REPORT OF COMMITTEE ON WARPING OF CONCRETE PAVEMENTS

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KANSAS EXPERIMENTAL CONCRETE PAVEMENTS

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SYNOPSIS

In an effort to determine the causes of the warping of concrete pavements and to develop practical and economical means of avoiding its occurrence on new construction, the Kansas Highway Commission built an experimental paving project, 5 mi in length, on Highway No 10, east of the city limits of Lawrence, Kansas The project was built in 1935 and was divided into 20 sections and in each of 13 of the twenty sections some special type of subgrade treatment was used Expansion joints were placed at intervals of 100 ft and intermediate contraction joints were used in some sections The subgrade treatments consisted of (1) Drying soil to an extremely low moisture content for depths of 6, 12 and 24 in , (2) Placing soil at plastic limits for depths of 6, 12 and 24 in , (3) Ponding subgrade until soil moisture exceeds the plastic limit, (4) Use of granular blankets over wet and dry soil, (5) Use of bituminous membrane over dry soil, (6) Sprinkling dry soil continuously for 48 hours

The observations made on the project have resulted in the following conclusions (1) Warping of pavement slabs is produced by volume change of expansive soils caused by a differential in the moisture content brought about by surface water entering the subgrade through joints or cracks, (2) Warping of pavement slabs was avoided by placing the subgrade soil at a moisture and density such that no subsequent differential moisture content resulted from the entrance of water through joints or cracks, (3) Warping did not occur on expansive soils when the subgrade moisture was equal to or greater than the plastic limit, (4) A blanket course of nonexpansive subsoil having moisture contents about ten per cent below the plastic limit, and (5) Warping caused by expansion of soil due to differential moisture contents was reduced in time as the moisture in the subgrade became evenly distributed

Prior to 1935, engineers of the Kansas Highway Commission found that some concrete pavements had developed surface roughness which in extreme cases was objectionable to the traveling public A preliminary study showed that the roughness was due to high joints resulting from warping of individual slab units The cause was not obvious, so an extensive study was made covering such possible contributing factors as design of slab, characteristics of the concrete and type and character of the subgrade soil Pavements which had warped as well as those which had not warped were included in the study. These studies pointed definitely to the type and character of subgrade soil and its moisture condition and density at the time of paving as being the major contributing factors

The results of the different phases of the study have been published in *American Highways*,[1] *Engineering News-Record*,[2]

Cooperating in making up this report were R D Finney, Materials Engineer, E L Larson and Ansel Myers, Resident Engineers on the project

[1] W V. Buck, "Warping of Concrete Pavements" *American Highways*, July 1934

[2] Harold Allen and A W Johnson, "Adding Water to Subgrade Levels Up Pavement" *Engineering-News Record*, October 11, 1934

H D Barnes and Harold Allen, "Fighting Subgrade Swelling on Kansas Roads" *Engineering-News Record*, March 18, 1937 and *Proceedings* of the Highway Research Board.[3] The information obtained in these studies was part of the data used by the Project Committee in their Progress Report presented at the Eighteenth Annual Meeting of the Highway Research Board in December, 1938.

In order further to substantiate the causes of warping and develop practical and economical means of avoiding its occurrence on new construction, as well as to provide information on several other problems, the Kansas Highway Commission built an experimental project 5 miles long located on highway No. 10 and extending easterly from the east city limits of Lawrence, Kansas. A contract for the project was let on May 25, 1935, and the work was completed about the middle of August 1936.

This report covers the construction details and the results of observations which have been carried on continuously since construction of the project. While other problems encountered in the construction of concrete pavement are included in the experiment, this report deals only with that phase which pertains to warping of the slab itself. The Kansas Highway Commission plans, after the expiration of a five year period, to compile and publish a report on all phases of the work.

The rainfall on the project beginning with September 1935, the first full month that observations were made, is shown in Table 1. The annual average was obtained from the records of the United States Weather Bureau at Lawrence, Kansas. The readings upon which the departure from normal were calculated were taken by means of rain gages installed at various points along the project.

During the spring of 1936, frost, as determined in inspection boxes in the slab, penetrated to a depth of from 23 to 36 in., corresponding to 24 to 40 in. in the shoulders outside the limits of the slab. In the adjoining fields the frost penetration was approximately 24 in. All frost was out of the ground by the middle of March 1936.

In 1937, frost penetrated from 13 to to 26 in., with a field depth of from 7 to 25 in. All frost was out of the ground by March 6 of 1937.

During 1938 and 1939, the frost penetrated only a few inches below the slab.

Air temperatures at the project, as shown by a recording thermometer, varied from a low of minus 13 deg. F. to a high of 112 deg. F.

TABLE 1

RAINFALL RECORD—KANSAS EXPERIMENTAL CONCRETE PAVEMENT

Year	Total	Departure from normal
	in.	*in.*
Average annual	36 7	
1935 (4 mo)	—	+3 4
1936	24 8	−11 9
1937	20 5	−16 2
1938	28 4	−8 3
1939	26 7	−10 0
1940	40 2	+3 5

The experimental project was divided into 20 sections on 13 of which special subgrade construction was used. On the remaining sections natural subgrade conditions were used and the moisture and density of the subgrade were measured periodically. The soil and moisture conditions, methods of treatment and a brief summary of the results obtained are described in the following paragraphs.

Unless otherwise noted, the concrete in all sections contained 5.75 gal. of water per sack of cement, the reinforcement consisted of $\frac{3}{4}$-in. round edge bars treated to destroy bond and the aggregates consisted of river sand and crushed

[3] Harold Allen and A. W Johnson, "The Results of Tests to Determine the Expansive Properties of Soils". *Proceedings*, Highway Research Board, Vol. 16 (1936).

stone. Subgrade paper was used throughout.

SECTION 1A

This section is 1028 ft. long and the pavement was laid on a natural subgrade consisting of A6 and A7 soils having plastic indexes of 14 to 22 percent and liquid limits of 33 to 44. The curing consisted of 72-hr. wet burlap. This section was laid without expansion joints, the purpose being to study the action of concrete in a slab of the maximum length possible to obtain in this experiment without expansion joints or mesh reinforcement.

The moisture content of the subgrade soil at the time of construction ranged between 14 to 18 percent. Samples taken annually by means of a core drill indicate that the moisture has increased to approximately 25 percent during the period of 1935 to 1940.

Some cracking has occurred in this section, but irregularities which may be classified as warping have not occurred. Two high points have developed in the profile but neither of them are at cracks or construction joints. No conclusions have been reached as to the cause of the uplift of the pavement at these points.

SECTION 1B

This section is 408 ft. in length and the concrete details were the same as in Section 1A except that a 56-lb. reinforcing fabric was used and expansion joints were placed at approximately 80-ft. intervals. The pavement was laid on the existing subgrade without special attention to moisture and density. The subgrade soil is of the A6 or A7 type having a range in plastic indexes from 18 to 33 and liquid limits from 41 to 54.

The moisture content of the subgrade soil at the time of construction varied from 18 to 26 percent. Samples taken annually from 1936 to 1938 and in 1940 indicate that the moisture content has increased slightly in the period covering 1935 to 1940. No warping has occurred in this section.

SECTION 2

This section is divided into three parts, each 1208 ft. long. In each subsection expansion joints were placed at 100-ft. 8-in. centers and consisted of a joint designed to permit the entrance of water into the subgrade. Dowel bars were used at alternate expansion joints. One contraction joint was placed midway between expansion joints.

In all of this section mixed aggregate (maximum size ¾ in.) was used in the concrete and 72-hr. wet burlap was used as a curing medium.

The subgrade in each section was treated by scarifying and mixing water with the soil by means of disks and blades until the moisture content was within 5 percent plus or minus of the plastic limit. The moistened soil was recompacted to a uniform density to form the finished subgrade. The treatment was made for depths of 6 in., 12 in. and 24 in. of the subgrade in Sections 2A, 2B and 2C respectively.

The purpose in building this section was to determine whether or not warping would occur on subgrades in which the moisture content was near the plastic limit of the soil, to obtain information on the depth of treatment required to prevent or reduce warping, and to afford a comparison with subsequent sections in which the moisture content of the subgrade was lower.

The moisture contents and densities of the subgrades at points one to two feet from expansion joints are shown in Table 2. Soil samples were taken by drilling cores through the pavement. The use of inspection wells was found to be impractical due to the collection of moisture caused by condensation and subsequent saturation of the subgrade in the vicinity of the well. It is significant that over the period covered by the data of Table 2 only slight fluctuations in moisture have occurred at open expansion joints. The range of moisture contents and densities was approximately the same for soil samples taken midway between expansion joints as for those shown in Table 2.

Profiles of section 2A made in 1935, 1936, 1938 and 1940 show that no warping has occurred. One section approximately 100 ft. in length has risen progressively about one inch

Profiles of section 2B drawn from levels taken over the five year period show no warping and very small up and down fluctuations from the original grade line.

Profiles of section 2C drawn from levels taken as indicated above over the five-year period, indicate that no warping has occurred. The elevation of most of the section has dropped progressively and the profile made in 1940 shows the departure from the original elevation as ranging from nothing to 0.1 ft.

TABLE 2

SOIL CHARACTERISTICS AND AVERAGE MOISTURE CONTENTS OF SOIL ON SECTION 2

Section	Depth of soil	Soil characteristics			Soil moisture			Sampled from
		LL	PL	PI.	Year	Density	Moisture	
	in.					*lb per cu. ft.*	*percent*	
A	0–6	47	19	28	1935	107	20	Original fill
	0–6	51	21	30	1935		23	Construction period
	0–6	34	21	13	1935	97	22	Construction period
	0–6				1936	96	25	Below cores
	0–6				1937		21	Below cores
	0–6				1938	99	21	Below cores
	0–6				1940		23	
B	0–6	49	25	24	1935	87	24	Original fill
	6–12	50	22	28		92	28	Construction period
	0–12	65	24	21	1936	90	27	Below cores
	0–12				1937		26	Below cores
	0–12				1938	90	27	Below cores
	0–12				1940		30	Below cores
C	0–24	53	24	29	1935	89	28	Construction period
	0–24	51	24	27	1936	84	27	Below cores
		66	26	40		—	—	—
	0–24				1938	87	29	Below cores
	0–24				1940		31	Below cores

SECTION 3

This section is 1208 ft. long and was divided into two 604-ft lengths Expansion joints were placed at intervals of 100 ft. 8 in. and with one intermediate contraction joint On section 3A, the expansion joints were of the water-tight load transfer type and on section 3B they were of the modified open type with dowel bars at alternate joints.

The pavement subgrade on both sections was scarified to a depth of 12 in. and ponded until the moisture content of the soil was within 5 percent ± of the plastic limit.

On section 3A the subgrade soil is the A-7 type having plasticity indexes ranging from 17 to 28 and liquid limits ranging from 40 to 51. The moisture content of the subgrade at time of construction ranged between 19 and 29 percent Samples taken annually since construction show no large variation in the moisture content but indicate a slight increase. The moisture content ranged between 27 and 33 percent in 1940 The dry density of the subgrade as shown by tests made in 1936 was 91 lb. per cu ft and was 81 lb per cu ft. by similar tests in 1938

Profiles of this section taken periodically since construction show no warping but the general profile is now about ⅓ in lower than following construction.

On section 3B the subgrade soil is of A-4 and A-7 types with plasticity indexes ranging from 13 to 26 and liquid limit from 40 to 51 The moisture content at construction ranged between 18 and 26 percent Samples taken periodically since construction showed no appreciable variation up to 1938 The samples taken in 1940 show that the moisture content has increased to approximately 30 percent

One expansion joint was noticeably high, however, this has settled and the riding surface today is generally good There is some indication that the high joint was caused by frost action

SECTION 4

This section is divided into three 1208-ft. lengths Expansion joints were placed at 100-ft intervals with intermediate contraction joints On section 4A joints of the water-tight load transfer type were used; on section 4B they were of the water-tight load transfer and modified open type with dowel bars at alternate expansion and contraction joints; on section 4C drains consisting of porous concrete were placed under expansion joints of the modified open type

The pavement was laid on a subgrade which was scarified in layers, pulverized and dried to a moisture content of 10 percent or less and recompacted with a roller at this moisture content On section 4A it was so treated to a depth of 6 in and on section 4B to a depth of 12 in and on section 4C to a depth of 24 in The moisture content of the subsoil below the treated depths averaged about 20 percent

The purpose of these sections was to determine the relative amount of warping which might develop on different depths of expansive soil having abnormally low moisture contents at the time of construction

On section 4A the subgrade soil is of the A-4 and A-7 types having plasticity indexes ranging from 14 to 16 and liquid limits of from 39 to 44. The moisture content of the 6-inch dried layer at the time of concreting ranged from 8 to 12 percent Samples taken periodically since construction show the following

(a) The moisture content of top 6-in layer of the subgrade near joints has steadily increased and was about equal to the moisture content of soil below at the end of the second year
(b) The moisture content of the top 6-in layer of the subgrade at mid-points in the slab increased more slowly and was about equal to that of the soil below at the end of about the third year
(c) In 1940 tests showed that the moisture content of the subgrade was reasonably uniform throughout the length of the slabs and was approximately 28 per cent

The profiles made periodically do not show any appreciable warping

On section 4B the subgrade soil is of the A-4, A-6 and A-7 types having plasticity indexes from 10 to 19 and liquid limit of 33 to 42 The moisture content of the 12-in dried layer at the time of concreting was about 10 percent Samples of soil taken in the spring of 1937 from the 12-in layer near joints showed the moisture content had increased to about 26 percent and similar samples taken away from any crack or joint to about 13 percent. Samples taken at the same locations in the fall of 1940 showed that moisture content of the 12-in. layer was about 25 percent and was practically uniform for the length of slabs

Profiles of the pavement in 1937 showed that all joints were from ¼ to 1 in. high. Profiles in 1938 show that the slabs are tending to smooth out by a gradual raise in elevation of the central portion of the slab. Profiles in the fall of 1940 show no appreciable difference in the elevation between the slab ends and center portion of the slab except at some few joints. The general elevation of the pavement in 1940 is from ½ in. to 1¼ in above the elevation immediately after construction.

On section 4C the subgrade soil is of the A-6 and A-7 types with plasticity indexes ranging from 16 to 17 and liquid limits from 36 to 37.

The moisture content of the 24-in. dried layer was about 10 percent at the time the concrete was placed. Soil samples taken from the 24-in. layer in the spring of 1937 showed that the moisture content of the subgrade soil near joints had increased to about 23 percent, while at parts away from cracks or joints it had increased very little. The increase in the moisture content at joints gradually diminished with the distance away from joints up to a distance of 15 ft. and indicates that most of the water entered the subgrade through the joints.

Similar soil samples taken in the fall of 1940 show that the moisture content of the subgrade soil was from 22 to 28 percent and was becoming uniform throughout the length of slabs. The data in Table 3 are typical of the moisture content of the subgrade soil in 1938, three years after construction. The values shown for 1940 indicate the distribution of moisture which occurred in a period of two years.

Profiles in 1937 showed that all joints were high, averaging from ½ in. to 1½ in above the midpoints of slabs. Similar profiles in 1938 show that the slabs are leveling out and the profiles in 1940 show, except in a few cases, no appreciable warping or high joints. The general elevation of the section in 1940 was from 1 in to 2½ in. above the elevation at time of placement.

The data from section 4A show that the 6 in. of dried expansive soil over a similar subsoil which had a moisture content of about the plastic limit, did not produce volume change sufficient to cause warping It is apparent from the data on sections 4B and 4C that 12 in. and 24 in. of dry expansive soil will cause sufficient differential volume change to produce noticeable warping as surface water seeps into the dried subgrade through the joints. It is also evident that the pavement levels out as the water in the subgrade soil is equalized through the length of the slabs.

TABLE 3

DISTRIBUTION OF MOISTURE IN SECTION 4C

Location			Moisture content		Dry weight per cu ft.	Depth of soil sampled
Distance from expansion joint	Direction from expansion joint	Distance to crack 1940[a]	1938	1940	1938	
ft.		*ft.*	*percent*	*percent*	*pounds*	*in*
20	W	6 W	10	22	93	24
15	W	2 W	10	23		24
10	W	4 E	13	23		24
5	W		21	23		24
1	W		23	23	94	24
1	E		24	22	95	24
5	E		21	22		24
10	E		17	22		24
15	E		9	17		24
20	E		8	16		24
23	E		7	25	96	24

[a] Crack in the pavement which appeared in the interval between 1938 and 1940 samples

SECTION 5

This section is 1006 ft in length Expansion joints were placed at 100-ft. 8-in centers and were of the modified open type designed to permit the entrance of water with dowel bars at alternate joints. Contraction joints were placed midway between the expansion joints and were constructed with dowel bars at alternate joints.

The subgrade soil is of the A-6 and A-7 types consisting of clay and silty clay soils having a range in plastic indexes from 20 to 25 and liquid limits from 43 to 45.

The subgrade was scarified in layers to a depth of 18 in. and the soil dried by disking, harrowing and blading until the moisture content was 10 percent or less. The dried soil was recompacted and covered with a layer of nonexpansive topsoil 6 in. in thickness. The average moisture content of the subsoil under the dried soil was approximately 20 percent

The moisture content of the dried soil in the subgrade increased with time throughout the section over the five-year period of observation. The maximum increase occurred close to the expansion joints and diminished with the distance from the joint indicating that most of the additional moisture came from infiltration of surface water into the joints.

The change in moisture content in relation to the distance from expansion joints was of the same order as illustrated by the data shown for section 4C in Table 3.

The profiles plotted from the level data taken in this section show that the warping was severe and reached a maximum of 2¼ in. on some joints in 1937. Since 1937 the profiles indicate some leveling of the pavement and a gradual increase in elevation throughout the length of the section. The profile made in 1940 shows a rise in the center portion of the slab lengths as related to the slab ends and an increase in the elevation of the entire section of approximately 1 to 3 in. as compared to the elevation at the time of construction.

The observations on this section indicate that a blanket course of 6 in. of nonexpansive topsoil will not prevent the volume increase of a dry expansive soil which causes warping of pavement slabs. It should be noted that such a blanket will aid in distribution of moisture and eventual leveling of high joints.

SECTION 6

This section is 604 ft. long. Expansion joints of the open type were placed at 100-ft. 8-in. centers with intermediate contraction joints Dowel bars were used at alternate expansion and contraction joints

The subgrade soil is of the A-4 and A-6 types having plastic indexes ranging from 11 to 28 and liquid limits from 32 to 47.

The soil in the subgrade was scarified in layers to a depth of 24 in. and the soil dried by disking, harrowing and blading until the moisture content was less than 10 percent. The soil was recompacted in the dry state and was sprinkled continuously for 48 hours just prior to the placing of concrete

The average moisture content of the subgrade soil after sprinkling was as follows:

6-in. to 14-in depth—21 percent
14-in to 24-in depth— 9 percent

Typical moisture contents of the soil adjacent to a joint as determined from samples taken through core holes are shown in Table 4. The average moisture content of the subsoil under the dried portion of the subgrade was approximately 20 percent at the time of paving.

It is interesting to note that the grade after sprinkling and prior to paving raised from ⅜ in. to ½ in. indicating a volume increase in the dried soil.

The profiles plotted from level data

over this section indicate an increase in the height of some joints of from 0 06 in. to 1 in. and no change in others In the length containing high joints a comparison of the 1937 and 1940 profiles shows a rise in the center portions of the slabs as related to slab ends and an increase in the elevation of the entire slab. This section reacted similar to sections 4 and 5 becoming rough in the spring of 1937 and decreasing in roughness as the moisture content became equalized throughout the length of slabs. There is no apparent warping in the slab now

SECTION 7

This section is 3,411 ft. in length A layer of sand ½ in. thick was placed on the subgrade prior to laying the pavement Curing consisted of 24-hr. wet burlap and saturated earth. The expansion joints were placed at 100-ft. 4-in centers with no contraction joints and were of the water-tight load transfer type Reinforcing consisted of 56-lb. mesh.

The subgrade soil is of the A-4 type having plasticity indexes from 15 to 19 and liquid limits of 34 to 39.

The average moisture content of the subgrade at the time of paving was approximately 18 percent or within about 1 percent of the plastic limit.

There has been no appreciable warping in this section. The profiles show a somewhat gradual raising of the grade throughout the section. In a short length the grade has raised 3.5 in. since placement. Throughout most of the section the raise in grade has been 0 to 1 in.

SECTION 8

This section is 604 ft long Expansion joints were placed at 100-ft. 8-in. centers with contraction joints midway between the expansion joints Both were of the modified open type with dowel bars at alternate joints

The subgrade soil is of the A-6 or A-7 type having plastic indexes ranging from 31 to 35 and liquid limits from 51 to 56.

The subgrade was prepared by scarifying to a depth of 6 in. and ponding until the moisture content of the soil was within 5 percent, plus or minus, of the plastic limit. The moistened and compacted soil was then covered with a layer or blanket course of nonexpansive soil 6 in. thick.

The average moisture content of the existing subsoil at the time of paving was

TABLE 4

MOISTURE CONTENT OF SOIL SAMPLES IN SECTION 6

Location		Depth of soil sampled	Moisture content	
Distance from expansion joint	Direction from expansion joint		1938	1940
ft.		*in*	*percent*	*percent*
20	W	0–12	21	24
15	W	0–24	24	23
10	W	0–24	23	24
5	W	0–24	25	24
1	W	0–24	25	25
1	E	0–12	25	24
5	E	0–24	25	24
10	E	0–24	24	23
15	E	0–24	23	23
20	E	0–24	23	22

28 percent and of the nonexpansive soil was approximately 12 percent.

No appreciable change occurred in the moisture content of the subgrade or blanket course soils during the five year period of observation

The profiles plotted from the level data indicate that no warping occurred and that the elevation of the slab remained approximately stationary.

SECTION 9

This section is 504 ft long Expansion joints of the modified open type were placed at 100-ft. 8-in centers with intermediate contraction joints. Dowel bars were placed at alternate expansion and contraction joints

The subgrade soil is of the A-4 or A-7 type having plastic indexes ranging from 16 to 28 and liquid limits from 38 to 48

The subgrade was prepared by scarifying in layers to a depth of 24 in and drying the soil to a moisture content of 10 percent or less by disking, harrowing and blading The dried soil was compacted by rolling The finished subgrade was then treated with an application of bituminous material from shoulder line to shoulder line followed by a sand cover The treatment consisted of the application of $\frac{1}{4}$ gal per sq yd of MC-1 followed on $\frac{1}{2}$ gal per sq yd of MC-3

The moisture content of the subgrade in this section remained low during 1936 and 1937 The samples taken in 1938 showed an increase in moisture in the soil close to the joints and those taken in 1940 showed an increase throughout the length of the slabs such that the moisture content at the joints and intermediate points was uniform and approximately 25 percent

The profiles of the section indicate a small amount of warping and a subsequent leveling of the section in 1940.

SECTION 10

This section was 504 ft in length. Expansion joints of the modified open type were placed at 100-ft 8-in intervals with intermediate contraction joints Dowel bars were placed at alternate expansion and contraction joints.

The subgrade soil is of A-7 type having plastic indexes of 24 and 25 and liquid limits of 45 to 47

The subgrade soil was mixed with portland cement at the optimum moisture for the soil-cement mixture and compacted to maximum density The quantity of cement used was 90 lb per sq yd for a 12-in. depth of undisturbed subgrade soil

After two years an examination of the soil-cement base disclosed that the top 5 in was hard and dense while the lower 7 in was soft and plastic

No appreciable warping has occurred in this section The profiles indicate a uniform rise of about $\frac{1}{2}$ in in the elevation of the slab since construction

SECTIONS 11 TO 14

All of these sections were approximately 1,200 ft in length In all of them expansion joints of the water-tight load transfer type were placed at 100-ft. intervals Intermediate contraction joints were used in sections 12 and 13 and were omitted in sections 11 and 14. Fifty-six pound reinforcing mesh was used in sections 12 and 13 The method used in placing and finishing the concrete was varied in each of the sections

The subgrade soil on all of the sections is of the A-7 type having plasticity indexes ranging from 16 to 22 and liquid limits from 39 to 44

On all of the sections the subgrade was scarified to a depth of 6 in and ponded with water until the moisture content of the soil was from 5 to 15 percent above the plastic limit

On section 11 the average moisture content of the subgrade soil at the time of construction was 27 percent There has been a moisture loss of about 2 percent since the pavement was placed

On sections 12 and 13 the average moisture contents of the subgrade soil at the time of construction were 28 and 24 percents respectively Since construction, the soil moisture has decreased about 2 percent on both sections

On section 14 the moisture content of the subgrade soil averaged 25 percent at the time of construction and has decreased approximately 4 percent since 1935

The profiles taken periodically since construction show no appreciable warping Profiles in 1940 show a general raising of the elevation of the pavements since construction of from 0 to about ½ in.

Sections 15 to 20 did not include special subgrade treatments. These sections were designed to study the effects of variations in concrete mixtures and methods of placing and finishing The subgrade soils were of the A-4 and A-7 types and contained from 14 to 26 percent moisture at the time of construction.

Subgrade paper was not used on sections 15 and 16.

The profiles of sections 15 to 20 inclusive show that no warping has occurred over the period from 1935 to 1940.

SUMMARY

The object of the subgrade sections of this project was to study the causes and the means of preventing warping of concrete pavements.

The soil and climatic conditions of the site were about average for many locations throughout the Middle West The rainfall from 1935 to 1939 was deficient and an opportunity was thereby afforded to study the effect of continued dry weather on subgrades treated by the methods included in the experiment. The data obtained from section 2 show that under these weather conditions no loss of moisture occurred over a period of five years from soil which had been placed at a uniform moisture content

The results obtained on section 2 indicate that the warping of pavement was entirely prevented by the bringing of the subgrade soil to an adequate and uniform moisture content prior to the placing of concrete. The total movement of the pavement on sections 2A, 2B and 2C as determined from successive profiles was very small and the fluctuations from the original profile were uniform. It is significant that the profiles on section 2A on which the subgrade treatment was 6 in. deep show a small progressive rise in the pavement while those taken on section 2C on which the treatment was 24 in. deep show a progressive drop in elevation. This would indicate that in section 2A an increase in volume occurred in the portion of the subgrade below the moisture treatment and that slight consolidation occurred in the subgrade of section 2C. Since the least movement occurred in section 2B, it follows that for the conditions existing on this project the preparation of the subgrade soil by moisture control to a depth of 12 in is most satisfactory.

The results obtained on section 4 indicate that warping was caused by the entrance of water into dry expansive subgrade soil through expansion joints It is significant that the increase in moisture of the subgrade soil was approximately the same for the joints designed to admit water and for those designed to be water-tight

The use of a 6-in. layer of nonexpansive soil over the subgrade in section 5 did not prevent or reduce the warping but was effective in aiding the distribution of moisture between expansion joints.

The sprinkling of the dried subgrade soil for 48 hours prior to placing concrete, while not entirely effective in the prevention of warping, reduced the severity of the distortion appreciably.

The saturation of the subgrade soil to a point well above the plastic limit was effective in reducing warping. It is significant that excessive drying of the soil did not occur in these sections even though the rainfall was deficient over a period of four years. It is also significant that no faulting or excess settlement has occurred over these sections during the period of observation.

CONCLUSIONS

The observations made on this project justify the following conclusions pertaining to warping:

1 Warping of pavement slabs is produced by volume change of expansive

soils caused by a differential in the moisture content brought about by surface water entering the subgrade through joints or cracks

2 Warping of pavement slabs was avoided by placing the subgrade soil at a moisture and density such that no subsequent differential moisture content resulted from the entrance of water through joints or cracks

3. Warping did not occur on expansive soils when the subgrade moisture was equal to or greater than the plastic limit.

4 A blanket course of nonexpansive soil, 6 in. thick, did not prevent warping over expansive subsoil having moisture contents about 10 percent below the plastic limit

5 Warping caused by expansion of soil due to differential moisture contents was reduced in time as the moisture in the subgrade became evenly distributed.

DISCUSSION ON WARPING OF CONCRETE PAVEMENT

QUESTION. Do you attribute any of the warping to the surface temperature?

MR. ALLEN No, we do not The Warping Committee has considered that and as compared with warping caused by expansion of soil, it is small. It will not cause excess distortion of the pavement It is the external force rather than the internal force which causes warping.

MR. W. W. MACK, *Delaware State Highway Department:* I was in Winnipeg this Fall and the Commissioner of Public Works pointed out to me the conditions of a great many of the streets due to the lowering of the ground water level Stretches of curb were noticeably very much out of profile, as much as 4 and 6 in. in a block. The bituminous pavements had longitudinal cracks in a great many of them caused by this settlement. The Commissioner stated that many buildings developed cracks and quite a few had to be shored up. They don't know what is going to happen when the water comes back.

CHAIRMAN WILLIAMSON: Is that caused by subgrade?

MR. MACK: It is caused by the lowering of the ground water level.