experience. While the outer lanes (Fig. 4D and F) clearly show the effects of traffic, the downward depression at the joints is peculiar to this job. In spite of roughness and depression at the joints this pavement has few transverse cracks. Perhaps cracks occur most frequently when pavement slabs are curled upward and are thus deprived of subgrade support. Fig. 4G to J show the difference between inner and outer northbound lanes of a four-lane highway.

These profilograms indicate that a concrete pavement is far from being inert or static. Fig. 5 and 6 show a magnified profile of single slabs 15 ft long on two different sections of pavement in southern California. Each shows a variation in surface contour between early morning and afternoon. Electronic deflection gages had been installed in these two slabs to measure vertical deflections under passing wheel loads at the ends of the slab, at the center point, and at the quarter point. These deflection measurements are plotted for comparison directly below the slab profiles and clearly indicate that the deflections are greatest when the slab is curled or warped to the greatest extent, which is not particularly surprising. Of greater interest is the fact that the *measured deflection at slab ends is little or no greater than at the centers of the slab when the pavement is flattened down and presumably resting upon the subgrade throughout the entire length of the slab.*

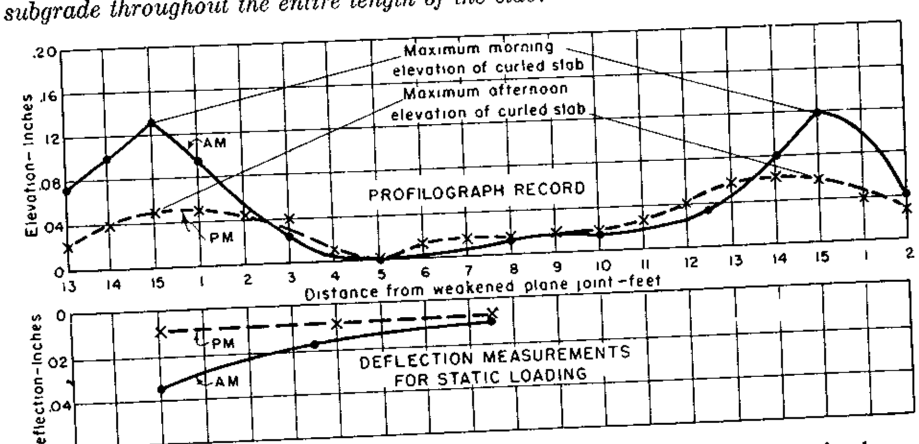

Fig. 5—Comparison of profilogram and deflection of single slab due to static load

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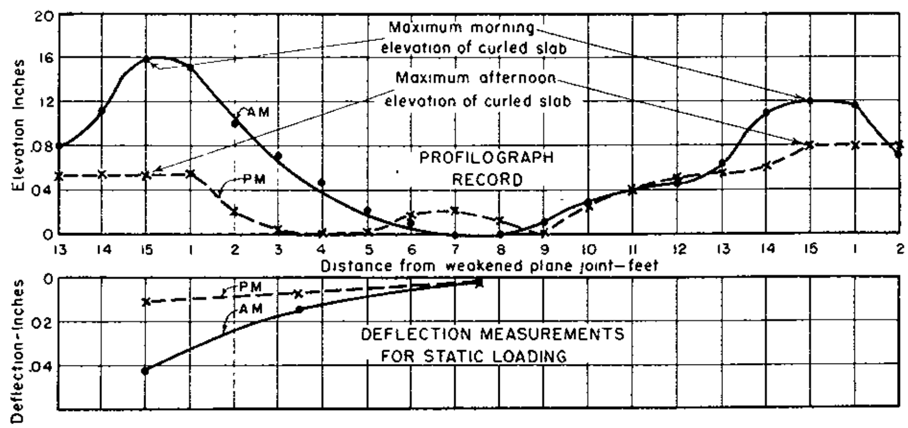

Fig. 6—Comparison of profilogram and deflection of single slab due to static load on another project

WARPING TESTS

To further investigate the factors which influence warping of slabs, a series of test specimens were prepared by cutting thin slices or discs from 8-in. diameter concrete pavement cores with a diamond saw. These discs were dried to constant weight and then placed in a specially designed frame or "spider" (Fig. 7) to measure expansion. The entire assembly was immersed in water and the total expansion measured.

Fig. 8 indicates expansion developed in seven days in thin discs of concrete sawed from cores taken from existing pavements. Discs are 8 in. in diameter and approximately ¼ in. thick. The ordinate on this chart represents expansion developed after the oven-dried discs were immersed in water. Expansion is expressed as a percentage of the diameter. Several days were required in most cases for the expansion to reach equilibrium after which the temperature of the water bath was varied, and the resulting expansion measured. For comparison it is expressed as the percentage of expansion developed due to a rise in temperature from 40 to 130 F.

On about ⅔ of the specimens, (counting from the left side of the figure) expansion caused by moisture exceeds that caused by temperature, while the remaining ⅓ of the specimens (represented by the group on the right side of the graph) show somewhat less expansion due to moisture compared to the effects produced by temperature. Admittedly, the variations in moisture were extreme, as under service conditions it is unlikely that the moisture content of concrete pavements would be reduced to that of the oven-dried specimens at the beginning of the soaking period. The test was conducted to show the response to the effect of moisture. There is no reason to believe that any "autogenic" process is involved in these volume changes. The thermal expansion for the corresponding discs is also shown. Of the 30 samples illustrated, 21 indicated greater expansion due to moisture than to temperature for the range shown (40 to 130 F). In the majority of cases, however, it

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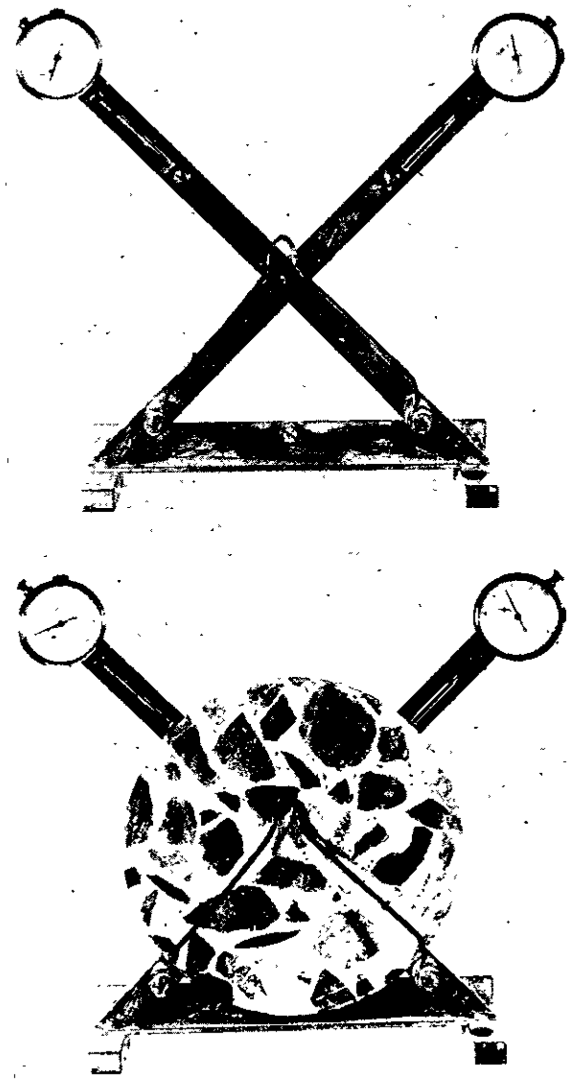

Fig. 7—"Spider" used in measuring thermal and moisture expansion of concrete

appears that under road conditions the expansions due to moisture and to temperature would be approximately the same.

EFFECT OF WEATHER

Volume change of a concrete pavement slab arising from either absorption of moisture or through changes in temperature must usually be nonuniform throughout the depth of the slab. During rain or periods of high humidity the pavement undoubtedly becomes saturated on both upper and lower surfaces and warping stresses are not developed. In summer the upper surface

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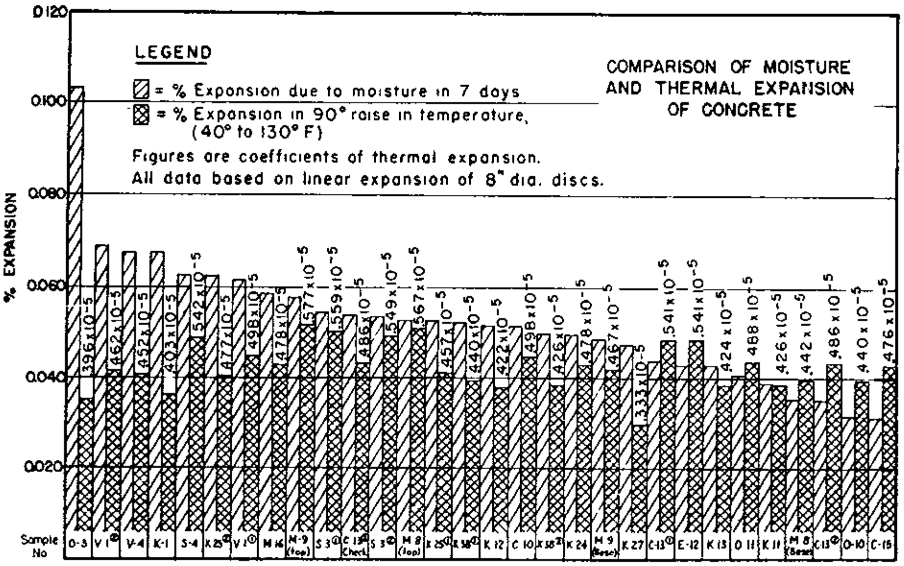

Fig. 8—Comparison of moisture and thermal expansion of concrete

of the pavement becomes dry and during the afternoon, at least, the surface of the pavement may reach temperatures equal to or greater than local atmospheric temperatures. The surface cools off rapidly at night, however, and the pavement will be curled to its greatest extent when the surface of the pavement is dry and cool and the underside is relatively warm and moist. Most of the rainfall in California occurs during winter months, and during this period curling or warping is less noticeable as the pavements tend to be more or less uniformly cool and damp throughout. Summer rains in California are infrequent, and as a result the greatest warping (causing the ends of the slabs to be lifted above the subgrade) occurs during early morning hours in late spring or early fall months.

While some pavements gave little or no evidence of daily warping and movement, the majority of concrete pavements in California do show such evidence, and this observation seems to warrant some speculation concerning the applicability of Westergaard's coefficient of subgrade reaction. Engineers have paid much attention to subgrade support for concrete pavements at or near the planned joints in the pavement, but if it is recognized that for a considerable portion of the time rigid pavement slabs do not rest on the subgrade for several feet either side of the joints, it seems pertinent to ask whether Westergaard's K is a significant index for the design of such pavement.

SUBGRADE TREATMENT

Most highway engineers experienced in maintenance work will be aware of the great difficulty, if not virtual impossibility, of completely sealing a

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pavement against the entrance of water into the subgrade. The space developed between a curled slab and subgrade provides room for the accumulation of water.

To combat the tendency for subgrade soils to be pumped out from beneath the slabs under the action of traffic, California has adopted the practice of hardening the subgrade with cement and covering with a bituminous membrane in an attempt to create an erosion resistant layer immediately beneath the concrete. The first installation of this type is now four years old, and so far no evidence of mud pumping has been observed. However, it will require several more years before adequate and conclusive proof is obtainable.

At the same time that special subgrade treatments were adopted, California also abandoned the use of expansion joints except at bridge abutments, etc. The standard concrete pavement now has an 8 in. uniform thickness, contraction or dummy joints at 15-ft intervals and no expansion joints. While it is evident that slabs continue to follow a daily cycle of curling with elevated joints in the early morning and there is evidence that moisture does collect beneath the slabs, there is no evidence of mud pumping or faulting over the treated subgrades.

CONTINUOUS REINFORCEMENT

Another means proposed for counteracting the ill effects of expansion of concrete pavements is continuous reinforcement. Several experimental sections have been constructed, one in California on the route between Sacramento and San Francisco constructed in 1949. This experimental section is one mile long on which a concrete pavement of uniform 8 in. thickness was placed over 16 in. of imported granular material of which the top 4 in. was "stabilized" or treated with cement. Continuous steel bars were placed at 4 and 5-in. centers, and SR-4 strain gages were attached to the reinforcing steel at a number of points on which readings have been taken periodically. Detailed data were not available to the author at the time this paper was prepared, but it appears that all gage readings indicate that the steel is in tension throughout.

Aside from frequent fine cracks the section is in excellent condition and may reasonably be expected to give long and satisfactory service. So far as present evidence is concerned, however, the same may be said of the adjoining unreinforced sections. Under the defense mobilization program it seems unlikely that reinforcing steel will be available for pavement construction or for any other purpose where substitute methods or materials can be used. Therefore, any question concerning the merits or demerits of continuous reinforcement in concrete highway pavements appears to be somewhat academic at the present time.

CONCLUSION

There is evidence that poor performance of a concrete pavement may be due to any one or a combination of factors among which the following are

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the most prevalent or probable causes: pavement joints at close intervals, high percentage of water in the subgrade soil, high percentage and frequency of heavy axle loads, or expansion and contraction of pavement due to variations in moisture content and nonuniform temperature.

The problem may be remedied by eliminating expansion joints and placing contraction joints as far apart as possible.

No practical or economical method has been developed that will prevent moisture from accumulating in the soil underlying a pavement.

There appears to be no ground for assuming that vehicle axle loads can be reduced or even controlled except within wide limits.

Any method or treatment that will reduce the volume change characteristics of portland cement concrete will be a major contribution to the more successful performance of concrete pavements.

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