REPORT OF COMMITTEE ON WARPING OF CONCRETE PAVEMENT SLABS

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SYNOPSIS

This report is a record of studies made to find the cause, means of prevention, and correction of warping of concrete pavement The data were obtained from observations of pavements and from field and laboratory tests in California, Kansas, Missouri, Minnesota and Texas

The results of a portion of the laboratory tests, made as a part of this study, to determine the expansive properties of soils were published in the Proceedings of the Highway Research Board, Vol 16, (1936) and pages 220-233

The data indicate that warping is caused by an external force produced by the differential swell, or shrinkage and subsequent swell, of subgrade soil Soil expansion results from absorption of water entering through leaky joints, cracks and at pavement edges In Minnesota, the swell usually develops from the formation of ice lenses but in California, Kansas, Missouri and Texas, frost action has only a minor effect and the volume change occurs largely because of the expansive characteristics of the soil itself

The amount of swell is dependent on the characteristics of the soil, on its moisture content and density at the time the pavement is placed, and on the subsequent absorption of moisture

That warping can be prevented by avoiding expansive subgrade soils is indicated by the data Objectionable warping can be prevented by controlling moisture differential and resultant volume change of the soil Bases and joint drains were only partially effective in preventing warping The recurrence of seasonal warping was prevented by efficient joint and crack maintenance

The most practical and economical means of correcting objectionable roughness due to warping is by means of the mud-jack

The occurrence of objectionable roughness of concrete pavement due to uplifted slab ends was first recognized about 1928. It was observed that with joints at frequent intervals the severity and frequency of distortion of the pavement imparted a rhythmic, rocking, jerking motion to fast passenger traffic which was very objectionable The distortions varied in magnitude from those which were negligible to those in which the slab ends were distorted two or more inches from their original position

Because of the number of projects affected and the severity of the distortions, it became necessary to make a study to determine the cause of the distortions to find the means of preventing them on future work and to determine methods for correcting those which had already occurred

The Committee was organized in June 1934 It was formed of representatives from the highway departments of California, Kansas, Minnesota, Missouri, Texas, the U S Bureau of Public Roads, and the Portland Cement Association Since its inception the Committee has presented as a part of this study, "The Results of Tests to Determine the Expansive Properties of Soils," which was published in Volume 16 (1936) Proceedings of the Highway Research Board, pages 220-233.

This present Progress Report summarizes the results of observations and tests and was compiled from the data obtained by the organizations represented on the Committee

Definitions

The Committee adopted the following definitions for use throughout this report

Curling. The distortion of the pavement slab from its proper plane caused by differential contraction resulting from a difference in moisture content or temperature between the top and bottom of the slab

Warping The distortion or displacement of the pavement slab from its proper plane caused by external forces

High Joint A condition resulting from warping or curling of the slabs on each side of a joint or crack

Swell The expansion or increase in the volume of a mass of soil, resulting in an increase in the porosity of the soil

Shrinkage The contraction or decrease in volume of a mass of soil, resulting in a decrease in the porosity of the soil

Bulk Density The weight of soil particles per unit volume of soil mass

Subgrade Soil The soil underlying the subbase, base, or pavement to which no addition other than water has been made

Base or Subbase Any layer artificially introduced between the subgrade soil and the pavement wearing course

Additional terms pertaining to soils and soil tests comply with the definitions given in Public Roads, Vol 12, Nos 4 and 5, 1931

SCOPE OF STUDIES

Probable Causes Investigated

A number of probable causes for the distortion of slabs were advanced These were separated as follows

A External Forces resulting from
  (1) Non-uniform soil swell caused by entrance of water into the subgrade soil
  (2) Non-uniform soil shrinkage caused by loss of moisture from the subgrade soil
  (3) Non-uniform soil swell caused by the action of frost
  (4) Flow or creep of the subgrade soil

B Internal Forces resulting from
  (1) Vertical temperature differential in the slab
  (2) Vertical moisture differential in the slab
  (3) Unequal deposition of crystalline matter in the top or bottom of the slab
  (4) Unequal hydration of the cement in top and bottom of the slab

Preventive Measures Investigated

Various measures which were expected to prevent distortion were investigated. They were separated as follows.

A Control of soil volume change
  (1) The selection and use of nonexpansive subgrade soils
    (a) Modification in the location of the road
    (b) Modification in grade line of the road
    (c) Selection and distribution of nonexpansive subgrade soils during grading operations
  (2) Changing the characteristics of expansive subgrade soils by means of admixtures
    (a) Granular materials
    (b) Powdered material, such as portland cement, lime, and stone dust
    (c) Bituminous material
  (3) Preventing the occurrence of a moisture differential between adjacent areas of subgrade soil
    (a) Soil moisture control during construction
    (b) Soil density control during construction
    (c) The use of layers to prevent differential absorption and evaporation
      1 Porous granular layers
      2 Impervious nonbituminous layers
      3 Impervious bituminous layers
    (d) Preventing percolation of water through joints into the soil
      1 Constructing watertight joints
      2 Maintaining joints watertight
      3 Use of joint subdrains

B Design of the pavement slab
  (1) Cross section
  (2) Plan and the amount of reinforcement.
  (3) Type and spacing of joints
  (4) Waterproofing top or bottom of the slab
  (5) Quality, composition and characteristics of the concrete mix

Correction of Existing Warped Slabs

The following methods of straightening distorted slabs were reported, either as experimental studies or as routine maintenance practices.

A Straightening by the artificial introduction of water to equalize the subgrade soil moisture
B Straightening by jacking
 (1) Mud jack
 (2) Jacking into level position and introducing granular materials to maintain the slab in position
C Shoulder treatments with porous granular materials

Extent and Nature of Field and Laboratory Work

The general procedure followed in these studies included an inital reconnaissance of pavement within each State to determine the amount, distribution and characteristics of distorted pavement The field work was then mapped out so as to determine from detailed study of a selected number of projects the nature of the distortion, the effects of the various probable causes, and the results of the preventive and corrective measures As the work progressed certain special tests were performed to prove the validity of the data

The laboratory work included routine analysis of subgrade soil samples, experimental work on the volume changes of small soil specimens as affected by moisture and density, the production of warping in a model slab and a study of the force exerted by soil expansion due to changes in moisture content

The field work included among other tests the construction of projects designed to include all known factors which might influence the formation or prevention of distortion

PRESENTATION OF DATA

The data presented have been selected by the Committee from the detailed reports of the various cooperating agencies and show the typical conditions accompanying the distortion of pavements The results in many instances showed sufficient similarity to make possible the selection of data to illustrate the most common features of the problem

The substantiating data as submitted by the cooperating agencies[1] will be referred to by number throughout the report in accordance with the following

(1) California
(2) Kansas
(3) Minnesota
(4) Missouri
(5) Texas

It was established that distortions were intimately associated with the type and condition of the subgrade soil at the time of concreting and that factors related to the design and construction of the pavement other than those affecting leakage of water into the subgrade had no influence

The most pertinent data relative to pavement distortion, its causes, means of prevention and means of correction, have been divided into two main groups depending upon whether the force or forces causing the distortion have originated from within or from without the slab Thus the data which pertain to the pavement and those which pertain to the subgrade are presented separately

CONCRETE PAVEMENT

Characteristics of Distorted Slabs

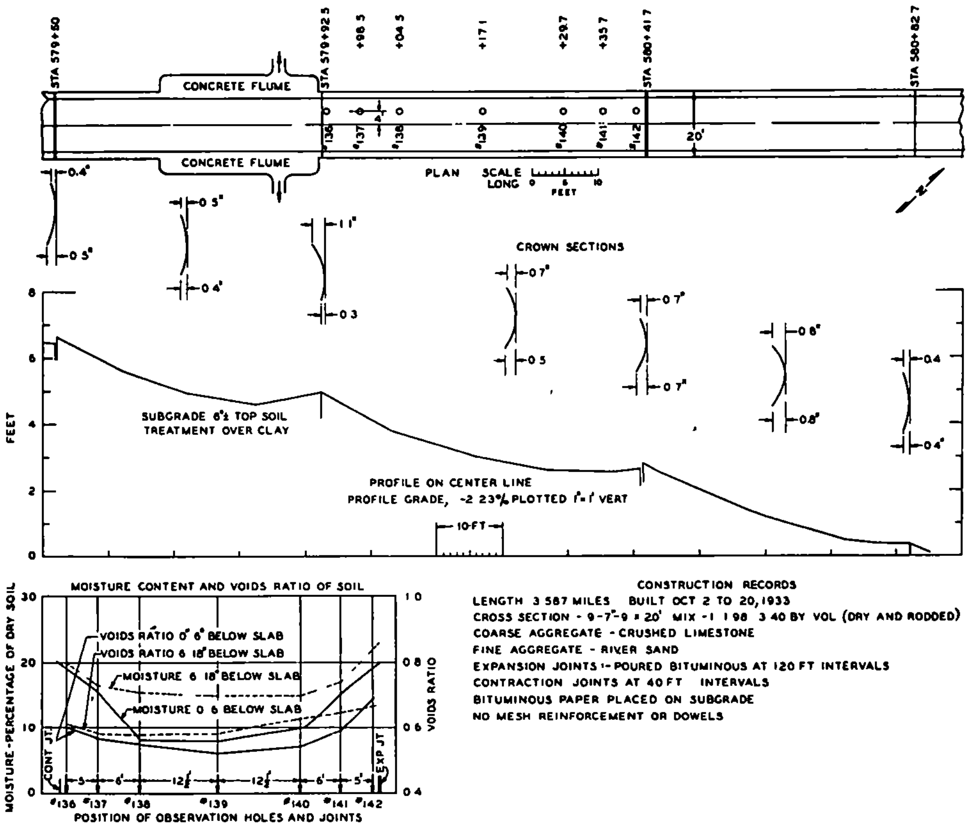
The results of periodical measurements of distorted slabs showed numerous changes in elevation for whole slabs, however, there was invariably a much greater vertical movement at the ends and edges of slabs A typical distorted slab is shown in Figure 1

The magnitude and shape of the distortion of the slabs varied from one side of the joint or crack to the other and from edge to edge of the slab These varia-

[1] Copies of the reports of the individual States are on file with the Highway Research Board

tions account for the decided irregularity of the longitudinal profile and the pavement crown as is shown in Figure 1 The faulting of the slab at the high joints is likewise shown in this figure The amount of distortion varied from a negligible amount to as much as 2 in or more in a 40-ft slab The edges of some slabs were distorted to such an extent that no crown remained in the pavement and in others it was appreciably increased The variations in transverse profile are shown in Figure 1

The distorted area extended from the high joint to a distance of from 10 to 20 ft, being somewhat greater on the downhill side Although the distortions themselves were neither uniform nor regular in their occurrence, all distortions were adjacent to joints, cracks or pavement edges Generally, where cracks and dummy joint openings were small, the adjacent pavement was distorted less than that near expansion joints (2) (3) (4) However, where cracks and dummy joint openings were relatively large, the



SUBGRADE SOIL TESTS

MECHANICAL ANALYSIS								PHYSICAL PROPERTIES OF PARTICLES PASSING 0.42 SIEVE								
LAB NO	DEPTH UNDER PAV'T INCHES	PERCENTAGE OF PARTICLES HAVING DIAMETERS (M M.) SMALLER THAN –						LAB NO	DEPTH UNDER PAV'T INCHES	LIQUID LIMIT	PLASTIC LIMIT	SHRINKAGE		MOISTURE EQUIVALENT		GROUP
		2.0	0 42	0 25	0 05	0 005	0 001					LIMIT	RATIO	CENTR	FIELD	
141A	0-6	100	79	55	33	21	15	141A	0-6	31	15	14	1 87	20	27	A-2
136B	6-18	100	98	96	93	63	31	136B	6-18	55	28	13	1 94	45	34	A-6

Figure 1. Typical Distorted Pavement

adjacent pavement was distorted as severely as that at expansion joints (5).

The removal of the shoulder material adjacent to the pavement and the cleaning of the sides of the slab disclosed that transverse cracks, invisible at the pavement surface had developed adjacent to high slab ends. These cracks occurred 10 to 20 feet from the slab end and varied considerably in width and height of crack opening. Some extended the full depth and others were visible only in the lower one-third to one-half of the pavement. Figure 2 illustrates a typical example of this type of transverse or "bottom" crack.

Figure 2. Bottom Crack in Warped Pavement

Cores were drilled near high slab ends through some transverse cracks which were visible at the pavement surface. The crack opening was found to be wider near the bottom than near the top of the slab This was also done on slabs which had not been distorted and the cracks were found to be approximately the same width for the entire depth of the slab.

Transverse cracks and in some instances (5) longitudinal cracks were associated with the development of distortion and as the distortion increased the cracks became more numerous. Where the slab was distorted on each side of a transverse crack the width of the crack was greater at the top than at the bottom. Transverse cracks appeared to occur somewhat closer to the joint on the uphill side, than on the downhill side of the joint. The average distance from a high joint to the first transverse crack was reported (2) as 17 ft. on the downhill side of the joint and 14 ft. on the uphill side.

Effects of Design on Distortion

Some features of the pavement itself had no influence and others some influence on the development of distortion.

Investigations were made to determine whether or not quality or composition of the concrete was in any way associated with distortion. No relationship was found between aggregates or the brand of cement used and the development of distortion. Distortions developed with a large variety of coarse and fine aggregates and brands of cement all of which were used on other projects where no distortions developed. Tests on the aggregates and cements showed they complied with standard specifications. As many as four different brands of cement and two aggregates from different sources were used on one project where distortions were found throughout the project irrespective of the materials used.

Compression tests (2) on 62 cores taken from a badly distorted project and tested at the age of 90 days showed an average compressive strength in excess of 4000 lb. per sq. in. Density determinations made of 75 cores from the same project showed densities of 2 22 in the top one-third and 2 23 in the bottom one-third The absorption varied from 4 60 percent in the top one-third to 4 29 in the middle to 4 25 in the bottom one-third of the slab

Concrete proportions or type of finishing did not influence the development of distortion Distortions were found to occur irrespective of the type of curing method Distortions at early ages were found in pavements cured by methods which permitted water to enter expansive subgrades through leaky joints and at the edges of the pavement Where identical proportions, finishing and curing methods were used throughout the entire length of projects, distortions developed only on intermittent sections of these projects

The expansion joints studied were of the premolded, tamped or poured, and the copper sealed air core type, and were constructed both with and without load transfer devices

It was found in these studies that a definite relationship existed between the watertightness of joints and cracks and the development of distortion The amount of leakage tends to increase with lowering temperatures of the pavement for premolded, tamped or poured joints ordinarily used (2) (5)

Expansion joints with copper seals, when properly installed and maintained, were (3) effective in reducing the intensity of warping Data available were too immature to indicate that this type of joints will remain effective after an appreciable period of time (3) (4)

In general expansion joints are more susceptible to leakage than contraction or dummy joints and therefore it is to be expected that more distortion due to subgrade swell will develop at expansion joints than at contraction joints This was found to be true although severe distortion also developed in some instances at contraction joints

In one State (3) much less distortion due to frost developed on projects constructed subsequent to 1932 The major difference in the projects constructed subsequent to 1932 was that a soft asphalt with 20 percent by weight of diatomaceous earth was used as a joint filler. This did not become brittle and crack as did the hard fillers used on pavements constructed prior to 1932 This condition was shown on an experimental project, a portion of which had the top 2 in of brittle expansion joint filler removed and refilled with the above type of soft filler The intermediate contraction joints were resealed with the same filler. Where the joints were sealed in this manner the seasonal recurrence of objectionable warping was reduced appreciably

It is significant that no tightly closed expansion joints indicating abnormal pavement expansion, were found between distorted slabs High joints were found to develop irrespective of the fact that the load transfer devices had or had not been used

The pavements included in these studies covered a large range in the spacing of expansion and contraction joints Contraction joints were used so as to form slab lengths of 10, 20, 30, and 40 ft and expansion joints, both with and without contraction joints, were used at 40, 60, 80, 116 ft and greater intervals In some cases expansion and contraction joints were used alternately The magnitude of the distortions tended to decrease with decreased length of slab Objectionable distortion occurred on slabs of all lengths

In 1931 alternate expansion and contraction joints were used to form slab lengths of 40 ft (4) In that year the distortion consisted principally of a lifting of the pavement at the expansion joint and not at the contraction joints In the following year the use of contraction joints was discontinued and expansion joints used at 40-ft intervals Pavements built on certain subgrade soils in that year were badly distorted and were distorted more symmetrically at the slab ends than in the preceding year The difference in leakage through expansion joints and through contraction joints accounts for the difference in distortion observed

Because of the evident relationship between leaky expansion joints and distortion, it was decided to attempt to collect water entering the joints by means of a drainage system and to carry the water out to the side ditches Tile drains of various designs and ordinary crushed rock drains were constructd in two States (2) (3) Their use was not successful in preventing distortion and an increased moisture content in the subgrade soil was found adjacent to them. On one project (2) after a severe winter the subgrade under the pavement thawed out to the depth of the drains before the shoulders thawed out to an equal depth The water from melting snow and the first rains entered the leaky joints and became trapped under the joint as the drains were still clogged with ice under the shoulders This allowed the water to enter the subgrade and resulted in severe distortion Excessive leakage through joints was shown by the large amounts of water discharged through the joint drains at other seasons In some instances this was great enough to erode the shoulder slopes

The plan of reinforcement used did not affect distortions No effect was found from placing the reinforcement near the top or the bottom of the slab. Distortions were found to be present and absent where reinforcement was used as well as on slabs where no reinforcement was used (4) (5)

Lip curb was found to be a contributory factor to distortion since it prevented water from flowing over the edge of the pavement to the shoulders Longitudinal distortions were especially severe where this type of cross section was used since more water drained onto the pavement for leakage through joints and cracks Pavements with lip curb even though badly distorted longitudinally showed less loss of crown than where none was used since less water entered the subgrade soil along the edge of the pavement

The entrance of water to the subgrade soil through cracks and joints was not prevented by the use of impervious paper on the bottom of the slab (2) (3) (5) or the application of bituminous surfacing to the top of the slab (5) Warping has occurred on pavements where these methods have been used

Variations in the pavement cross section were not effective in preventing warping Objectionable warping occurred on all sections investigated, the thickest section studied being 10 by 8 by 10 in (5)

Significance of Curling

Data obtained on the action of pavement curl was limited to measurements of the daily movement of a slab due to temperature changes Ames dials were used and for a maximum difference in temperature between the top and bottom fibers of 24°F the movement was only 0 03 in A review of available literature showed that the greatest curl caused by combined influence of temperature and moisture was never larger than about 0 25 in which is much less than the distortions observed in these studies (3) (5)

SUBGRADE SOILS, BASES AND SOIL TREATMENT

Relation of Soil Characteristics to Distortion

The presence or absence of distortions was found to be definitely associated with characteristics of the subgrade soils Distortions were not found on sand subgrades of the A3 group, on sandy loams of the A1 group, on some of the more sandy soils of the A2 group nor on some of the sandy loams and less plastic silty loams of the A4 group

Table 1 shows the test constants of soils taken from under a number of distorted slabs All of the soils upon which distortions were found were of a cohesive nature, being plastic when wet All were of an expansive nature and had a relatively high clay content

distances ranging from 10 to 20 ft back of high joints Figure 1 illustrates a typical condition The depth of the increased subgrade moisture content ranged up to 4 ft at the high joint and diminished as the distance from the joint increased The extent of the distortion was proportional to the increased moisture content of the soil although the relationship was not linear Increased moisture content of the subgrade soil usually extended to a greater depth and

TABLE 1

AVERAGE AND RANGE IN SOIL CONSTANTS OF SOILS ON WHICH WARPING HAS OCCURRED

Soil property	Kansas (2)		Minnesota (3)		Missouri (4)		California (1)		Texas (5)	
	Range	Av	Range	Av	Range	Av	Range	Av	Range	Av
Liquid limit	32-62	46	36-79	46	32-57	42	35-80	53	36-58	46
Plasticity index	12-37	23	18-46	25	10-35	21	19-55	33	17-38	25
Shrinkage limit	10-27	16	13-18	16	8-22	14	8-15	13	6-15	10
Shrinkage ratio	1 50-2 03	1 82	1 68-1 93	1 81	1 64-2 07	1 89	1 6-2 1	2 0		
Field moisture equivalent	24-36	30	15-35	21	21-40	29	22-43	30	26-40	33
Clay and colloids	23-57	40	19-64	33	28-51	36	33-96	71		
Colloids	14-42	27	2-32	13	15-32	22	12-30	20		
U S B P R Group	A4, A6, A7	6-A4	A4, A6, A7	1-A4	A4, A6, A7	1-A4	A4, A6, A7	1-A4-6	A2-A4	1-A4-7
		7-A6		10-A6		2-A4-6		4-A6	A6-A7	3-A7
										1-A6
		15-A7		1-A6-7		2-A6		1-A6-7		1-A6-2
				17-A7		4-A7		2-A7		1-A6-7

(1) Based on 8 tests on 6 projects
(2) Based on 28 tests on 9 projects
(3) Based on 29 tests on 19 projects
(4) Based on 9 tests on 9 projects
(5) Based on 7 tests on 7 projects

Distortions were found on silty clay loams and clay loams of the A4 group and on silty clays and clays of the A6 and A7 groups The majority of the distortions developed in pavement laid on the soils of the A6 and A7 groups or borderline soils between the A4 and the A6 or A7 groups

Relation of Soil Moisture and Density to Distortion

Tests of the subgrade soils under high joints showed that the moisture content decreased as the distance from the joint increased This condition existed for

over a greater length on the downhill side of the joint as compared to the uphill side, also more moisture existed on the inside of superelevated curves as compared to the outside of the curve This was probably due to gravitational flow of the water and has resulted in greater distortion on the inside of such curves

The location and extent of the areas of increased moisture content of the soil under a pavement with lip curb differed somewhat from that found under a slab having no lip curb On pavements without lip curb, water entered the subgrade along the edges resulting in a typical moisture distribution shown in "A" on Figure 3 The increased moisture content where lip curb was used was found to be largely a longitudinal distribution from the joints since very little water drained to the edges of the slab as shown in "B" of Figure 3.

On sandy and silty soils water leaking through joints resulted in an increase of the moisture content in the subgrade soil adjacent to the joint The moisture increase, however, had not caused distortion where frost action was not a factor

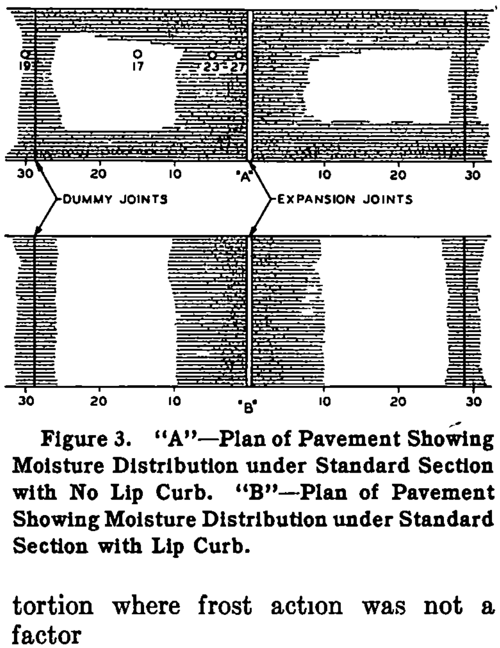


Figure 3. "A"—Plan of Pavement Showing Moisture Distribution under Standard Section with No Lip Curb. "B"—Plan of Pavement Showing Moisture Distribution under Standard Section with Lip Curb.

The voids ratio (volume of voids ÷ volume of soil particles) of the subgrade soils under *distorted* pavements was found to increase directly with increased moisture content and was greater adjacent to high joints (see Fig 1) Where no distortion was present, the voids ratio did not show an increase at cracks or joints. On sandy nonexpansive soils an increase in the moisture content of the soil at a leaky joint or crack was not accompanied by an increase in the voids ratio.

Tests of the expansive subgrade soils showed that during prolonged dry periods, the soil moisture decreased and the soil contracted along and under unprotected outside edges of the slab As a result of the removal of subgrade support, longitudinal cracks occurred (5).

Relation of Soil Moisture at Time of Concreting to Distortion

Distortions were found to be related to the state of the subgrade soil moisture content and state of compaction which existed at the time of concreting High joints were found to be much more prevalent on pavements placed on expansive subgrade soils having abnormally low moisture contents, than on similar soils known to have been set at the time of concreting

Pavements laid on wet soils, generally in excess of the Proctor optimum moisture but depending upon the characteristics of the soil, did not result in high joints due to soil swell (2) (4). In one State (5) (where the wet and dry seasons of the year were extreme) on a project where the soil moisture was raised to approximately its F. M E by ponding water thereon, warping was delayed but not prevented. Differential shrinkage and subsequent swell of the soil at the joints and at other places under the slab was the cause of the warping

In one State (2) where soil densification and proper moisture control during construction were used, such projects remained free of noticeably high joints resulting from either differential soil swell or soil shrinkage No data were available which indicated that these conditions applied when frost action was a factor

Although many leaky joints were observed on pavements which had not been distorted, studies of soil moisture under these joints showed that where expansive soils existed in a wet, compacted state at the time of concreting, moisture increases sufficient to cause excessive soil swell and objectionable warping did not occur (2) (4)

Supplementary Data to Show the Influence of Soil Condition on Distortion

Because the data tended to point toward soil swell as a cause of distortion, certain special tests and investigations were devised to test the validity of these data and the manner in which they were interpreted

The data obtained on these special tests are summarized as follows

Laboratory Test Slab A concrete slab was laid on a silty clay-loam soil (A4 group) containing 10 percent moisture (see Figure 4 for details) Water was added to a joint in the slab The resulting distortion was similar to that observed in the field and was accompanied with increased moisture content and voids ratio of the soil (2)

Expansive Properties of Soils The results of the research into the expansive properties of soils were published in vol 16 (1936) Proceedings of the Highway Research Board These results showed that the amount of soil swell depended on the characteristics of the soil itself as indicated by its test constants, the structural arrangements of the soil in its natural state and upon its state of compaction and moisture content The greatest swell was found on expansive soils placed in a comparatively dry and compact state prior to testing The least swell was found, regardless of initial density, when the voids prior to the swell test were filled with water

The data showed that the relative swell of a soil tested at different original moisture contents and densities in the laboratory, closely paralleled the relative swell of soils observed in the field

Expansion Force of Soil The same soil used in the laboratory test slab was compacted into a cylinder to a density of 1 60 and at a moisture content of 10 percent The swell of the soil when water was introduced into the cylinder exerted a unit pressure approximately eight times the unit force required to lift a 7-in concrete slab (2)

Swell of Undisturbed Soil Column This test was performed under the same technique in two States (2) (4) and was conducted as a means of obtaining proof of the possibility that natural soils might swell enough to cause an appreciable uplift of the pavement In one State (2) a structured soil swelled vertically a distance of 0 9 in in three weeks' time, while in an equal time a structureless soil showed practically negligible swell. In the other State (4) at the conclusion of the test which was conducted for one year, the soil was swelled vertically 0 9 in and the moisture in the soil was raised from about 9 percent to 21 percent Laboratory swell tests of undisturbed samples of soil taken from around the soil columns showed the same trend in results as indicated in the field tests

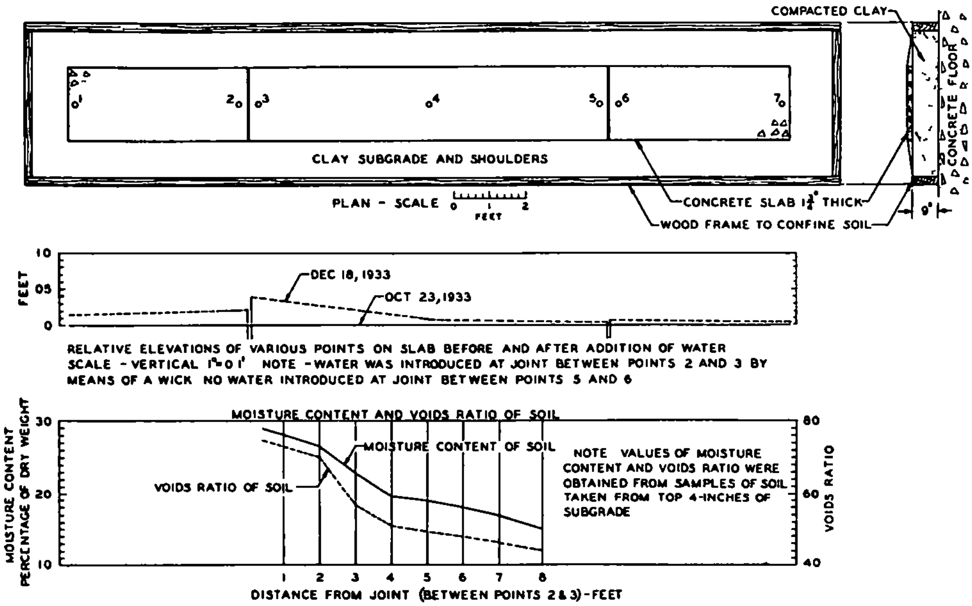
Artificial Control of Distortion In order to further clarify the interpretation of the data, it was felt that if high joints could be produced or eliminated by artificially introducing water into the subgrade soil under the slab, the experiment would be of considerable value

The moisture content of the soil at the joints was materially raised (3) but remained unchanged in the mid-portion of the slab, on a section of pavement on which water was introduced into five opened expansion joints Distortions due to frost action after the introduction of water into the joints appeared the following winter and were much worse the second winter

In two States (2) (4) water was introduced into the subgrade in the central portion of distorted slabs by means of perforated pipes and in a third State (3) by means of holes bored transversely under the slab In the first (2) and third (3) States, the data show that the distortion was largely eliminated although in one State (3) it is significant that this did not occur until ice lenses formed in the soil The resultant uplift of the pavement was sufficient in one State (4) to affect only a 25 percent straightening of the slabs

Soil Flow

In the early stages of the investigation there was some doubt as to the possibility of the soil swelling sufficiently to account for the excessive distortion and lifting of the slabs; however, after periodical levels showed that numerous slabs throughout their lengths continued to rise while some of the others remained at about the same elevation, it became evident that the subgrade soil was lifting the pavement Either the soil was swelling due to moisture expansion, frost action, or a combination of the two, or it was slowly flowing and accumulating beneath those slabs that were being elevated Although no positive data resulting from measurement of soil creep or flow were obtained, further study caused the idea regarding flow to appear incredible Often several whole slabs were raised, yet there was no falling or depressing of adjacent areas The data showed numerous instances in which the entire length of pavement in a test section was definitely elevated A number of tests and measurements were then made to substantiate these findings



RESULTS OF SOIL TESTS

MECHANICAL ANALYSIS							PHYSICAL PROPERTIES OF PARTICLES PASSING 0.42 SIEVE							
SAMPLE NO	PERCENTAGE OF PARTICLES HAVING DIAMETERS (M.M) SMALLER THAN -						SAMPLE NO.	L L	P I	SHRINKAGE		MOISTURE EQUIVALENT		GROUP
	2 0	0 42	0 25	0 05	0.005	0.001				LIMIT	RATIO	CENTR	FIELD	
1A	100	99	98	79	27	14	1A	34	15	15	1.86	23	26	A 4

CONSTRUCTION RECORDS
SOIL-RED SILTY CLAY LOAM, SOIL WAS UNIFORMLY COMPACTED AT A MOISTURE CONTENT OF 10 PERCENT
CONSTRUCTED OCT 19, 1933.
WATER INTRODUCED BETWEEN POINTS 2 AND 3 FROM OCT 24 TO NOV 7, 1933

Figure 4 Laboratory Test Slab

Effect of Freezing the Subgrade Soil

There is evidence that in the central States freezing will affect the magnitude of the distortion but is not a primary cause For instance, periodical profiles taken on one State's (3) projects showed that in general the greatest warping was attained during periods when freezing temperatures prevailed On the other hand, some instances were noted where the greatest warping was attained during the summer months Furthermore, in another central State (2), it was observed on some projects that warping began in the spring and increased in severity during the summer and fall before any frost action occurrred

In northern States (3) freezing of the subgrade soil may be the major cause of distortions Higher moisture contents which accumulated in the subgrade soil adjacent to leaky joints and cracks and the pavement edges did not result in distortions until frost penetrated the subgrade soil Distortions increased in magnitude with increase in depth of frost penetration Ice lenses developed to a greater extent under the joints and cracks and near the edges of the slab, where the moisture concentration was greater Slabs remained distorted during freezing temperatures, but subsided almost completely after the spring thaw Only slight distortions remained through the summer months

The relationship of the formation of distortion to frost action is illustrated in Figure 5 Figure 6 illustrates the ice lenses in soil taken from under a high joint

Effect of Bases, Soil Treatment, and Shoulder Protection

On six projects in one State (2), 5 to 6-in compacted bases extending 1 ft beyond the edges of the pavement composed of sandy loam soils of the A2 and A4 groups were used Slight to severe distortions occurred in all of these projects The data showed that, due to the more permeable nature of the material, the moisture had progressed a greater distance from the joint than where no base course had been used and the jolt to traffic was not so severe as at distorted joints where no sub-base course had been used

In one State (1), the use of bases composed of granular materials up to 12 inches in depth or thin bituminous membranes placed directly under the pavement were not successful in preventing distortion. This State now places 9 in of selected soil from borrow pits over a bituminous membrane and reports that negligible distortions have developed on several projects where this method of treatment was used It is probable that the method has been satisfactory because the bituminous membrane is preserved in an unbroken condition The depth of 9 in was found to be sufficient to prevent perforation of the membrane by form stakes, etc It was also expected to spread traffic loads over a greater area and prevent excessive deflections of the membrane

No distortion developed over a period of four years on a pavement laid in one State (5) and separated from an expansive subgrade soil by a 12-in sand base extending from outside shoulder line to outside shoulder line of the roadway Distortion developed, however, on an adjoining section on which the sand base extended only for the width of the pavement Moisture determinations indicated drainage of the surface water to the side slopes and ditches on the first section and an impounding of water in the sand under the pavement on the second

On a third section of the experimental project, a bituminous membrane of 2 gal of 90 penetration asphalt was placed entirely across the roadway and down the side slopes for a total width of 48 feet The concrete was placed directly on the bituminous membrane The bituminous membrane on the roadway shoulders was covered with clay soil to the top of the edges of the 9–6–9-in pavement slab During hot summer weather a part of the asphalt under the slabs worked up to the top of the expansion and contraction joints and cracks, apparently maintaining a watertight pavement. After 4 years, no appreciable warping has been found in the pavement. Data from one State (5) indicated that where pavement surface irregulatities had developed the replacing of the impervious clay shoulders with granular pervious material retarded further impounding of water under the slab and allowed the excess water that had previously accumulated to evaporate eventually and become equalized—thus reducing the magnitude of the pavement surface irregularities.

The use of different varieties of subgrade paper (2) (3), road oil or tar treated subgrades (3) (5), and a mixture of road oil and kerosene (3) introduced into the subgrade soil through holes in the slab were not effective in preventing distortion. The subgrade paper was found to stick to the bottom of the pavement and tear apart at joints and cracks. Actually as used greater uplift was found on the portions treated with road oil than on adjacent untreated sections. The tar treatment was $1\frac{1}{2}$ to 2 in. thick and thoroughly compacted yet proved ineffective. There was not enough tar used to form an impervious membrane.

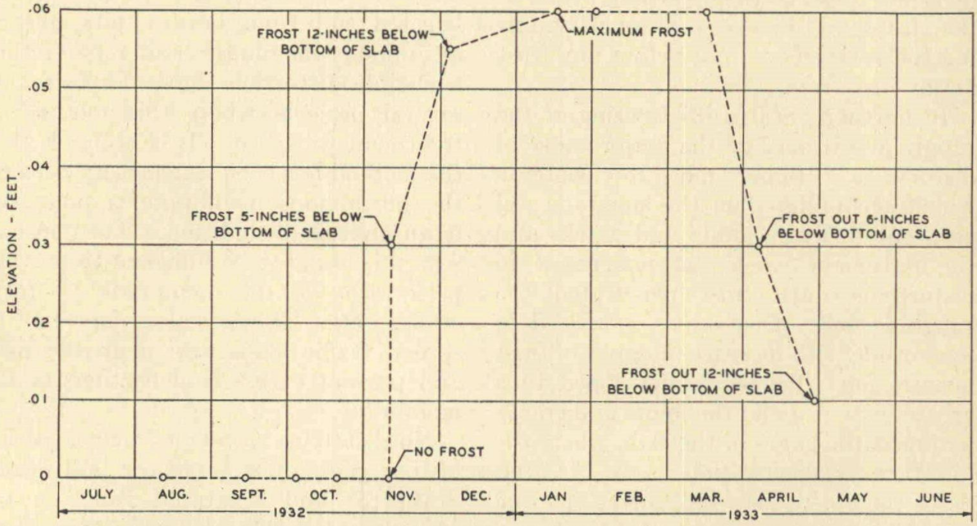


Figure 5. Seasonal Slab Movements at Expansion Joints Due to the Formation of Ice Lenses.

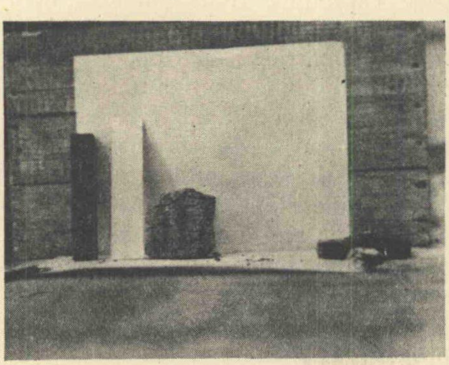


Figure 6. Ice Lenses Formed in Subgrade Soil

Granular bases of less than 9 in. in depth laid from outside shoulder to outside shoulder lines were not effective in preventing distortions in a northern State (3). No appreciable distortions were found in pavements placed on bases of 9 in. or more in thickness.

In one State (4) the data on test sections to determine the efficacy of an admixture of sand disked into the soil to a depth of 2 in. and a $1\frac{1}{2}$-in. sand blanket did not yield much information. Appreciable distortion developed neither on the test sections with the 2-in. sand admixture nor on the adjacent untreated sections When open joints were used, the soil moisture changed more in the subgrade under the $1\frac{1}{2}$-in sand mat than in the adjacent sections without sand mats and the moisture gain in the subgrade was more uniform between joints indicating that the blanket had some effect on distributing water entering the joints

The admixture of granular materials to heavy clay soils for appreciable depth was found to be impracticable in one State (5) due to mechanical difficulties

The subgrade soil was given a moisture treatment prior to concreting on a number of projects (2) This treatment consisted of the addition of water by means of diking and ponding or sprinkling the scarified subgrade until water had penetrated the soil to a depth of 18 to 24 in The subgrade was then rolled with a 3-wheeled roller Moisture treatment was first begun during the construction season of 1934. Inspections of the pavement late in 1937 showed that where adequate subgrade moisture content and proper density were obtained, no distortions had developed

Excellent agreement was obtained on the above projects (2) between the indicated results obtained by the laboratory investigation on the expansive properties of soils and actual results obtained in the field on water-treated subgrades The laboratory data indicated that expansive soils swelled least when compacted to maximum density at a moisture content just filling the voids A moisture content for the compaction used (a 3-wheeled roller) about equal to the lower plastic limit was found to be the optimum one as regards soil swell

In one State (5) the water treatment to a depth of 3 ft consisted of the addition of water by ponding until the moisture content of the soil was approximately equal to the F M E The subgrade was not rolled prior to placing the concrete The initial appearance of warping was delayed but eventually developed due to the excess shrinkage and subsequent swell of the subgrade soil during the alternate dry and wet weather

METHODS USED TO CORRECT EXISTING DISTORTIONS

The following methods were used to straighten distorted slabs.

Straightening by introducing water into the subgrade soil was reasonably successful in two States (2) (3), but in another State (4), on account of the imperviousness of the soil, only 25 percent of the distortion was removed

Mud-jacking has been extensively used in one State (5) and to a lesser degree in another (4). A mixture of soil, cement and water mixed to the consistency of thin batter was injected through holes bored in the mid-portion of the slab Observations on 9 test sections (4) before and after mud-jacking showed that the distortion was largely eliminated and has remained so for over 3 years However, the uplift caused cracking, some breakage and faulting of the slab ends The average cost of this work in this State (4) was $0 14 per square yard In another State the slabs were satisfactorily straightened although a considerable amount of cracking and breakage developed The cost for an average lift in this State (5) ranged from $0 15 to $0 20 per square yard Considerable skill is required in the operation to avoid excessive breakage of the slabs

Warping was corrected in one State (5) by raising the slabs the entire length of the warped section of pavement to a smooth surface by means of hydraulic jacks. The minimum amount the slabs were raised was approximately 2 in. Sand was then rammed under the slabs to support the pavement in its raised position. The pavement has retained a fairly smooth riding surface. However, during the jacking up of the pavement, it was badly cracked, also the method was not found to be economically practical

SUMMARY OF DATA

Causes of Pavement Distortion

Curling of the pavement slab due to internal forces within the slab is not sufficient to cause pavement distortions of the amount found in these studies Investigation shows that the curling action is diurnal and that the maximum amount of distortions from this cause could account for only a small part of the distortions observed

Factors such as cross section, plan of reinforcement, character and quality of aggregates and cements, proportions of the concrete and methods of finish, were found to have no effect on the development of distortion Distortions were found to occur on localized sections of the same project built to the same design, of the same materials, and according to the same construction procedure throughout Also distortions were found to occur or not to occur irrespective of these design or construction features

Warping of pavement slabs due to swell or shrinkage of the subgrade soil was found to be definitely the cause of the distortions This was shown from observations of the slab itself and observations and tests of the subgrade soil

The occurrence of warping is definitely associated with the characteristics of the soils which make up the subgrade Warping was found only on expansive soils of the A4, A6 and A7 groups It was most prevalent on soils of the A6 and A7 groups and on border line soils between the A4 and A6 and A7 groups.

Tests and observations showed high moisture content in the expansive subgrade soil under high joints and showed that the moisture content diminished with increased distances from the joints and cracks or edges of the slab These moisture gradients resulted from the entrance of more water and subsequent absorption by the subgrade at the joints and cracks and at the edges of the pavement Tests on these soils also showed that a decrease in density was coincident with the increase of absorbed moisture, which indicated that the subgrade soil in these localized areas had expanded from its former state

This expansion was found to be caused by the swell of the soil due to absorption of moisture or by frost action Where frost action played no part the swell was caused entirely by absorbed moisture Frost action was found to be the major cause of soil swell in one State (3), the slab ends rising during the winter months and receding during the summer months

Tests proved that swell of the expansive soil produced sufficient force to cause an uplift of the slab ends and edges

Evidence of action of external force was found in cracks which developed 10 to 20 ft back of the joint and at the point of flexure of the distorted slabs These cracks were not always visible on the surface but were at all times definitely wider at the bottom than at the top of the slab

In this investigation there are no indications that soil flow had any important influence on the development of warping

Methods of Preventing Distortions

Warping can be prevented by the modification of location and grade line of the road and by grading operations so that nonexpansive soils may be selected and used for the subgrade No warping was found on pavements placed on subgrade soils of a nonexpansive nature Soil types and soil conditions which are conducive to warping may vary between comparatively wide limits The depth of cover required to prevent the detrimental action of the expansive soils has not been definitely established However, the data indicate that a depth of

12 in of granular soil from shoulder slope to shoulder slope will be sufficient to prevent warping under severe conditions

Detrimental warping of pavement on expansive soil subgrade has been prevented by construction methods that provided adequate moisture in and proper densification of the subgrade at the time the pavement was placed This is true regardless of whether the moisture was introduced artificially or naturally. Moisture was introduced during grading operations or was later introduced by diking, ponding, or sprinkling the scarified subgrade until the water had penetrated to a depth of 18 to 24 in

Since no distortion has occurred on natural subgrades of the nonexpansive type, it is inferred that warping can be prevented by changing the properties of expansive soils to those of nonexpansive soils to an effective depth However, the available data indicate that the use of granular admixtures did not prevent warping due to imperfect mixing with the soil and insufficient depth of treatment

Warping can be eliminated by design or construction features which prevent the entrance of water into expansive subgrade soils The use of a bituminous membrane sufficiently protected by a granular base has proven effective The data on the use of bituminous membranes without granular bases are contradictory Joints having copper seals of various types when properly installed and maintained have been beneficial Insufficient data are at hand to establish the period of their effectiveness

The prevalence of high joints due to frost action has been minimized by careful joint maintenance The results obtained in one State (3), indicate that special joint sealing material properly applied is effective in preventing leakage of water through joints. The maintenance of contraction joints in a watertight condition has been found to be much easier than that of expansion joints

Distortions can be prevented by any treatment which insures the maintenance of a uniform moisture content in the soil under the slab Data from one State (3) on projects totaling 8 miles in length having variable thicknesses of sand base, indicate that 9 in was sufficient to prevent detrimental heaving due to frost action The sand base extended from outside shoulder line to outside shoulder line

Where adequate moisture existed or was introduced into the subgrade the use of nonexpansive soils or granular material in the shoulder was effective in preventing variation in the subgrade moisture content beneath the pavement

In general, observations and tests showed that less water leaked through contraction joints than through the usual type of expansion joints and less uplift occurred at the contraction joints

Methods for Correcting High Joints

The most effective method of restoring a satisfactory riding condition to the pavement was through the use of the mud-jack The central low area of the slab was raised by this means so that approximately the original contour of the pavement was regained The cost varied according to the availability of materials and the lift required but averaged about $0 20 per square yard

The introduction of water into the soil by artificial means has been partially successful in the correction of high joints

CONCLUSIONS

Causes of Warping

(1) Distortion in concrete pavement of the type to which this Committee has confined its studies, characterized by objectionable high joints and loss or gain in crown is due to warping caused by differential swell or shrinkage of the subgrade soil

(2) Curling is not a cause of objectionable distortions

(3) The swell of the subgrade soil results from the absorption of water which enters the subgrade through leaky joints, cracks and along edges of the pavement Where frost action is a major factor, swell results largely from the formation of ice lenses in the soil

(4) The amount of swell which results from the absorption of water by the soil is dependent on

- (a) The physical characteristics of the soil
- (b) The amount of water absorbed by soil which in turn depends on the moisture content and density of the soil at the time of concreting

(5) Shrinkage is caused by differential moisture loss in the subgrade soil

Methods of Preventing Warping

Warping of pavements can be prevented by

(1) Careful location of the road and selection of nonexpansive soils for the subgrade

(2) Controlling the differential swell or shrinkage of the subgrade soil

- (a) By insuring adequate moisture content and proper density at the time of concreting
- (b) By changing the characteristics of expansive soils to those of nonexpansive soils
- (c) By preventing or controlling changes in moisture in the subgrade through the use of proper design, construction and maintenance practices.

Means of Correcting High Joints

(1) Mud-jacking, carried on with proper precautions, is an effective method of straightening warped slabs It is the most economical method known

(2) The introduction of water into the soil by artificial means has been partially successful in the correction of high joints.

SUGGESTIONS FOR FUTURE RESEARCH

While the major cause of the warping of concrete pavement has been established and means of prevention and correction have been determined it is felt that there is a need of further study of the following factors

(1) Research should be carried on to determine the required depth of water treatment, its permanency, and the possible detrimental effect of freezing and thawing Similar research should be carried on for coverings of nonexpansive soils over expansive soils

(2) Further research is required in field and laboratory to obtain information regarding the optimum moisture content and degree of compaction to result in minimum swell and shrinkage

(3) The need of some standard method for measuring the supporting value of subgrade soils is apparent and study should be made to determine the maximum safe moisture content which should be used for various soils

(4) Additional studies should be made of the so-called watertight joints and the efficacy of different materials and methods of sealing joints

(5) Further observations of sections of pavement placed on granular subbases may be of value particularly where the soils were known to be of the type and in the condition to cause warping

(6) Additional research should be conducted on different methods of treating the subgrade soil with chemicals and admixtures so as to reduce or control detrimental volume change.

(7) Investigations should be made of the effect of manipulations caused by the deflection of slab ends under load on the moisture absorption and swelling of the soil