Tests of Concrete Pavement Slabs on Cement-Treated Subbases

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Concrete pavement slabs were built on cement-treated subbases and tested to determine deflection, strain, and pressure response to static loads. Concrete thickness varied from 3 to 8 in. and subbase thickness from 3 to 9 in. Subbase surface treatments were (a) cement-sand grout to produce bond; (b) a polyethylene film to prevent bond; and (c) in one instance, an asphalt emulsion.

The pavements were evaluated relative to 8-in. concrete on a 5-in. gravel subbase by measuring deflections, slab strains, and subgrade pressures when loads were applied at interiors, edges, and joints. Based on equal edge deflections, the ability to carry loads ranged from 200 percent of the standard for 8-in. concrete bonded to 5-in. cement-treated subbases, to 45 percent for 3-in. concrete on a 3-in. cement-treated subbase with an asphalt emulsion treatment. It was shown that bonded interlayers increased the ability to carry load as much as an additional $\frac{1}{2}$ to 1 in. of concrete.

Experimental deflections at interiors and edges were in good agreement with those computed by the Westergaard formulas when the bearing value of the cement-treated subbase was measured by a 30-in. plate.

•THE SERVICEABILITY of a concrete pavement depends largely on the stability and uniformity of the material on which it is built. Because highway systems traverse areas with different soils and corresponding differences in bearing capacity and volume change characteristics, it is often necessary to temper the effects of these variations on serviceability by building subbases of stable material.

Granular materials, ranging from a maximum size compatible with layer thickness to a minimum where not more than ten percent passes the No. 200 sieve, have proven successful for subbases for primary pavements. Laboratory tests on both open-graded and dense-graded materials in this category have shown that if the materials were placed according to standard density and moisture conditions, there was negligible densification under repetitive loads (1), and pressures on the subgrade were small for all thicknesses tested (2). It was also found that the slight increase in bearing value achieved by thickening the subbase layers did not significantly improve the ability of 8-in. concrete slab pavement systems to support loads.

Because granular materials suitable for subbases are not readily available in all parts of the country, marginal soils of low plasticity have been treated with cement and compacted on the subgrade to serve as pavement subbases. The success of this method prompted an extension of the laboratory study of subbases to include a study of the load-deflection, strain, and pressure response of pavements incorporating concrete on cement-treated subbases.

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OBJECTIVES AND SCOPE

Studies by Abrams (4) have shown that cement-treated bases offer considerable resistance to deflection under load. As the load that can be carried by a concrete pavement increases with the improved bearing value of the foundation, it follows that concrete slabs on cement-treated subbases should be capable of carrying greater loads than those on granular subbases.

The tests had a threefold objective: (a) to measure the deflection, strain, and pressure response of loaded concrete slabs on cement-treated subbases; (b) to investigate the feasibility and desirability of developing full interface friction between the concrete and the cement-treated subbase by establishing interlayer bond; and (c) to study the adaptability of current design methods to concrete pavements on cement-treated subbases.

The program includes pavements of 3, 5, 7 and 9 in. of concrete on 3, 6, 9 and 12 in. of cement-treated subbase, in addition to pavements of 8-in. concrete on 5-in. cement treatment which were built and tested for direct comparison with pavements of 8-in. concrete on 5-in. granular subbases. Tests were scheduled to permit the reporting of data on pavements of concrete less than 9 in. thick prior to completion of the total program. Tests on thicker slabs were deferred for later study.

This progress report is restricted to an evaluation of nine pavements. In addition to the data from tests of 8-in. concrete on 5-in. cement-treated subbase (CTS), results are shown for combinations of 3-, 5-, and 7-in. concrete slabs on 3- and 6-in. CTS; and 3- and 5-in. concrete on 9-in. CTS. For this phase of the study the concrete and CTS materials were not varied, and the subbase material contained sufficient cement to meet minimum requirements for soil-cement as determined from ASTM test procedures and PCA weight-loss criteria.

Load-deflection and strain responses of the various combinations were measured when the slabs were subjected to static loads. A limited repetitive load study was made on two bonded structures to explore early bond failure, but equipment was not available for complete fatigue tests.

MATERIALS

Subgrade.—A silty clay soil was placed in a 4-ft deep waterproofed pit to form the subgrade for the pavements. Gradation and moisture-density relations are shown in Figure 1. The soil was compacted in 6-in. lifts to standard conditions as determined by AASHO method T99 or ASTM Method D698 with mechanical tampers. To maintain a low subgrade bearing value, it was necessary to rework the surface each time a new pavement was placed. This value, k, measured with a 3-in. diameter plate at 0.05-in. deflection, ranged from 70 to 90 psi per in. of deflection.

Cement-Treated Material.—A nonplastic soil with a gradation curve labeled cement-treated material in Figure 1 was mixed with 5.5 percent cement by weight and 11 percent water in a pug mill and compacted on the subgrade. The cement requirement was determined from ASTM Standard Methods D559 and D560 and the Portland Cement Association criterion for weight loss (5). The moisture-density curve, determined by ASTM Method D558 (Fig. 1) indicated standard conditions to be 125 pcf at 10.5 percent moisture.

The cement-treated material was compacted by mechanical tamper and vibrating sled as shown in Figures 2 and 3, and moist cured until concrete was cast. In-place densities, moistures after compaction, and bearing values measured at age 14 days with a 30-in. diameter plate at 0.05-in. deflection are given in Table 1.

The pavement code is made up of two numbers and a letter. The first number is the concrete thickness; the letter denotes interface treatment (as shown by Column 3); and the last number is CTS thickness. The reference for these tests is 8-in. concrete on 5 in. of compacted open-graded gravel (8G5) (3).

Specimens were molded as suggested by Felt and Abrams (6) from samples of the material during placement. These were tested in compression and flexure and for sonic modulus at ages 7, 28, and 60 days. The results are given in Table 2.

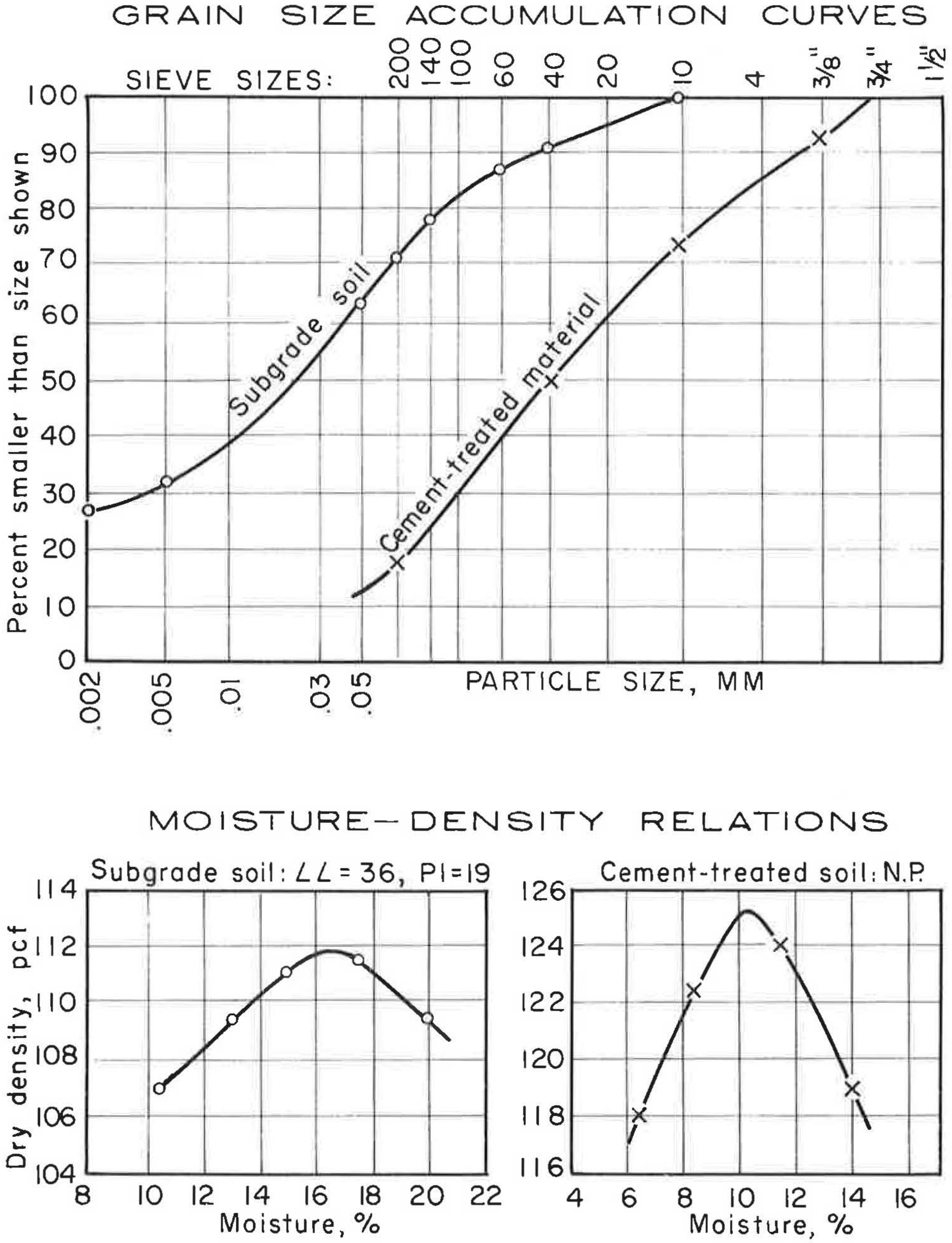


Figure 1. Foundation materials.

Figure 2. Consolidation of subbase with mechanical tamper.

Figure 3. Final consolidation and leveling with vibrating sled.

TABLE 1

IDENTITY AND PROPERTIES OF SUBBASE AND SUBGRADE

Identity				Subbase in Place Data			
Layer Thickness		Upper Interface Condition	Pavement Code	Dry Density (pcf)	Moisture (%)	30-In. Plate Bearing, k (pci)	
Concrete	Subbase					Subgrade	Subbase
8	5 in. gravel	—	8G5	135	7.3	75	130
8	5 in. s/c	No bond	8N5	127	9.8	88	350
8	5 in. s/c	Bond	8B5	131	10.6	90	360
7	6 in. s/c	No bond	7N6	129	10.2	80	405
7	3 in. s/c	Bond	7B3	130	10.3	70	200
5	9 in. s/c	No bond	5N9	126	10.0	66	540
5	6 in. s/c	No bond	5N6	124	11.3	74	410
5	3 in. s/c	No bond	5N3	119	11.2	75	203
5	3 in. s/c	Bond	5B3	122	11.4	65	188
3	9 in. s/c	Bond	3B9	118	11.6	69	510
3	6 in. s/c	Bond	3B6	123	10.6	75	378
3	6 in. s/c	No bond	3N6	119	9.7	71	365
3	3 in. s/c	Bond	3B3	121	10.8	68	190
3	3 in. s/c	SS-1[a]	3S3	119	10.5	78	210

[a] CTS surface coated with asphaltic emulsion SS-1.

TABLE 2

CTS SPECIMEN PROPERTIES

Pavement[a]	Cylinders, Comp. (psi)			Beams, Flex. (psi)			28-Day Sonic Modulus (10^6 psi)
	Days			Days			
	7	28	60	7	28	60	
8N5	330	420	490	65	105	160	1.42
8B5	320	505	610	75	110	170	1.62
7N6	280	380	470	68	112	165	1.65
7B3	350	520	630	77	119	177	1.68
5N9	290	410	500	60	95	150	1.36
5N6	305	515	610	73	120	170	1.70
5N3	355	530	640	68	98	146	1.47
5B3	330	500	615	78	103	180	1.55
3B9	270	390	480	73	100	145	1.49
3B6	310	480	590	70	113	166	1.67
3N6	340	520	625	66	108	153	1.60
3B3	300	490	580	80	120	158	1.50
3S3	280	460	550	97	123	172	1.52

[a] Identifying code in Table 1.

TABLE 3

CONCRETE SPECIMEN DATA

Pavement[a]	Cylinders, Comp. (psi)			Beams, Flex. (psi)			28-Day Sonic Modulus (10^6 psi)
	Days			Days			
	7	28	60	7	28	60	
8G5	4,400	5,200	5,500	500	580	640	5.2
8N5	3,920	4,850	5,420	510	590	695	5.9
8B5	3,700	4,450	5,100	545	605	710	6.0
7N6	3,860	4,710	5,330	560	670	750	5.9
7B3	4,085	4,625	5,220	600	720	790	6.0
5N9	3,690	4,580	5,270	520	650	720	5.8
5N6	3,390	4,525	4,960	555	635	690	5.5
5N3	4,160	4,505	5,135	608	706	740	5.6
5B3	4,090	4,800	5,450	586	680	722	5.6
3B9	3,750	4,530	5,265	563	605	760	5.9
3B6	3,780	4,690	5,100	536	675	790	5.8
3N6	3,520	4,380	5,150	510	610	700	5.7
3B3	3,630	4,160	4,825	520	570	660	5.3
3S3	3,980	4,660	5,070	490	565	655	5.5

[a] Identifying code in Table 1.

Concrete.—The concrete was made with 1-in. maximum gravel aggregate and was mixed in the laboratory plant. The cement factor was 6 sk per cu yd, water-cement ratio 0.50, slump 2.5 to 3.5 in., and air content 4 to 5 percent. Standard 6- × 12-in. cylinders and 6- × 36-in. beams were molded when the slabs were cast. Compressive and flexural strengths and sonic modulus values of fog cured specimens are given in Table 3.

The slabs were cured with wet burlap until mortar dikes could be constructed to contain water on the surface and protect the areas designated for application of strain gages. When these were completed, the slabs were flooded and water was retained on the surface throughout the first series of tests to prevent upward curl due to differential changes in moisture content. Later, 8 to 10 weeks, the water was removed for the second series of tests on curled slabs.

INSTRUMENTATION AND OPERATIONS

The pavements were constructed and tested in an area where temperatures were maintained between 65 and 75 F. Loads were applied by hydraulic jacks reacting against an overhead frame. Circular steel plates on rubber pads distributed the load to the concrete (Fig. 4).

The first two pavements tested were 8-in. concrete on 5-in. CTS. These slabs were 12 × 18 ft and were cast with a doweled $^3/_8$-in. wide butt joint connecting the slabs along the 18-ft edges. The subbase extended 1 ft beyond the edge of the concrete on all pavements except a duplicate 8N5 that was built without the ledge (Fig. 5).

Two treatments were used at the interlayer between the concrete and subbase. In one case, the CTS was covered with 4-mil polyethylene film prior to concreting to prevent bond; and in the second case, a grout of equal parts of fine sand and cement was brushed onto the subbase to assure bond. At the end of test the shear strengths at the bonded surface, measured by direct shear tests on 6-in. diameter cores, ranged from 100 to 200 psi. Figure 6 shows a sawed and broken section of pavement illustrating the composite bonded construction.

The 8-in. slabs were instrumented with SR-4 type A-9 gages and pressure cells as shown in Figure 7. Deflections were measured with 0.001-in. dial indicators at the edges of the 12- and 16-in. plates, and at intervals on a transverse line in the vicinity of the load.

For the remaining combinations of concrete on the cement-treated subbase, the pavements were altered to include two types of transverse joints. The slab dimensions were reduced from 12 × 18 ft to 10 × 14 ft, and 5-ft slabs were built at each end to provide joints that could be tested for load transfer effectiveness when loads were placed at the joints. The test slab and one end slab were connected by a smooth-faced construction joint with no provision for load transfer. This was formed by casting fresh concrete

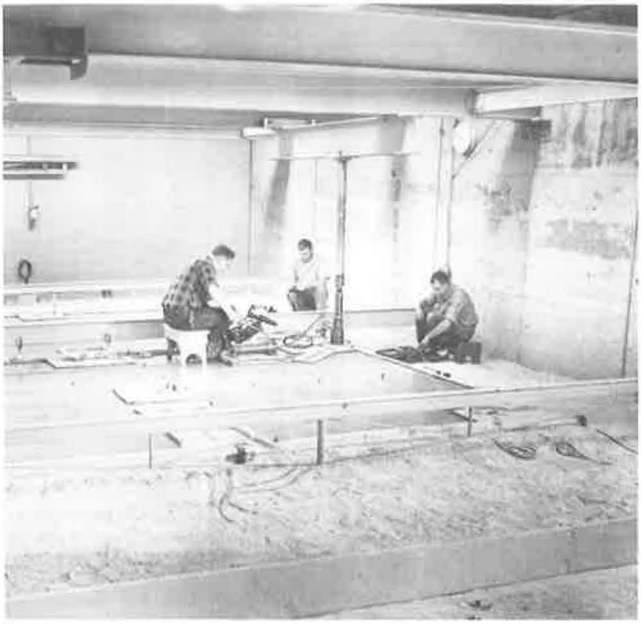


Figure 4. Static load tests at doweled corner of flat slab.

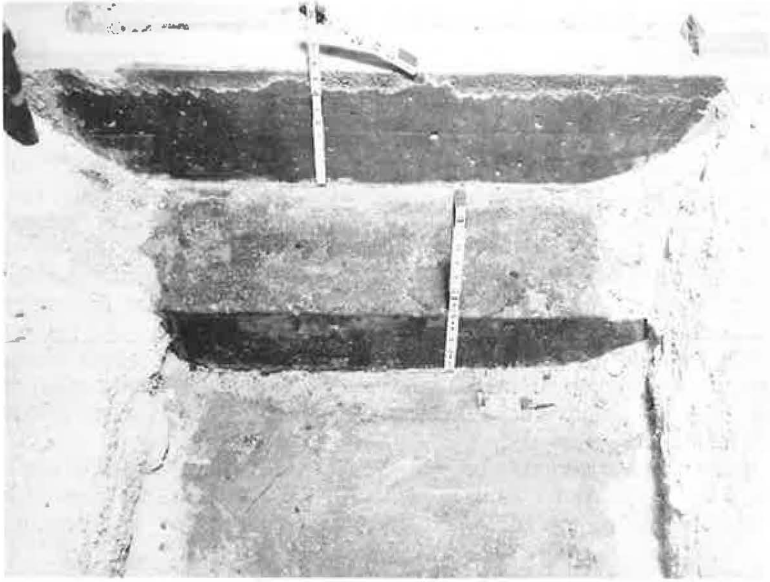


Figure 5. Ledge of 5-in. cement-treated subbase (CTS) 1-ft beyond edge of 8-in. concrete slab.

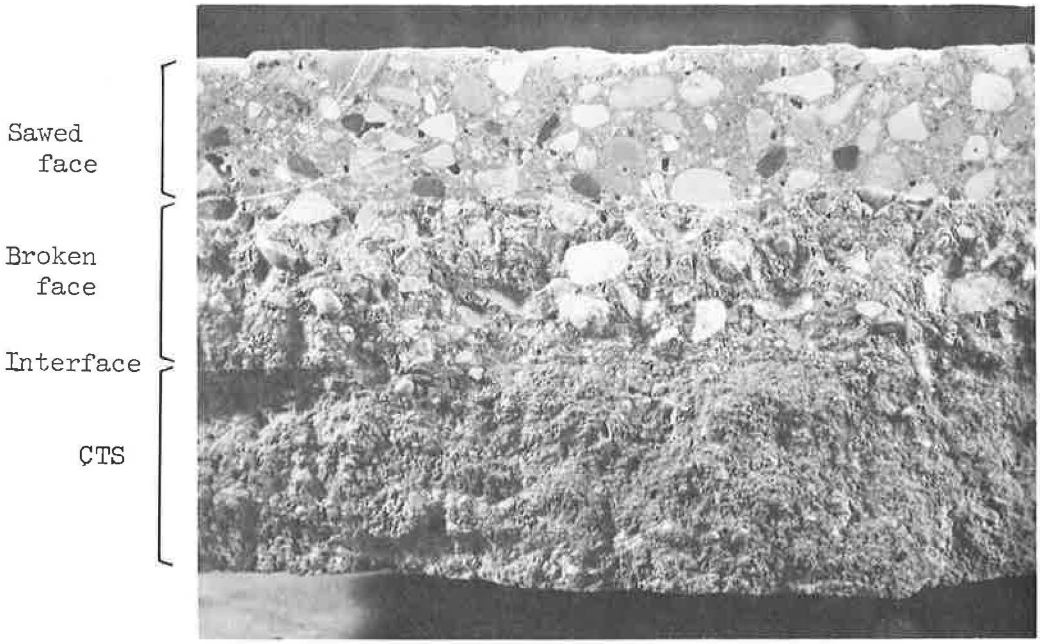


Figure 6. Efficacy of bond between concrete and cement-treated subbase.

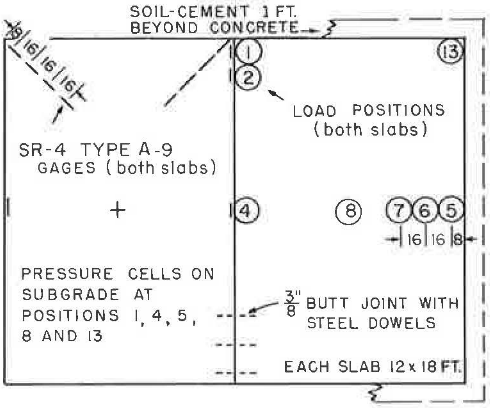


Figure 7. Gage and load locations for 8-in. concrete.

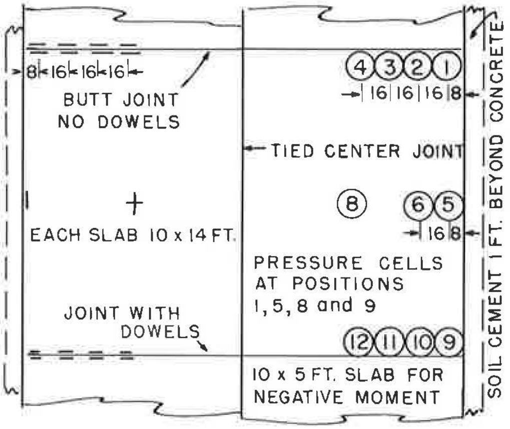


Figure 8. Gage and load locations for 10- × 14-ft slabs.

against the hardened concrete of the test slab. On the opposite end, the same casting procedure was followed, but round steel dowels extended through the joint. These joints differed from the usual contraction joint because there was no interlock of aggregate. Dowel diameters were $^{1}/_{8}$ in. for each in. of concrete thickness, and spacing was 12 in. except that dowels in 3-in. concrete were $^{1}/_{4}$ in. diameter and 6 in. on centers. All joint openings remained less than 0.02 in. throughout the tests. The interlayer treatments were the same as those described for 8-in. concrete on 5-in. CTS and are designated N or B except for combination 3S3, on which an asphalt emulsion was applied to the 3-in. subbase.

Loads on 10- × 14-ft slabs were distributed by 16-in. diameter plates. The area under the 16-in. plate was equivalent to the effective contact area of a pair of 7.00-20 dual truck tires. Maximum loads varied with load position and pavement response. On the thinner combinations, edge loads rarely exceeded 9,000 lb. Load positions are shown in Figure 8.

TEST RESULTS

Deflections, strains, and pressures for all load increments were recorded for eleven positions on the 8-in. concrete and for 13 positions on the other thicknesses. From these data, trends were established and the influence of specific variables was determined.

Flat Slabs

Data from Tests at Interiors, Edges, and Joint Corners.—The effect of load intensity on slab deflections, strains, and subgrade pressures for three combinations are shown in Figure 9. Curves for 8-in. concrete on 5-in. gravel, 8G5, are included for comparison. The small deviations from linearity are typical of all combinations tested. Due to this the deflections, strains, and pressures caused by loads were compared at a 9-kip load because it is the legal wheel load limit in many States, and all unrestricted roads and streets must be capable of carrying a limited number of loads of this intensity.

Relative Response of Test Pavements to Load.—The deflection, strain, and pressure responses to 9-kip loads at interior and free edge positions on all combinations are shown in Figure 10. The ability to support loads is an inverse function of these measurements, therefore low magnitudes indicate high load capacity. The order of increasing magnitude of deflection, strain, and pressure is not always the same; but if the 8-in. slab on 5-in. gravel is ignored, the order is well established for combinations of

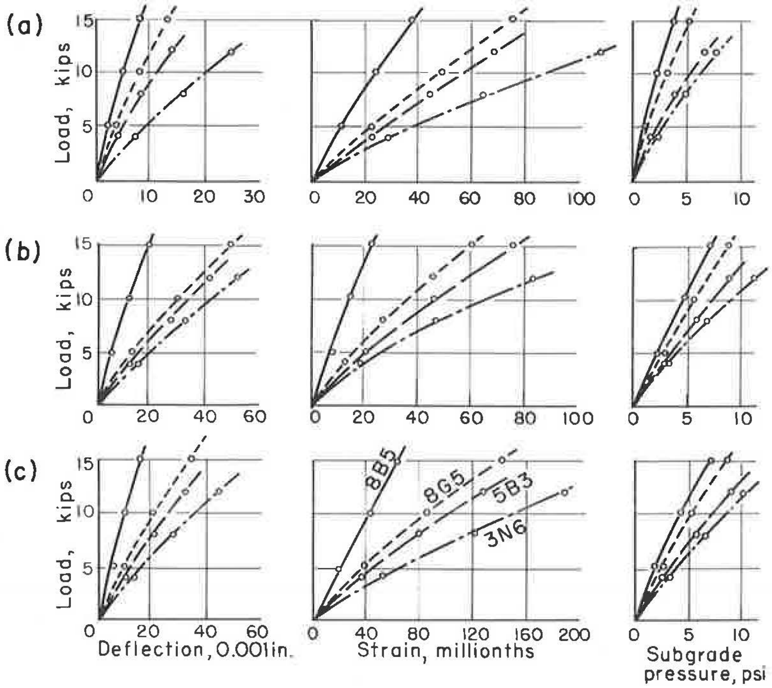


Figure 9. Representative data: (a) interior, (b) joint corner, and (c) free edge (8B5 and 8G5, doweled; 5B3 and 3N6, undoweled).

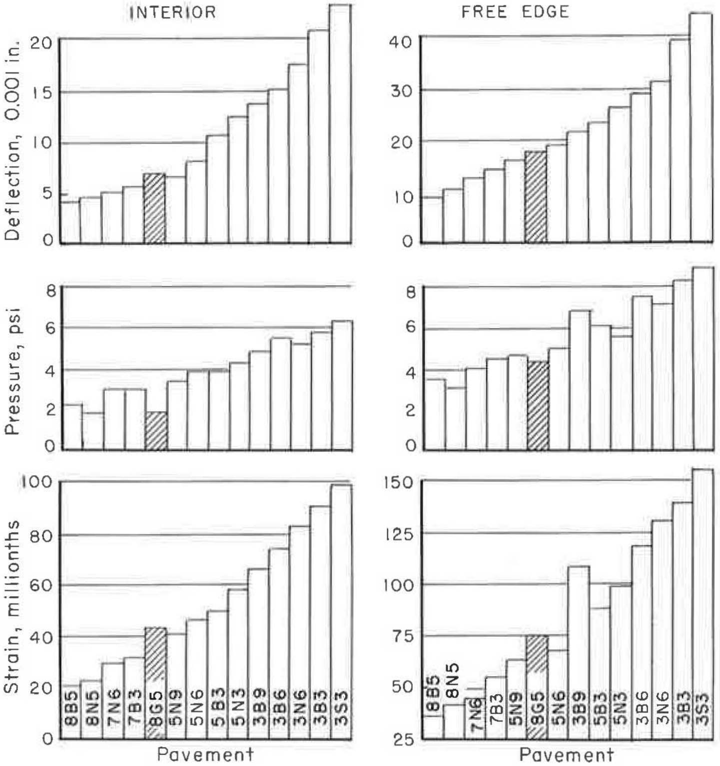


Figure 10. Deflections, strains, and pressures for all pavement combinations at 9 kips.

low response or high response and there is some variation in the middle range. When deflections and strains of the concrete pavements on CTS are compared with those of the standard 8G5, it is evident that combinations 8B5, 8N5, 7N6, 7B3, and 5N9 are stronger than the standard.

Loads causing edge deflection of the test pavements equal to that of 8G5 at 9 kips were computed and are as follows: 8B5, 18 kips; 8N5, 15 kips; 7N6, 13 kips; 7B3, 11½ kips; 5N9, 10 kips; 5N6, 8½ kips; 3B9, 7½ kips; 5B3, 7 kips; 5N3, 6½ kips; 3B6, 5½ kips; 3N6, 5 kips; 3B3, 4½ kips; and 3S3, 4 kips. It was assumed for this computation that load varied inversely as deflection. The 9-kip load for the standard 8G5 pavement is justified by the fact that the edge stress on this pavement at 9 kips was one half the modulus of rupture. The previous values may be modified in practice because all pavements are not designed for the same traffic life and higher loads are tolerated when the number of applications is limited.

Estimates of loads that would produce equal critical stress were not made because the strains measured in these tests were in the top fibers of the concrete, and on bonded pavements there is evidence of a shift in the neutral axis position away from the mid-plane of the concrete. Supplementary tests are needed to locate the position of critical tensile stress in these bonded pavements. It is noted that the 9-kip loads produced low compressive strains on the concrete surface of the stronger combinations and high strains in the concrete of the weaker pavements. However, during a checkout test of a repetitive load machine, more than 50,000 9-kip loads were applied to the 3S3 structure without evidence of concrete failure.

Effect of Load Placement on Measurements at Slab Edge.—Sensitivity of pavements to transverse location of load was explored by measuring edge deflections, strains, and pressures when loads were positioned inward from the free edge. Figure 11a compares data for 8-in. concrete slabs on 5-in. CTS with those for the standard 8-in. concrete on 5-in. gravel. The 8N5 structure was tested near an edge (a) without a subbase ledge,

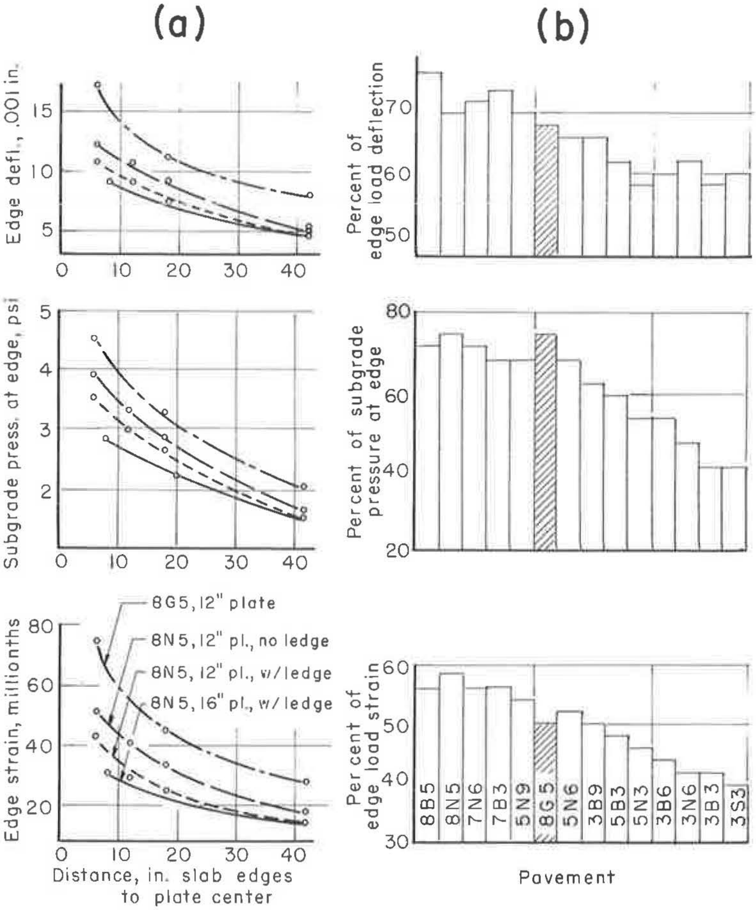


Figure 11. Slab response to 9-kip load near edge: (a) effect of lateral load placement on edge measurement, and (b) percent of edge load measurement developed when load center was 24 in. from edge.

i.e., the edge of the CTS was directly beneath the edge of the concrete, and (b) with a ledge of CTS extending 1 ft beyond the slab edge. Loads were applied with a 12-in. plate for direct comparison of the two types of edge construction with the granular subbase and repeated with a 16-in. plate on the treatment with a ledge to show the change in response to edge loads when the distribution area was increased to that of a pair of dual tires.

Plate Size and Ledge Effect—When loads were applied with 12-in. plates tangent to slab edges, deflections and strains for the 8N5 structure without the subbase ledge were about 70 percent of those for the standard. The 1-ft ledge caused further reduction, and edge deflections and strains were about 60 percent of those for 8G5. Additional relief was achieved by enlarging the bearing area, and values recorded with a 16-in. plate on the 8N5 structure with the ledge were about half those measured in the 8G5 standard. The effect of plate size and ledge diminished as the load position moved inward from the slab until at the 42-in. position no advantage was apparent.

Response to Load 2 Ft from Edge —Figure 11b shows the effect of inward placement of load on measurements at the slab edge for all combinations. The data, obtained when a 16-in. plate was placed with its center 2 ft from the slab edge and loaded to 9 kips, are expressed as percent of the value recorded when the plate was tangent to the edge.

Strains were more sensitive than deflections to lateral load placement. When loads were in from the edge, pressures and deflections for combinations having a greater ability to support loads than the standard 8G5 were approximately 70 percent of those due to edge loads; but as the pavements became more sensitive to deflection and strain, the ability to distribute a load also was reduced as evidenced by the lower strains, deflections, and pressures measured at the edge due to the inward load. Although longitudinal strains at slab edge due to inward loads on the thinner pavements are much less than those caused by loads on plates tangent to the edge, the reduced rigidity of these pavements results in higher transverse strains at the load, and longitudinal cracking is imminent.

Effect of Load Along Joint. —All combinations except the 8-in. concrete on 5-in. CTS were built with a butt joint with no mechanical interlock on one end of the test slab and a joint with dowels on the other. The slabs were tested under static loads at four locations along each joint as shown in Figure 8. Strain gages and deflection dials were located to read maximum compressive strains in the upper surface of the concrete and maximum deflections. In most cases the maximum tensile strain due to a load at the corner (position 1) was read on the gage at position 3 which was 40 in. in from the slab edge, although on occasion the gage located 56 in. from the edge indicated the largest strain.

There was no undoweled joint investigation for the 8-in. concrete on 5-in. CTS. At the doweled joints of these slabs, loads were placed at corners and also placed with plate centers 24 in. inward, as shown in Figure 7. Compressive strains were measured at the load, and tensile strains were measured along the corner bisector.

Strain and Deflection Profile at Transverse Joint—Transverse profiles of deflections and strains produced by 9-kip loads for each of the four load positions along a joint are shown for the undoweled joint of pavement 5N6 in Figure 12. The solid lines represent measurements on the loaded side of the joint, and measurements on the opposite side are shown as dashed lines.

When the loading plate was at the corner, tangent to the free edge, a maximum tensile strain parallel to the joint developed in the top fibers about 40 in. inward from the free edge. This strain was close in magnitude to the transverse compressive strain at the joint edge directly at the plate. As the load was moved inward along the joint from the slab edge, the compressive strain at the load increased until the load was 40 in. from the free edge, and deflection decreased until the load was 56 in. from the edge.

Summary of Joint Test Data—Figure 13 exhibits maximum deflections and strains on both the loaded and opposite sides of undoweled joints for each of four load positions when 9-kip loads were applied. Similar strains are shown in an order approximating increasing magnitude.

The trends exhibited for combination 5N6 in Figure 12 are corroborated by the measurements on the remaining combinations. In all cases the maximum deflections occurred under corner loading and diminished as the load was moved away from the longitudinal edge. Maximum measured strains occurred at the joint edge tangent to the plate when the load was 40 or 56 in. from the free edge.

When loads were applied at positions 1, 5, and 9, representing truck wheels along slab edges, strains at joint edges were always less than those at free edges. However, when the load plate was placed inward from the free edge at position 6, representing a more frequent wheel position, joint edge strains for positions 2, 3, and 4 exceeded those at free edges (Figure 11b). Thus, the area of critical strain in pavements depends on the path of a wheel with respect to the slab edge.

Doweled vs Undoweled Joint—Data from tests at doweled joints are shown in Figure 14. In most cases measurements for the same magnitude and load position were slightly lower at doweled joints than those at undoweled joints. However, doweled joints rated about the same as undoweled joints in load transfer effectiveness. Deflection differences and load transfer effectiveness are shown for the two 9-kip load locations on each of three slabs in Table 4.

Ratings for the remaining combinations may be computed from the data in Figures 13 and 14. Effectiveness is the Teller and Sutherland (7) ratio of deflection of the unloaded slab to the average deflection of both slabs. With one exception, effectiveness

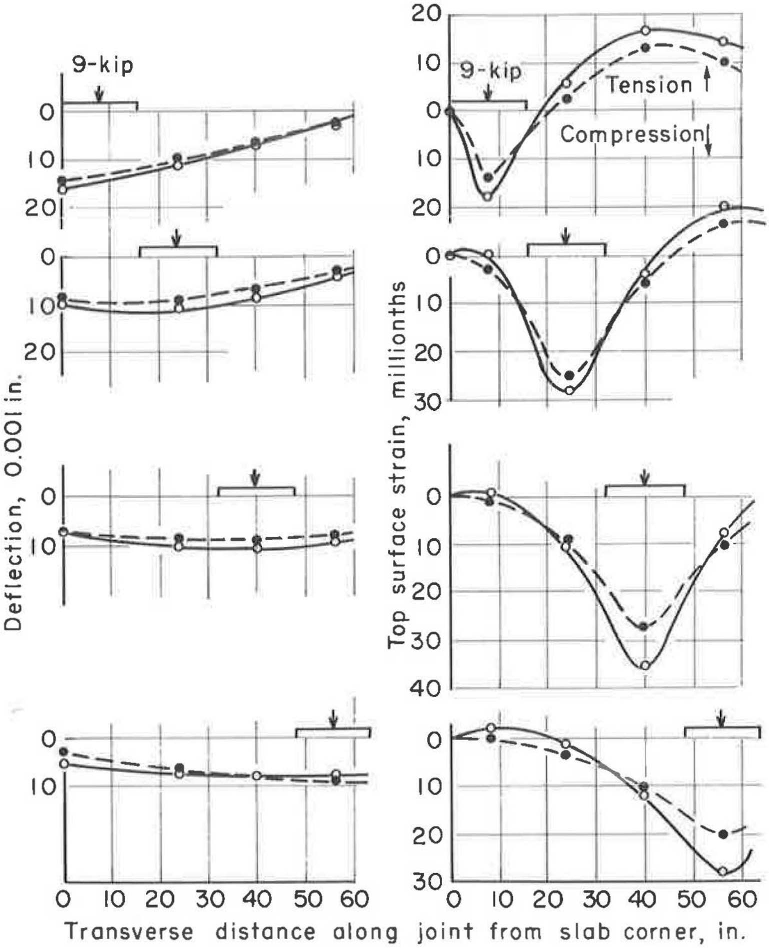


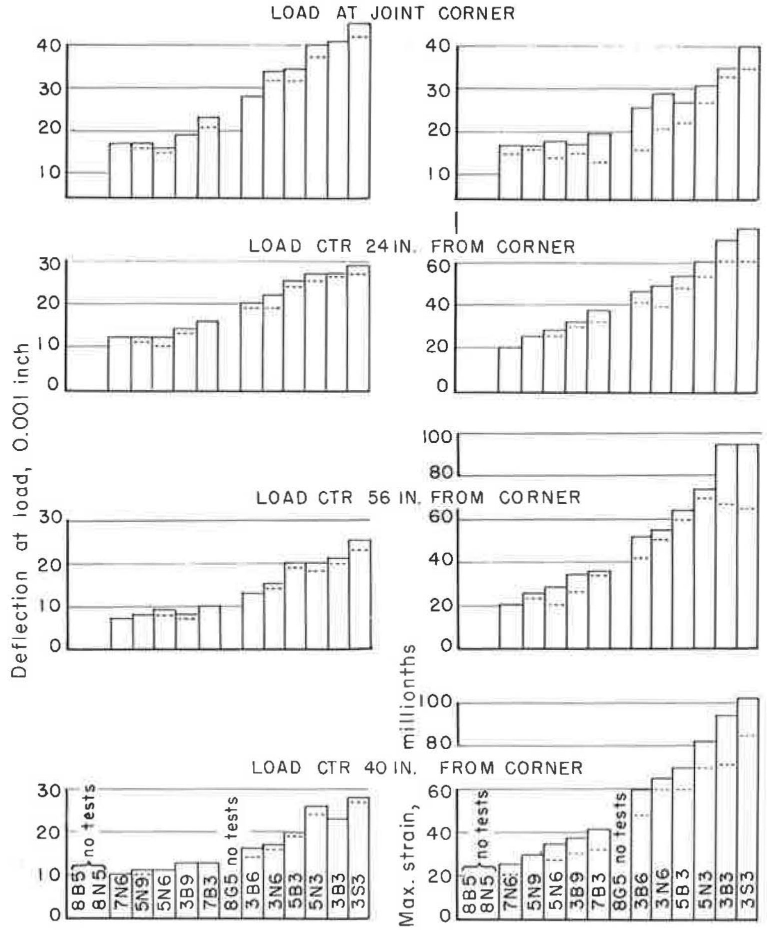
Figure 12. Undoweled joint of 5-in. concrete slab on 6-in. cement-treated subbase.

was greater than 90 percent for all combinations and there was no significant difference in effectiveness between doweled and undoweled joints.

Relative Effect of Each Pavement Layer.—Although the evaluation study of concrete on a cement-treated subbase is not complete, the data in Figure 10 are sufficient to permit the construction of 3-point curves showing the effect of concrete thickness on deflections and strains when the subbase thickness was constant, and the effect of subbase thickness when the concrete thickness was constant. Figure 15 shows the influence of 3-, 5- and 7-in. concrete on 3-in. bonded and 6-in. unbonded CTS, and the effect of 3-, 6- and 9-in. CTS on 3- and 5-in. concrete.

For both the 3-in. bonded CTS and the 6-in. unbonded subbase, deflections and strains decreased significantly with increasing concrete thickness. For example, as concrete thickness was increased from 3 to 5 in., deflection reductions on the 3-in. bonded subbase averaged 45 percent and those on the 6-in. unbonded subbase 47 percent. Similarly, strain reductions on the 3-in. CTS averaged 40 percent, and those on the 6-in. CTS 45 percent. As concrete thickness was increased from 3 to 7 in., deflection reductions averaged 69 and 65 percent, respectively, on the 3-in. and 6-in. subbases, and strains were reduced 62 and 64 percent.

When the top layer of the pavement was 3-in. or 5-in. concrete, a 6-in. CTS reduced deflections 26 percent and strains 20 percent, on the average, below those of pavements



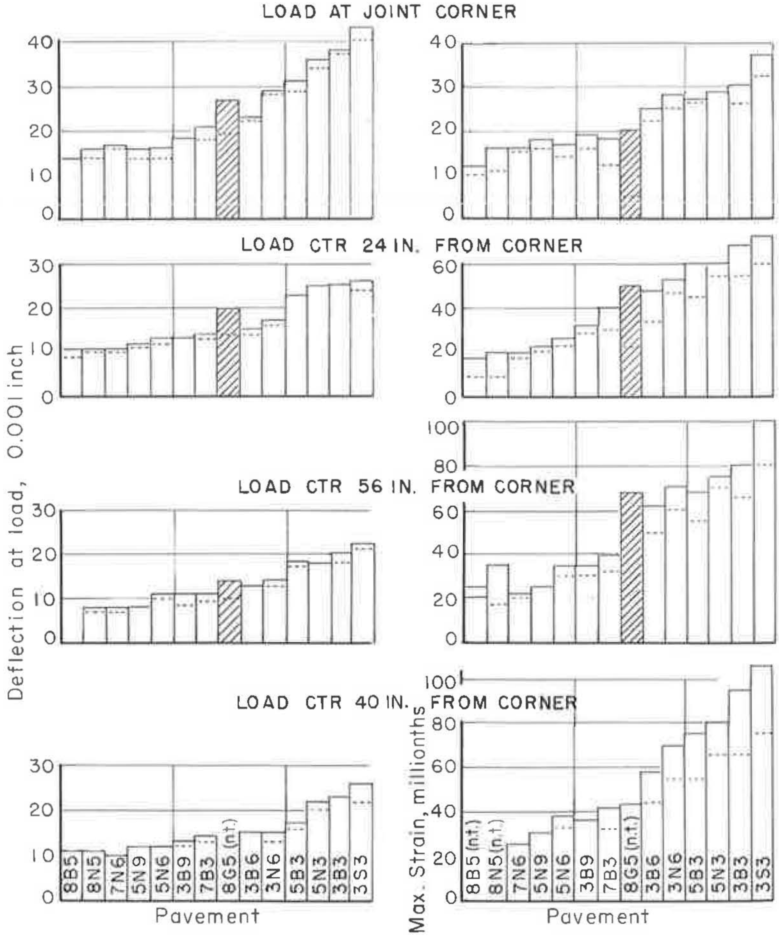
Note: Dashed height = value across joint from load.
(n.t.) = no test Load = 9 kips on 16 in. plate.

Figure 13. Deflections and strains at undoweled joint.

TABLE 4

JOINT DEFLECTIONS AND LOAD TRANSFER EFFECTIVENESS

Pavement	Distance to Load (in.)	Deflection				Effectiveness	
		Undoweled Joint		Doweled Joint			
		Load (in.)	Opp. (in.)	Load (in.)	Opp. (in.)	Undoweled (%)	Doweled (%)
5N6	0	0.016	0.015	0.016	0.014	97	93
	56	0.009	0.008	0.011	0.010	94	95
7B3	0	0.023	0.021	0.021	0.018	96	92
	56	0.010	0.010	0.011	0.009	100	100
3B3	0	0.041	0.041	0.038	0.037	100	99
	56	0.021	0.020	0.020	0.018	98	95



Note: Dashed height = value across joint from load.
(n.t.) = no test Load = 9 kips on 16 in. plate.

Figure 14. Deflections and strains at doweled joint.

with 3-in. CTS. Subbases 9 in. thick resulted in deflection and strain reductions of 38 and 29 percent, respectively, below those when the subbase was 3 in. On a unit thickness basis, it is evident that the stronger material (concrete) reduced deflections and strains to a greater degree than the CTS.

Strength factors contribute also to the advantages of CTS over granular subbases in a pavement system. Load studies of concrete slabs on gravel (3) showed that gravel subbases in 5-, 10-, and 15-in. thicknesses reduced deflections at loaded edges of 8-in. concrete slabs by 7, 12, and 16 percent, respectively, below the values recorded when there was no subbase, and reduced edge strains 4, 10, and 13 percent, respectively. A 5-in. layer of unbonded CTS reduced deflections and strains about 50 percent. Thus, the 5-in. CTS was much more effective in increasing load capacity of 8-in. concrete pavements than 15 in. of gravel.

A tentative method for estimating combinations of concrete and CTS with equivalent load capacity is given in Figure 16. Maximum deflections caused by 9-kip loads at interior and free edge positions were expressed in terms of those of the 3B3 combinations. These values, in percent, were plotted as ordinates above the appropriate concrete thickness and CTS thickness. Trends for 3- and 6-in. subbases were estimated by curves on the left, and for 3- and 5-in. concrete by curves on the right. Ordinates for

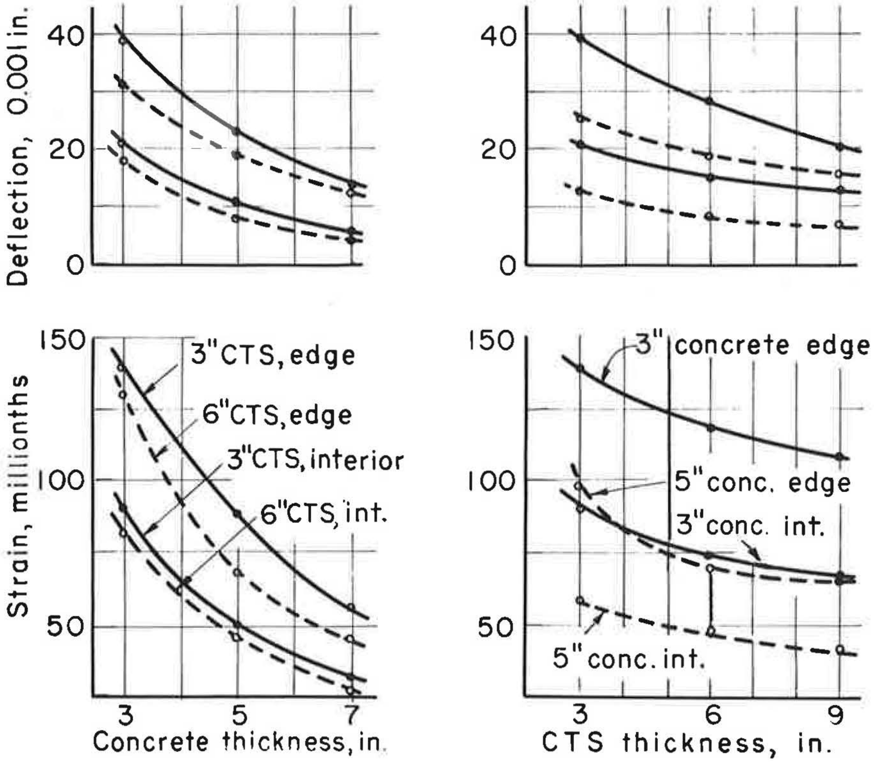


Figure 15. Influence of layer thickness.

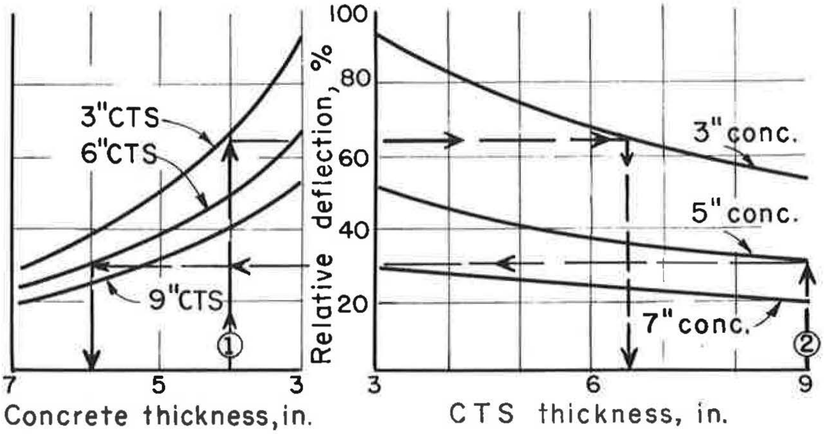


Figure 16. Pavements with equal deflections.

3- and 5-in. concrete on 9-in. CTS were transferred to the left to estimate the 9-in. CTS curve, and ordinates for 7-in. concrete on 3- and 6-in. subbase were brought to the right for the 7-in. concrete curve.

Examples of equivalent combinations of concrete and CTS are indicated by the arrows. Example 1 shows 4-in. concrete on 3-in. CTS to be equivalent to 3-in. concrete on 6½-in. subbase. Example 2 indicates that 9 in. of CTS under 5 in. of concrete is about equal to 6 in. of concrete on 6 in. of subbase.

Effect of Interlayer Bond on Deflections and Strains.—Four of the pavement structures were tested with interlayer bond and without bond. The deflection and strain data from edge and interior tests, as shown in Figure 10, reveal that bond at the interlayer reduced pavements deflections below those of unbonded pavements. The data in Table 5 indicate that when subjected to 9-kip loads, deflections and strains of bonded layers ranged from 85 percent to 92 percent of the corresponding value for unbonded layers.

Reductions in deflection or strain of 8 to 15 percent due to the bond were not sufficient to change the deflection response of a weaker pavement system to that of the next stronger system tested. This is apparent in Figure 10. The significance of measure-

TABLE 5

EFFECT OF INTERLAYER BOND

Pavement	Deflection (in.)		Strain (10^{-6})		Bonded vs Unbonded			
					Deflection (%)		Strain (%)	
	Interior	Edge	Interior	Edge	Interior	Edge	Interior	Edge
8B5	0.0042	0.009	21	36	87	86	92	86
8N5	0.0048	0.0105	23	42	-	-	-	-
5B3	0.0105	0.023	50	88	85	90	86	89
5N3	0.0123	0.0255	58	99	-	-	-	-
3B6	0.015	0.0285	74	118	86	92	90	91
3N6	0.0175	0.031	82	130	-	-	-	-
3B3	0.0205	0.039	90	139	89	88	92	90
3S3	0.023	0.044	98	155	-	-	-	-

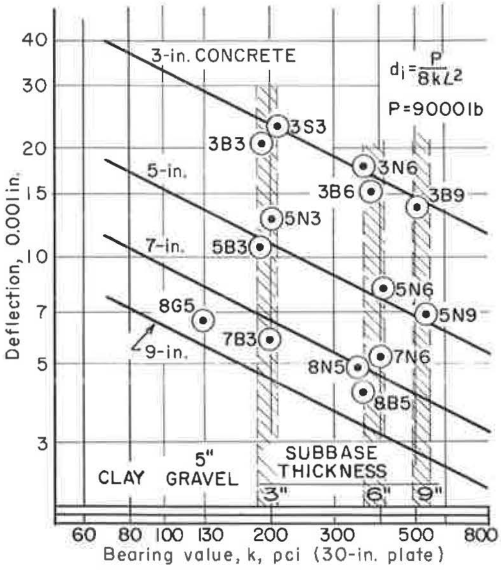


Figure 17. Comparison of experiment data and theory at interior load position.

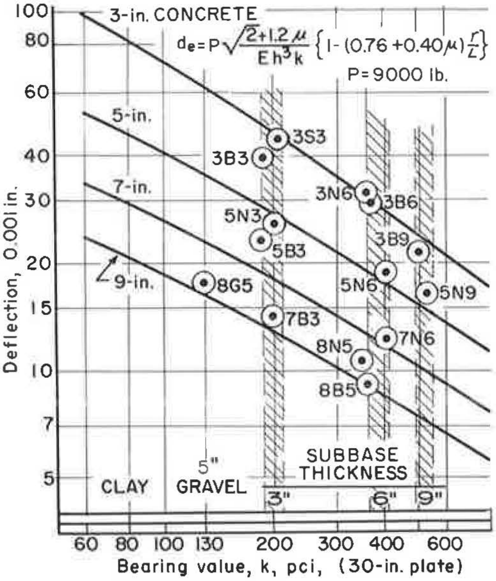


Figure 18. Comparison of experiment data and theory for load at slab edge.

ment reductions due to bond in terms of thickness of concrete is shown in Figures 17 and 18.

It should be noted that bond was obtained in the laboratory without difficulty by the application of cement-sand grout to the surface of the subbase. Cleansing alone or the application of an asphaltic emulsion did not guarantee bond. Weathering tests on beams of concrete and CTS bonded with cement grout showed negligible loss of bond.

Curled Slabs

After the static loadings of test pavements were completed, the ponding water was drained and the top surface of the concrete was allowed to dry. Corner and edge movements were recorded, and when corners moved upwards 0.025 in., or apparently stabilized at some lesser level, the static load tests were repeated. The time lapse between tests on flat and curled slabs varied from 10 to 20 days, depending on temperature and relative humidity.

Changes in Slab Shape.—The test slab surfaces became concave upward; Table 6 gives changes in elevation at joint corners, mid-joint, free edge, and interior locations. The amount of curl generally reached approximate stability in each panel, after which elevations varied a few thousandths of an inch on either side of the tabulated value. It is noted that corners of the thinner pavements tended to curl upward more than the thicker combinations.

Effect of Curl on Response to Load.—When 9-kip loads were applied to curled slabs, deflections were usually greater than those of flat slabs except at interior positions. Table 7 gives these deflection changes for six load locations: two joint corners, two mid-joints, a free edge, and an interior position. Trends in the data are difficult to perceive, but it is noted that the increase in deflection of the loaded side of joints is greater than that of the opposite side in most cases.

TABLE 6

SLAB ELEVATION CHANGES IN INCHES

Pavement	Undoweled Corner	Doweled Corner	Free Edge	Interior
8B5	0.026[a]	0.016	0.005	-0.010
8N5	0.030[a]	0.026	0.007	-0.009
7N6	0.027	0.026	0.009	-0.009
5N9	0.034	0.031	0.012	-0.007
7B3	0.030	0.018	0.004	-0.010
5N6	0.040	0.028	0.006	-0.009
8G5	0.035[a]	0.028	0.012	-0.003
3B9	0.016	0.015	0.008	-0.007
5B3	0.028	0.025	0.013	-0.008
5N3	0.042	0.031	0.015	-0.010
3B6	0.046	0.035	0.024	-0.012
3N6	0.051	0.039	0.029	-0.012
3B3	0.053	0.040	0.020	-0.012
3S3	0.060	0.045	0.030	-0.013

[a] Indicates free corner with no adjacent slab.

Changes in transverse strain along the joint and longitudinal strain at the free edge and interior are shown in Table 8. Strain on the loaded side of a joint usually increased more than that on the opposite side, but there were also some instances

TABLE 7

DEFLECTIONS OF CURLED SLABS UNDER 9-KIP LOADS

Pavement	Increase or Decrease in Deflection over Flat Slab Deflection (in.)									
	Undoweled Joint				Doweled Joint				Free Edge	Interior
	Corner		Mid-Joint		Corner		Mid-Joint			
	Load	Opp.	Load	Opp.	Load	Opp.	Load	Opp.		
8B5	-	-	-	-	0.008	0.006	0.002	0.002	0.001	0.001
8N5	-	-	-	-	0.014	0.010	0.004	0.003	0.006	0.001
7N6	0.010	0.008	0.007	0.006	0.007	0.005	0.006	0.005	0.005	0.001
5N9	0.012	0.009	0.006	0.005	0.017	0.015	0.007	0.005	0.006	0
7B3	0.007	0.005	0.006	0.004	0.005	0.003	0.003	0.004	0	0
5N6	0.006	0.005	0.003	0.004	0.010	0.007	0.001	0.001	0.006	0
8G5	-	-	-	-	0.008	0.004	0.001	-0.001	0.007	0
3B9	0.005	0.004	0.009	0.009	0.005	0.001	0.002	0.004	0.003	-0.002
5B3	0.010	0.001	0.007	-0.002	0.012	0.009	0.008	-0.003	0.004	-0.002
5N3	0.020	0.007	0.004	-0.003	0.018	0.016	0.005	0.001	0.008	0.002
3B6	0.004	-0.002	0.002	0	0.001	0.001	0.001	0	0.004	-0.002
3N6	0.024	0.011	0.012	0.014	0.007	0.014	0.009	0.009	0.024	0.001
3B3	0.020	0.008	0.015	0.008	0.006	0.002	0.007	0.004	0.004	0
3S3	0.024	0.023	0.013	-0.001	0.025	0.023	0.020	0.016	0.016	0.001

TABLE 8

TOP SURFACE STRAINS IN CURLED SLABS UNDER 9-KIP LOADS

Pavement	Increase or Decrease in Strain over Flat Slab Strain (in.)									
	Undoweled Joint				Doweled Joint				Free Edge	Interior
	Corner		Mid-Joint		Corner		Mid-Joint			
	Load	Opp.	Load	Opp.	Load	Opp.	Load	Opp.		
8B5	-	-	-	-	0.006	0.002	0.007	0	0	0
8N5	-	-	-	-	0.012	0.003	0.007	0.002	-0.003	-0.002
7N6	0.012	0.010	0.010	0.005	0.005	0.005	0.005	0	0	0.003
5N9	0.015	0.012	0.012	0.009	0.010	0.008	0.008	0.004	-0.005	-0.003
7B3	0.002	-0.001	0.005	-0.007	0.006	-0.001	0.006	-0.001	-0.008	-0.004
5N6	0.002	0.004	0.011	-0.001	0.011	-0.005	0.015	0.001	-0.006	-0.001
8G5	-	-	-	-	0.005	0	-0.006	0.005	-0.007	0
3B9	0.013	0.008	0.013	0.008	0.010	-0.008	0.012	0.012	-0.008	-0.010
5B3	0.006	-0.005	-0.008	-0.009	0.011	0.007	-0.004	-0.002	-0.006	-0.004
5N3	0.016	0.005	0.014	-0.008	0.014	0.002	0	-0.004	-0.002	0.005
3B6	0.004	-0.002	0.020	-0.009	0.011	0	0.003	-0.004	-0.020	-0.007
3N6	0.019	0.019	0.023	-0.007	0.020	0.013	0.019	0.023	0.005	0.009
3B3	0.010	0.004	0.020	0.010	0.019	0.010	0.014	-0.010	0.019	-0.013
3S3	0.014	-0.001	0.025	-0.018	0.017	0.016	0.004	0	0.030	0.003

of decreased strain. At the free edges and interior locations there were more cases of strain reduction than of strain increase.

Influence of Curl on Joint Effectiveness.—It was noted that increases in deflection due to loads at joints were greater for the loaded side than across the joint. The effectiveness ratios were computed for all combinations from the data in Figures 13 and 14 and Table 7. It was found that the effectiveness of undoweled joints varied from 77 to 98 percent in curled slabs as compared with 93 to 100 percent in flat slabs. Also, doweled joint effectiveness ranged from 80 to 98 percent in curled slabs as against a range of 83 to 100 percent in flat slabs. Although joints on curled slabs were slightly less effective than those in flat slabs in these static load tests there was excellent load transfer across the joint in both flat and curled slabs.

Comparison with Theory

Data from these tests on flat concrete pavements on CTS were checked by Westergaard's interior (8) and free edge (9) deflection formulas. These are relatively simple expressions and require only an evaluation of the elastic modulus of the concrete and the bearing value of the supporting base. A second method based on soil pressures may be used, but analysis by pressures in layered systems requires knowledge of the elastic constants of the materials under load restraints. Moment analysis, a third method, may be used to check strain measurements if the distribution of stresses through the layers is known.

A comparison of experimental measurements and theory is shown by Figure 17. A logarithmic plot of theoretical relations between interior slab deflection, d_i, and bearing modulus, k, of the subbase was constructed for slab thicknesses, h, equal to 3, 5, 7, and 9 in. from the Westergaard formulas:

$$d_i = \frac{P}{8kL^2} \qquad (1)$$

in which

$$L^4 = \frac{Eh^3}{12(1 - \mu^2)k} \qquad (2)$$

For these computations load P = 9,000 lb, $E = 5 \times 10^6$ psi, and $\mu = 0.15$.

Nominal subbase thicknesses were superimposed on the abscissa at locations determined from Table 1. Experimental deflections due to 9-kip interior loads were plotted as ordinates above the proper bearing value. These points were circled and labeled to identify the pavement.

The experimental points cluster about appropriate theoretical lines. Although deflections of bonded pavements are shown, the analysis assumes no horizontal stress due to interlayer friction, therefore, it is not directly applicable to bonded pavements. The combinations with 3-in. concrete compare more closely with the theory than those with thicker concrete, but in general the agreement is reasonable. The advantage of bond may be estimated to be equivalent to an added concrete thickness of from ½ to 1 in.

A second comparison was accomplished in a similar manner using Westergaard's edge equation

$$d_e = P\sqrt{\frac{2 + 1.20\mu}{Eh^3k}}\left[1 - (0.76 + 0.40\mu)\frac{r}{L}\right] \tag{3}$$

in which the loading plate radius $r = 8$ in. A logarithmic plot was drawn and experimental edge deflection points were located above appropriate bearing values as shown in Figure 18.

As in the case of interior loading, the experimental data for unbonded combinations fell reasonably close to the theoretical curves. Resistance of pavment 3B6 to edge deflection was slightly less than anticipated, but in other combinations bond at the interlayer improved deflection resistance as much as ½ to 1 in. of additional concrete.

SUMMARY AND CONCLUSIONS

Cement-treated subbases were built on silty clay subgrades of relatively low bearing value and were covered with concrete surfaces. Deflections, strains, and pressures were measured when static loads were applied to the concrete slabs. Pavements were built with and without interlayer bond and the principal variables were subbase thickness and concrete thickness. Each structure included a doweled transverse joint, and all combinations except 8-in. concrete on 5-in. CTS included a transverse joint without dowels.

Progress toward accomplishing the objectives of the study was made as follows:

1. The ability of concrete pavements on CTS to support load was rated relative to that of 8-in. concrete on 5-in. gravel. Based on constant edge deflection, an 8-in. concrete slab bonded to 5-in. CTS was able to support 200 percent of the load carried by the standard 8-in. slab on 5-in. gravel, and a slab of 3-in. concrete on 3-in. CTS, unbonded, was able to support a load equal to 45 percent of the standard. At this same deflection other combinations were able to support loads distributed between these limits.
2. A cement-sand grout on the subbase surface prior to casting concrete effectively bonded the concrete and CTS layers. Load capacities of bonded pavements were equivalent to unbonded pavements with the concrete thickness increased by ½ to 1 in. Corner movement due to curl was less for bonded pavements than for those without the bonding treatment.
3. Experimental deflection data were in good agreement with values computed by the Westergaard deflection formulas.

Instrumentation and test procedures provided an opportunity for the following observations incidental to the primary objectives:

1. Pressures on the subgrade directly under interior 9-kip loads increased with decreasing pavement thickness and varied from 2 to 6 psi for all combinations tested. Under edge loads, subgrade pressures were approximately 50 percent greater than under interior loads.
2. Edge deflections and strains were reduced as the load was moved inward from the slab edge. At the 24-in. position, edge deflections of the thicker pavement combinations with load-carrying ability equal to or greater than the standard 8-in. slab on

5-in. gravel averaged about 75 percent, and those with lesser ability about 60 percent of the edge deflections due to edge loads. Edge strains of the thicker pavement combinations were reduced almost ½ for the 24-in. load position, and strains were reduced by greater amounts on the thinner pavements. Edge strains produced by inward loads on thin pavements are not necessarily critical and there is evidence to suggest that maximum strains on thin pavements are at the load plate in a transverse direction.

3. The deflections at both doweled and undoweled transverse joints were maximum when the load was at the outer corner; but for this load position top surface compressive strains at the load were sometimes exceeded by tensile strains parallel to the joint at 40 to 56 in. from the edge. The highest strains measured at joints were compressive at the load when the load center was at least 40 in. from the free edge of the concrete. At this location of maximum joint edge strain, the strains were always less than those caused by a free edge load but greater than those at the free edge caused by a load 24 in. inward from the edge. Therefore, the critical strain in a pavement due to a moving truck may be at a free edge or at a joint, and its location will be determined by the position of the wheel with respect to the free edge.

4. Joints in concrete pavements on cement-treated subbases effectively transferred load. Doweled joints offered very little advantage over joints without dowels in flat pavements of concrete on cement-treated subbases.

5. The concrete was approximately 3 times as effective in limiting deflections and strains as the CTS. In the range of layer thicknesses studied, and additional 2-in. thickness of concrete resisted slab deflections to the same degree as an additional 6 in. of CTS. Previous studies also have shown that a 5-in. CTS subbase under 8-in. concrete offered more resistance to deflection than 15 in. of gravel.

6. The combination slabs curled due to drying of the top surface in much the same manner as slabs on granular subbases, and the greatest movement occurred in pavements of low load capacity. Slabs with bonded interlayers curled slightly less than those without bond.

7. Deflections due to 9-kip loads on flat slabs were less than those for similar load positions on curled slabs except at interior locations. Top surface strains in flat slabs were usually less than corresponding strains in curled slabs except at free edges and interiors.

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