Significance of Layer Deflection Measurements

RICHARD D. WALKER, Assistant Professor of Civil Engineering, V.P.I.;
ELDON J. YODER, Research Engineer, Purdue University; and
WALTER T. SPENCER, and ROBERT LOWRY, Research Engineer and Soils Engineer,
Indiana Highway Commission

An understanding of pavement behavior is essential to the development of an effective method of pavement design. To this end, a system for evaluating the structural performance of existing pavements is required. One system of evaluation and its effectiveness is described in this paper.

Data obtained from a test road located on US 31 near Columbus, Indiana, were used to develop the evaluation methods. Procedures such as the analysis of existing crack patterns and wheel track rutting and their relationships to subgrade soil type were examined. Total surface deflections under load, measured with a Benkelman beam, were analyzed in an attempt to establish a relationship between deflection and cracking of the pavement surface.

Failure to establish total deflection as an indicator of the pavement behavior led to the development of a method using the Benkelman beam to measure deflections of the individual layers of the pavement structure. Four-inch holes were drilled to the interface of the different layers of the pavement, and the holes were cased with pipe. Steel rods were referenced at the bottom of each hole, extending upward to near the top of the pavement. Measurements were made under rear axle loads of 12,000, 18,000, 22,000 and 27,000 lb.

Relative modulus values using layer deflections were calculated to compare the relative deflection of one pavement layer with another. Theoretical stress distribution was used as a basis of the calculations.

The important conclusions reached by this study were that total deflections were ineffective in establishing the cause of the flexible pavement cracking and that knowledge of the individual layer deflections was required in order to evaluate the pavement fully.

● THE AMOUNT a flexible pavement deflects under load indicates, in part, its adequacy insofar as structural capacity is concerned. Repeated deflection may cause the pavement to crack and distort as a result of (a) fatigue, (b) excessive bending stresses, and (c) accumulated plastic deformation and other factors.

The deflection of a flexible pavement is partly elastic in character, but it is also made up of plastic strains. Elastic strains are regained on removal of an applied load whereas plastic strains are not. Thus, the accumulation of these nonrecoverable plastic strains with repeated applications of load can result in distortion of the paving surface.

It must be recognized at the outset that performance of a flexible pavement is influenced by many factors. These include gross load, tire pressure, repetition of load, thickness and quality of the various pavement components, and the elastic plastic properties of the pavement components (particularly the subgrade soil). Pavement failure may result from excessive shear stresses, vertical deflection, or a combination of these.

Several methods of flexible pavement design are based on limiting deflection criteria.

These include procedures adopted by the Kansas State Highway Department and the Navy Department. Both of these methods of design are predicted in part on theoretical considerations that relate pavement stresses and deflections to the applied load. Certain simplifying assumptions are made regarding the shape of the tire imprint upon the pavement surface, the relationship between tire pressure and contact pressure and homogeneity and isotropy of the structural system.

Many engineers use deflection measurements to evaluate the adequacy of existing pavements. The literature contains numerous references to deflection measurements, including the work done on the WASHO and AASHO Road Tests. Deflection measurements are but one tool that can be used by the researcher to formulate concepts regarding the behavior of flexible and rigid pavements. Deflection measurements are subject to many limitations and therefore must be considered to be a means towards an end rather than an end within themselves.

The primary purpose of determining the deflection of an existing pavement, insofar as structural adequacy is concerned, is to obtain basic data, either by inference or direct measurement, relative to the stress-strain properties of the pavement materials. Mere measurement of gross deflection at the pavement surface may not yield the desired results. Such factors as pavement layer deflection, radius of bending and the viscoelastic properties of the pavement components must also be considered.

To be of maximum benefit to the engineer, deflection measurements must be planned so that a large amount of information is obtained without resorting to elaborate field installations. This is true inasmuch as the time required to install deflection gages in pavements is great, which in turn limits the number of measurements that can be obtained.

Surface deflection is made up of cumulative deflections of all the pavement components including the subgrade. Also, for the usual case a large portion of the deflection occurs in the subgrade. It is to be noted that the pavement may tend to "heave" both between and outside the dual wheels.

As depth increases, the profile of bending changes from that found immediately under the wheels and is saucer shaped. Surface deflection results from an accumulation of strains from the surface downward; the distance a particle moves when a load is applied at the surface decreases with depth.

It appears that measurement of surface deflection alone may be misleading in some cases unless depth of the layer contributing the largest portion of the deflection is known. As a rule, if the major portion of the deflection is in the subgrade, large radii of curvature occur, whereas small radii result if the deflection occurs in the upper layers of the pavement. Because tensile stress varies inversely with radii of curvature of the deflected surface it is apparent that knowledge of depth of the deflected layer is important.

A series of deflection measurements were made on the US 31 Test Road near Columbus, Indiana. The purpose of making these measurements was to determine the significance of layer deflection and in particular to ascertain whether correlations could be established between total deflection and pavement condition and between layer deflection and pavement condition. A large number of surface deflections were determined with the Benkelman beam. Layer deflections (that is, top of base, subbase and subgrade) were made at selected locations. Comparisons were made among surface rutting, cracking, surface deflection and layer deflections.

The test pavements offered an excellent opportunity to study these comparisons because the pavement was constructed under closely controlled construction conditions. An intensive testing program was carried out during the planning and construction phases. Detailed information was available regarding soil conditions, construction problems, strength properties of all pavement components and perhaps most important, detailed information on the pavements' performance was available.

DESIGN AND CONSTRUCTION OF TEST PAVEMENT, US 31

The flexible pavement design was based on a combination of the Corps of Engineers CBR and the Group Index methods. Subgrade types ranged from A-1-a sands and gravels to plastic A-6 clays (AASHO soil classification). The basic design of the pavement structure was as follows:

1 in. — asphaltic concrete surface course,
1½ in. — asphaltic concrete binder course,
2½ in. — asphaltic concrete base course,
8 in. — waterbound macadam base course, and
5 in. — (inside edge) to 8 in. (outside edge) — open-graded drained granular subbase course.

The subgrade, after compaction to 100 percent of the maximum standard AASHO value, received at least two coverages of a heavy pneumatic roller (20- to 35- tons gross load and 50- to 70- psi tire pressure).

The subbase, which was open-graded and had an average of 2.8 percent fines passing the No. 200 mesh sieve, was compacted with a multiple shoe vibrator to 100 percent of maximum standard AASHO density. Because the subbase lacked cohesion, the heavy pneumatic compactor could not be used. The multiple shoe vibrator was not employed until the top 2 1/2 in. were mixed with 70 lb per sq yd of limestone screenings.

Crushed stone was used in the construction of the waterbound macadam base course. Each layer was compacted with a multiple shoe vibrator and a heavy pneumatic roller. Two complete coverages were made with the heavy pneumatic roller loaded to a gross weight of 35 to 50 tons, producing contact pressures of approximately 70 to 85 psi.

A 60- to 70- penetration asphalt was used in all three bituminous concrete layers, 4.5, 5, and 6 percent for the base, binder, and surface courses, respectively. All pavement was placed during the 1953 construction season. The final section was opened to traffic December 11, 1953.

OBSERVANCE OF CRACKING AND RUTTING

Early in 1957, longitudinal cracking began to appear at several locations of the flexible pavement. The cracking generally occurred in both the outer and inner wheel tracks. Where the cracking was severe, some transverse cracking was apparent. Wheel track rutting was observed at the same time as the cracking. In general the rutting did not exceed 0.5 in.

CRACKING, RUTTING, AND SURFACE DEFLECTION STUDY

Initial studies of the test pavement included an analysis of the extent of cracking, rutting, and measurement of surface deflection.

Cracking and Soil Type

Table 1 gives the linear feet of cracks per station (100 ft) for the four basic soil types found under the flexible pavement. All types of cracks are included except those which seemed to delineate the pavement centerline giving the appearance of a plane of weakness or a "cold joint."

TABLE 1

RELATIONSHIP BETWEEN CRACKING AND SOIL TYPE, JANUARY-FEBRUARY 1960

Soil Type	No. of Stations	Linear Ft of Cracks	Avg. Linear Ft of Cracks per Station
A-1	39	4,814	123
A-2	53	5,863	111
A-4	177	23,901	135
A-6	109	11,138	102
All	378	45,716	121

Table 1 shows that more cracks occurred in the pavement built over the A-4 subgrade than pavement built on the other subgrade types. Also shown is that fewer cracks have resulted in pavement built on A-6 subgrades.

Other crack data not presented here have shown that more cracks have occurred in the traffic lane than in the passing lane, and that cracking is not directly related to pavement surface thickness. Also, observation has shown that the cracking has progressed since first appearing.

Surface Deflection Study

During the first week of June 1959, and the second week of May 1960, Benkelman beam deflection measurements were made at the test road site.

Deflection measurements were made at 48 carefully selected locations. Thirty-two of these locations fit into a pattern of variables given in Table 2. The variables selected were bituminous pavement surface thickness, crack frequency, lane, and soil type. In general, a pavement showing high crack frequency had 80 or more lineal feet of cracks per station. A section of pavement showing 25 or less lineal feet of cracking was classified as having low crack frequency. The nominal bituminous pavement thickness was 5 in. and this was used as the demarcation line for the surface thickness variable. The sites were also selected on the basis of soil type.

TABLE 2

DESIGN OF EXPERIMENT FOR BENKELMAN BEAM DEFLECTION MEASUREMENTS

Soil Type	Lane	Crack Frequency	Bituminous Pavement Thickness (in.)
A-1	Traffic	Low	5+
			5-
		High	5+
			5-
	Passing	Low	5+
			5-
		High	5+
			5-
A-2	Etc.		
A-4	Etc.		
A-6	Etc.		

Deflections were measured under an 18,000-lb rear axle load. Deflections reported in this paper are those taken between the tires of both the rear dual wheels of the truck. In taking the measurements, the truck, initially 10 ft away, was backed to the point of measurement so that its rear axle passed approximately 3 in. beyond the point, and then it was moved forward. In this manner, the rear wheels came no closer than 7.5 ft to the reference feet of the Benkelman beam. In only four out of several hundred tests did a dial reading of other than zero result when the truck was 7.0 or more feet away from the probe of the beam. It is therefore believed that significant movement of the reference feet did not occur.

Table 3 presents the combined 1959 and 1960 inner and outer wheel path data. A four-way classification analysis of variance was made to study the effects of soil type, surface thickness, crack frequency and lane type on the deflection data. Significance of a factor was determined by variance ratios or "F" tests at 0.05 and 0.01 levels. For

TABLE 3

SUMMARY OF TOTAL DEFLECTION FOR 1959 AND 1960 DATA, INNER AND OUTER WHEELPATH

Crack Frequency	Bituminous Pavement Thickness (in)	Total Deflection (10^{-3}in)								Total		
		A-1 Soil		A-2 Soil		A-4 Soil		A-6 Soil				
		Traffic Lane	Passing Lane	Traffic Lane	Passing Lane	Traffic Lane	Passing Lane	Traffic Lane	Passing Lane			
Low	5+	15	15	17	9	20	13	24	14	127		
		18	18	17	18	32	17	32	22	174		
		14	14	12	11	18	14	20	12	115	559	
		16	16	15	15	20	18	25	18	143		1,200
	5-	21	13	20	16	30	24	22	17	163		
		20	13	19	19	30	36	21	21	179		
		20	11	16	10	25	19	18	16	135	641	
		20	14	19	20	24	26	19	22	164		
High	5+	11	12	17	11	26	10	18	13	118		
		10	14	26	12	26	16	19	30	153		
		13	15	15	13	20	10	14	17	117	533	
		12	12	22	18	23	22	19	17	145		1,144
	5-	14	16	18	12	24	20	34	15	153		
		15	11	18	13	24	22	34	17	154		
		15	13	17	10	25	18	34	14	146	611	
		15	13	17	8	24	24	34	23	158		
Total		249	220	285	215	391	309	387	288	2,344		
		469		500		700		675				

TABLE 4

FOUR-WAY ANALYSIS OF VARIANCE RESULTS FOR 1959 AND 1960 DEFLECTION DATA, INNER AND OUTER WHEELPATH

Source of Variance	F	$F_{0.05}$	$F_{0.01}$	Significance
Soil type, A	36.40	2.71	4.03	0.01 level
Lane, B	50.98	3.95	6.96	0.01 level
Crack frequency, C	2.00	3.95	6.96	NS
Surface thickness, D	16.66	3.95	6.96	0.01 level
Interactions A x B	2.33	2.71	4 03	NS
A x C	2.92	2.71	4.03	0.05 level
B x C	1.33	3.95	6.96	NS
A x B x C	2.17	2.71	4.03	NS
A x D	3.75	2.71	4.03	0.05 level
B x D	1.08	3.95	6.96	NS
C x D	0	3.95	6.96	NS
B x C x D	5.00	3.95	6.96	0.05 level
A x B x D	4.83	2.71	4.03	0.01 level
A x C x D	7.00	2.71	4.03	0.01 level
A x B x C x D	7.91	2.71	4.03	0.01 level

the effect of soil type on deflection, the Tukey method for determining a studentized range allowance for a set of means was applied (1).

Table 4 summarizes the results of the analysis of variance of the data presented in Table 3.

The statistical analysis shows that soil type, lane, and bituminous pavement thickness have an effect on the deflection data. Deflections on the traffic lane were higher than those on the passing lane and those on thick pavement surfaces were lower than those on thin pavement surfaces. Deflections were shown not to be related to crack frequency.

The Tukey analysis showed that real differences exist in deflection measurements made on course- and fine-grained soils, but that differences between the A-1 and A-2 were not significant or the differences between the A-4 and A-6 soils were not significant. Deflections on A-1 and A-2 subgrades were lower than those on A-4 and A-6 subgrades.

The interactions shown to be significant in the analysis of variance were mostly due to a fairly small error mean square. This is not unusual when a large number of values, such as in this case, are used in the analysis.

Wheel Track Rutting Study

During the first week of August 1959, a transverse profilometer constructed by the Bureau of Materials and Tests of the Indiana State Highway Department was used to obtain the wheel track rutting measurements at the same 48 locations used in the surface deflection study. A rutting value was determined for each location by determining the maximum difference in elevation for that location in inches.

Table 5 presents a summary of the wheel track rutting data. Table 6 summarizes the results of the analysis of variance on these data. As with the deflection data, the rutting data are affected by lane position and soil type but not by crack frequency. Higher rutting values were recorded in the traffic lane than in the passing lane. Unlike the deflection data, the rutting data were unaffected by pavement surface thickness.

Tukey's method was applied in the same manner as in the deflection data in order to determine which soil types might be significantly affecting the rutting data. Real differences exist in rutting measurements made on A-1 subgrades and the fine-grained subgrades. The A-2 soil group was so variable that it could not be established as performing differently from any of the three other soil groups. Thus, rutting measurements of pavement built on A-1 subgrades are significantly lower than those of pavements on A-4 and A-6 subgrades.

TABLE 5

SUMMARY OF INNER AND OUTER WHEEL TRACK RUTTING DATA

Crack Frequency	Bituminous Pavement Thickness (in.)	Rutting (10^{-2} in.)								Total		
		A-1 Soil		A-2 Soil		A-4 Soil		A-6 Soil				
		Traffic Lane	Passing Lane	Traffic Lane	Passing Lane	Traffic Lane	Passing Lane	Traffic Lane	Passing Lane			
Low	5+	13	11	27	22	36	33	62	25	229	439	851
		33	16	28	22	21	31	33	26	210		
	5-	40	11	44	12	44	24	53	18	246	412	
		27	10	26	17	30	16	24	16	166		
High	5+	16	11	34	21	62	23	60	25	252	449	945
		12	12	33	23	38	24	31	24	197		
	5-	28	19	41	31	61	22	79	21	302	496	
		15	14	22	26	35	24	40	18	194		
Total		184	104	255	174	327	197	382	173	1,796		
		288		429		524		555				

TABLE 6

FOUR-WAY ANALYSIS OF VARIANCE RESULTS FOR INNER AND OUTER WHEEL TRACK RUTTING DATA

Source of Variance	F	$F_{0.05}$	$F_{0.01}$	Significance
Soil type, A	7.83	2.92	4.51	0.01 level
Lane, B	34.00	4.17	7.56	0.01 level
Crack frequency, C	1.20	4.17	7.56	NS
Surface thickness, D	0.06	4.17	7.56	NS
Interactions: A x B	2.00	2.92	4.51	NS
A x C	0.84	2.92	4.51	NS
B x C	0.19	4.17	7.56	NS
A x B x C	1.75	2.92	4.51	NS
A x D	0.38	2.92	4.51	NS
B x D	1.95	4.17	7.56	NS
C x D	0.74	4.17	7.56	NS
B x C x D	0.76	4.17	7.56	NS
A x B x D	0.08	2.92	4.51	NS
A x C x D	0.30	2.92	4.51	NS
A x B x C x D	0.86	2.92	4.51	NS

Relationship Between Deflection and Rutting

As can be seen by Figure 1, there is a good relationship between maximum deflection and wheel track rutting. The fitted line of Figure 1 was obtained by the method of least squares. It should be noted, however, that the points in this figure represent average values, and that the data for the A-4 soil are erratic.

Summary

Concerning the cracking study, the following summary statements are applicable:

1. Cracking was not shown to be related to subgrade type.
2. More cracking occurred in the traffic lane than in the passing lane, no doubt due to heavier, and greater traffic volumes on the traffic lane.
3. Bituminous pavement thickness was not shown to be related to cracking.

The following statements summarize the surface deflection and rutting results:

1. Subgrade type, lane, and pavement thickness affected the deflection data.
2. Subgrade type and lane affected the rutting data.
3. Crack frequency was not shown to be related to total deflection or to rutting.
4. A direct relationship existed between rutting and total deflection.

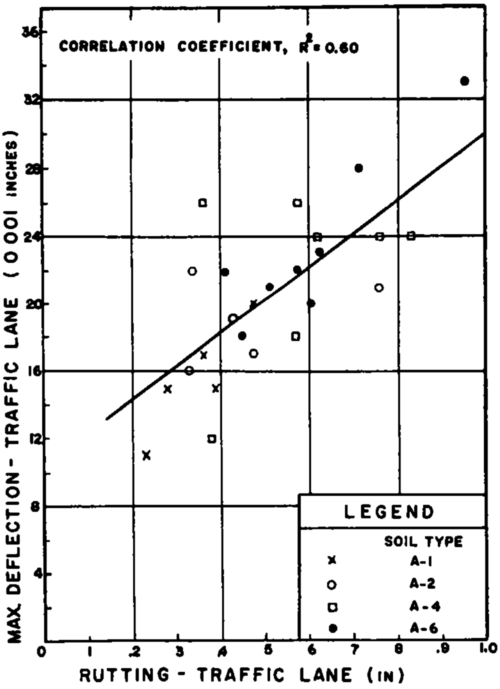

Figure 1. Maximum deflection vs rutting.

LAYERED SYSTEM DEFLECTION STUDY

It is significant to note the previous study indicated that no correlation existed between cracking and surface deflection. Further, a correlation did exist between rutting and deflection and between rutting and soil type. The data suggest that surface deflection was directly related to soil type, fine-grained subgrades resulting in the highest deflection. Also rutting was influenced by soil type in the same manner. Thus it is indicated that the major portion of the rutting occurred in the subgrade itself. However, the probable cause of the longitudinal cracking was not apparent from the study.

The next step in the investigation concerned the study of deflection patterns within the component layers of the pavement. It was hypothesized that if the deflection of each pavement layer was determined at all of the sites previously tested, a relationship between these deflection data and pavement cracking could be established. Through the use of the stress distribution theory, relative moduli values, E, could be derived from the deflection data. The term relative modulus is used instead of elastic modulus, inasmuch as the pavement structure is imperfectly elastic. It should be noted that it was necessary to assume that materials under the cracked pavement underwent the same relative changes, with time, as the materials under the pavement that did not crack.

A scheme was devised in which the Benkelman beam was adapted to measure the vertical movement of steel rods referenced at the top of the different layers of the pavement system. This scheme (Fig. 2), used 4-in. diameter holes, with pipe casing and steel reference rods of varying lengths.

It was considered impractical to install a complete set of reference rods at all 32 sites of the previously discussed experiment; therefore, only eight sites were selected. The tests were made at eight locations in the passing lane where the surface was ap-

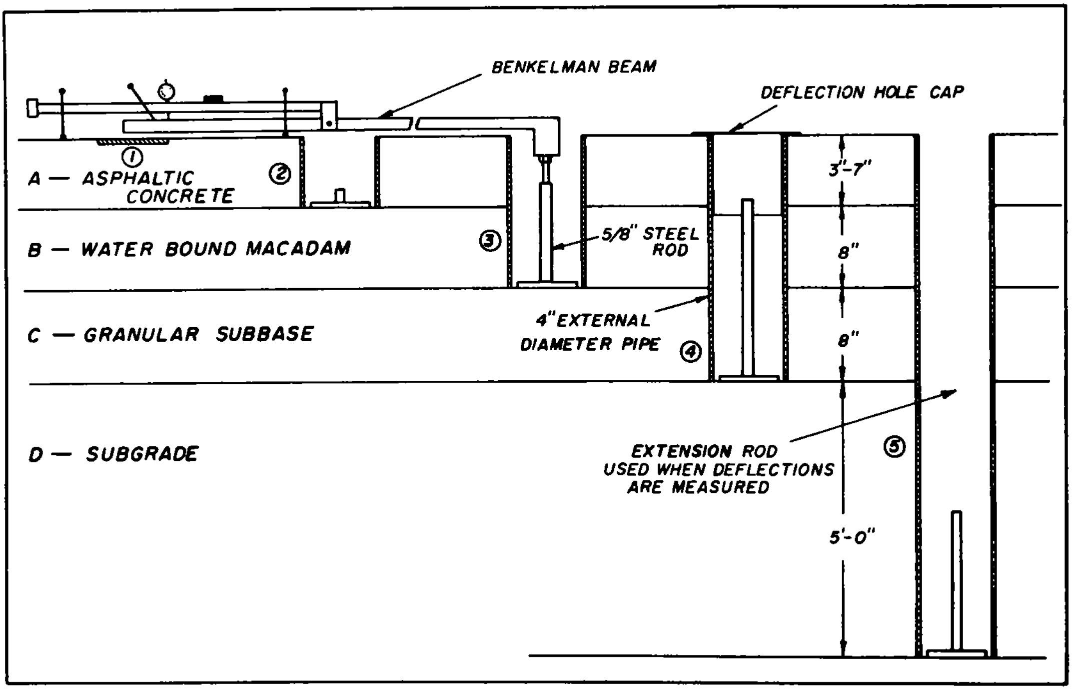

Figure 2. Use of Benkelman beam for layered system deflection study.

proximately 5 in. thick. Because of the importance of soil type, and because crack frequency was the factor for which an existing relationship was sought, these two factors were retained in the experiment. The eight sites selected for this study conform to the pattern of variables given in Table 7. All of the field work was completed during the months of September 1960 and April 1961.

TABLE 7

DESIGN OF EXPERIMENT FOR LAYERED SYSTEM DEFLECTION STUDY*

Soil Type	Station No.	
	Low Crack Frequency	High Crack Frequency
A-1	438, F-1	426, F-1
A-2	453, F-1	460, F-1
A-4	275, F-1	304, F-1
A-6	349, F-1	347, F-3

*All measurements were made in the inner wheelpath of the passing lane where the bituminous pavement was approximately 5 in. thick.

Test Procedures

Four different truck loadings were used: (1) 6,000 lb, right rear dual wheels, September 1960; (2) 11,250 lb, right rear dual wheels, September 1960; (3) 13,390 lb, right rear dual wheels, September 1960; and (4) 12,000 lb, right rear dual wheels, April 1961. The testing procedures were essentially the same as used for the surface deflection study; that is, the truck was backed from a distance 10 ft from the deflection point to a position over the point and then forward again.

Relative Moduli Values

Relative moduli values were obtained for the subgrade, subbase, and base courses for six of the eight locations. These are relative values only, because they are based on Boussinesq stress distribution and on the deflection measurements made through holes cased with pipe. Relative moduli offer a means of comparing the stress-strain properties of one layer to another.

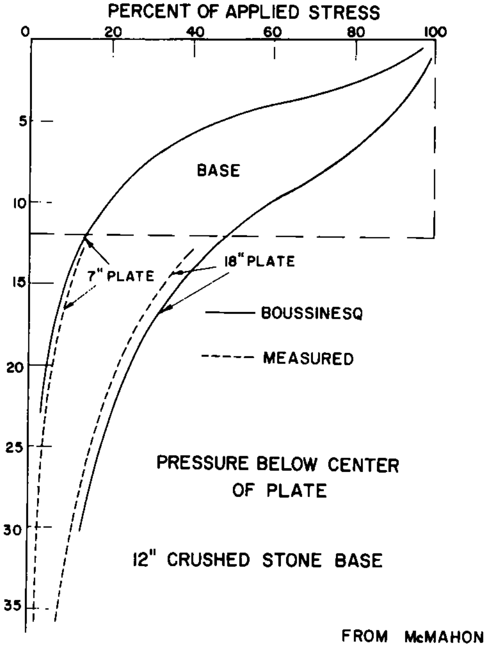

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Figure 3.

It is recognized that in calculating these relative moduli values, application of elastic theory is made to a problem involving the stress-displacement properties of an imperfectly elastic material. However, inasmuch as the deflections dealt with in this study are not of the permanent type, but are primarily recoverable, the application of elastic theory to this problem appears justified.

Additional justification for use of the theoretical stress distribution computation to this problem is based on the fact that although numerical values of stress vary from the calculated values, the measured stress-depth curves are shaped similar to calculated curves (2, 3). Also changes in stress with depth are used in the moduli computations. Thus, because the measured and calculated curves have the same shape, the amount of error which is introduced into the computation is minimized. Figure 3 illustrates the comparison of curves obtained by test to calculated curves.

Considering the magnitude of loads received by the average highway, the use of elastic theory in the analysis of pavement

TABLE 8

SUBGRADE MODULUS, E_3, IN 1,000 PSI

Station	Dual Wheel Load, (lb)			Crack Frequency	Soil Type
	6,000	11,250	13,390		
347	32.8	20.5	19.1	High	A-6
249	26.4	27.5	19.0	Low	A-6
304	26.4	27.4	23.8	High	A-4
275	43.4	30.7	31.9	Low	A-4
460	32.8	32.5	31.9	High	A-2
453	21.7	27.4	31.9	Low	A-2
426	21.7	40.6	35.8	High	A-1
438	26.4	40.6	35.8	Low	A-1

TABLE 9

RESULTS OF TWO-WAY ANALYSIS OF VARIANCE OF SUBGRADE MODULI VALUES

Source of Variance	F	$F_{0.1}$	$F_{0.25}$	Significance
Soil type, A	2.37	2.49	1.50	0.25 level
Crack frequency, B	0.33	3.07	1.42	NS
Interaction: A x B	1.48	2.49	1.50	0.25 level

TABLE 10

SUBBASE MODULUS, E_2, IN 1,000 PSI

Station*	Dual Wheel Load (lb)			Crack Frequency	Soil Type
	6,000	11,250	13,390		
249	13.4	12.8	26.8	Low	A-6
304	13.4	12.8	13.2	High	A-4
275	10.8	14.9	13.4	Low	A-4
460	17.7	13.9	17.7	High	A-2
426	10.8	12.8	13.4	High	A-1
438	26.1	30.8	35.4	Low	A-1

*Station 347 and 453 had to be eliminated from this analysis because of defective hole installation referenced on top of subbase.

TABLE 11

RESULTS OF TWO-WAY ANALYSIS OF VARIANCE OF SUBBASE MODULI VALUES

Source of Variance	F	$F_{0.1}$	$F_{0.25}$	Significance
Wheel load, C	0.70	2.81	1.53	NS
Crack frequency, B	3.76	3.18	1.46	0.1 level
Interaction, B x C	0.43	2.81	1.53	NS

structures can be quite valuable, especially after the highway has been subjected to several years of traffic. During the past few years, several research efforts have produced results which point toward the concept that under any single application of a moving wheel load on a pavement surface, nearly elastic behavior exists (4). Deformation of the subgrades on the WASHO Road Test was elastic-like in that practically equal and recoverable deflections were produced by several thousand loads following the conditioning period by initial loads (5).

The equation used to compute moduli values was as follows:

$$S = \frac{pa}{E} F \tag{1}$$

in which

S = vertical elastic deflection, in.;

E = modulus of elasticity of the material (herein called relative modulus), psi;

p = unit load over circular area, psi;

a = radius of circular area, in.; and

F = deflection factor dependent on depth and radius of contact.

Values of deflection factor, F, can be determined for any depth or offset value using influence charts developed by Foster and Ahlvin (6) from work by Newmark (7).

Contact Pressures. — For the purpose of calculating the elastic moduli values, the contact pressure, p, was assumed to be equal to the tire pressure. The contact area between the wheel and pavement was assumed to be circular.

Test Results

The moduli for each layer that were calculated from the September 1960 data were analyzed by a two-day analysis of variance. Significance of a factor was determined by variance ratios or "F" tests (1). Tables 8 through 13 summarize the moduli results and the statistical analysis. Inasmuch as the April 1961 data were limited to one wheel load, the resulting moduli data are given in Table 14 for comparison purposes only.

The moduli of the bituminous courses were not determined from the deflection meassurements because of the insensitivity of the Benkelman beam. In many cases no deflection was measured within the bituminous pavement; this resulted in calculated moduli equal to infinity.

TABLE 12

BASE COURSE MODULUS, E_1, IN 1,000 PSI

Station*	Dual Wheel Load, (lb)			Crack Frequency	Soil Type
	6,000	11,250	13,390		
249	49.7	101.2	132.0	Low	A-6
304	49.7	101.0	73.2	High	A-4
275	55.2	50.6	28.1	Low	A-4
460	27.6	65.0	47.2	High	A-2
426	55.2	50.6	69.4	High	A-1
438	17.8	24.0	47.2	Low	A-1

*Station 347 and 453 had to be eliminated from this analysis because of defective hole installation referenced on top of subbase.

TABLE 13

RESULTS OF TWO-WAY ANALYSIS OF VARIANCE OF BASE COURSE MODULI VALUES

Source of Variance	F	$F_{0.25}$	Significance
Wheel load, C	1.07	1.56	NS
Crack frequency, B	0.06	1.46	NS
Interaction: B x C	0.14	1.56	NS

TABLE 14

COMPARISON OF FALL AND SPRING LAYER DEFLECTIONS, 0.001 IN., 12,000-LB DUAL WHEEL LOAD OR 24,000-LB AXLE LOAD

Station	Subgrade		Subbase		Base		Soil Type	Crack Frequency
	Fall	Spring	Fall	Spring	Fall	Spring		
347	3.7	17.8	2.8	0.9	2.8	14.5	A-6	High
249	4.6	11.1	3.7	9.2	1.0	2.1	A-6	Low
304	4.6	6.3	3.7	12.8	1.0	3.2	A-4	High
275	2.8	7.6	4.6	8.8	0.9	7.4	A-4	Low
460	3.7	8.4	2.8	6.4	1.8	2.9	A-2	High
453	5.6	8.5	0.0	3.7	4.6	4.5	A-2	Low
426	5.6	9.3	4.6	5.0	0.0	4.2	A-1	High
438	4.6	9.3	1.9	3.6	2.8	3.8	A-1	Low

Summary

Figures 4 through 9 summarize the relative modulus values obtained from the fall deflection measurements.

No significant relationship was shown to exist between subgrade modulus values and crack frequency. A significant relationship between crack frequency and subbase moduli was established (at the 0.1 level). It was shown that with 10 percent chance of error, low crack frequency areas have higher subbase modulus values than high crack frequency areas. There appeared to be no relationship between crack frequency and base course moduli. In general, the results indicated that the base course had a higher relative modulus than the subgrade, and the subgrade somewhat higher than the subbase.

The springtime data were obtained only under a 12,000-lb dual wheel. It is to be seen in Table 14 that the macadam base course showed greater relative deflections in the spring than in the fall. The increase in deflection of the base at locations of high frequency was approximately 230 percent as contrasted to the base at low crack frequency locations, 59 percent. The springtime deflections for all the pavement layers were greater than the fall values, the subgrade and base course showing the largest increases. The fall measurements indicated that the subbase contributed significantly to the total deflection, whereas the spring measurements indicated that the base course and subgrade were more significant.

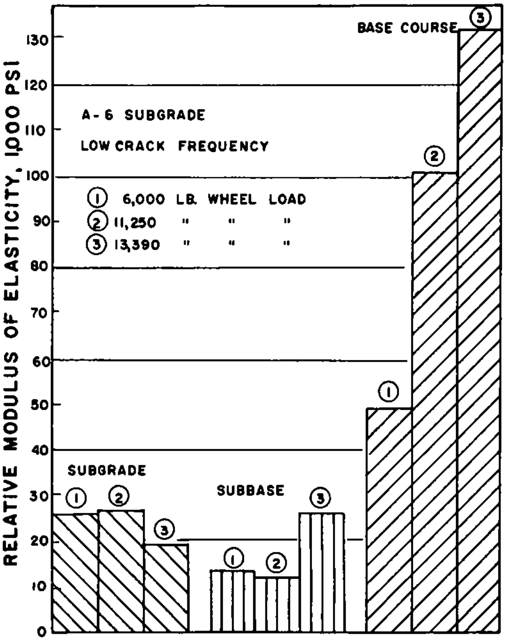

Figure 4. Relative modulus of pavement layers, station 249 (based on fall measurements).

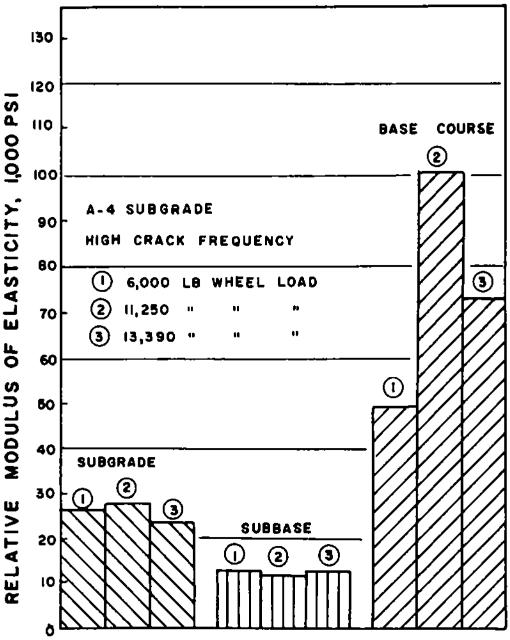

Figure 5. Relative modulus of pavement layers, station 304 (based on fall measurements).

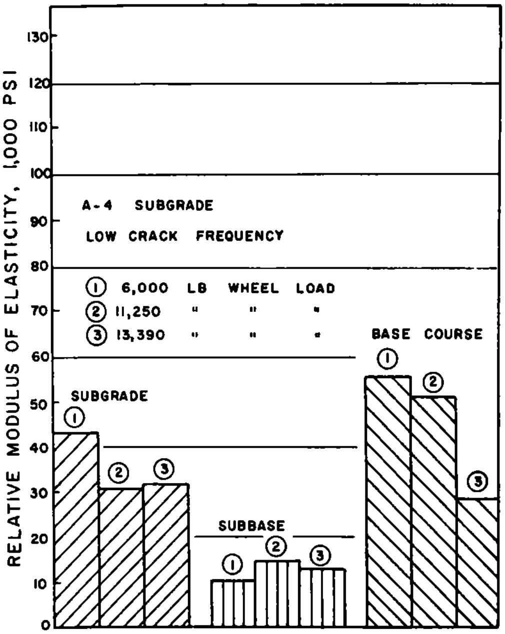

Figure 6. Relative modulus of pavement layers, station 275 (based on fall measurements).

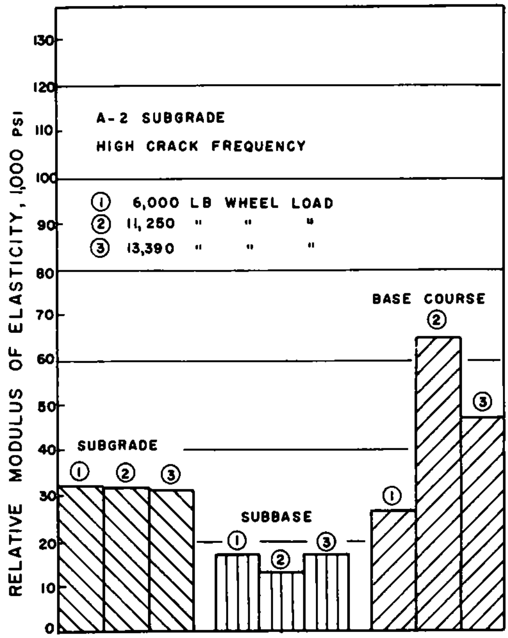

Figure 7. Relative modulus of pavement layers, station 460 (based on fall measurements).

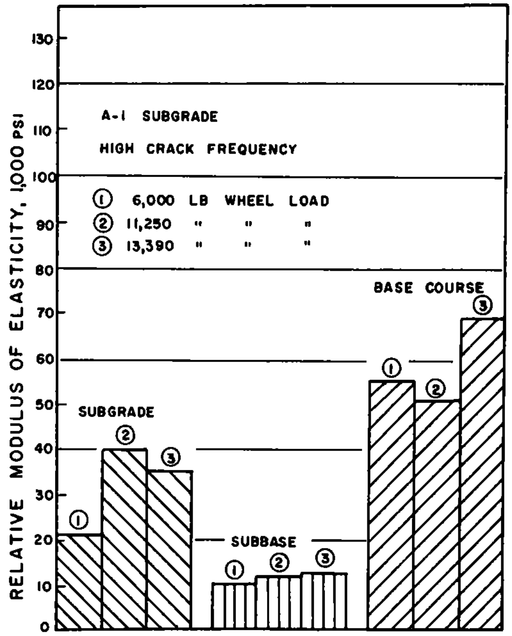

Figure 8. Relative modulus of pavement layers, station 426 (based on fall measurements).

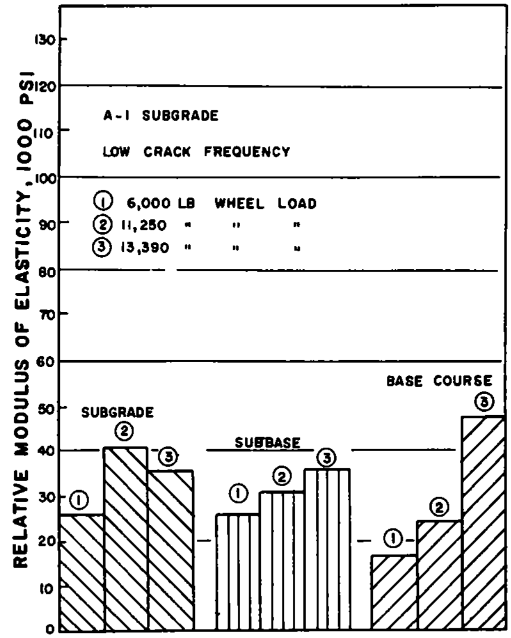

Figure 9. Relative modulus of pavement layers, station 438 (based on fall measurements).

DISCUSSION

Deflection, Rutting and Cracking

As shown in Table 1, pavements built over each of the four subgrade types showed on the average more than 100 lin ft of cracks per station. Because the subgrades ranged from granular materials)A-1-a classification) to silty clay (A-6 classification), it is concluded that low subgrade support was not primarily responsible for the pavement cracking.

More cracks have occurred in the traffic lane than in the passing lane suggesting a relationship between cracking and traffic intensity. The cracking however has progressed since first noticed in 1957 to the point where some sections of passing lane over all the subgrade types are beginning to show as many cracks as sections of the traffic lane; observation seems to indicate that the cracking is continuing at an increasing rate.

The absence of a significant relationship between surface deflection and crack frequency is perhaps the most important finding of the study. In the statistical analysis, the hypothesis was made that no relationship existed between crack frequency and deflection. This hypothesis could not be rejected even at the 0.01 or 0.05 level (Table 3).

Surface deflection, which is the sum of the deformations that occur in all the layers of the pavement structure and the subgrade, is dependent on many factors. Gross load, tire pressures, moisture content of the subgrade, and base, density of all the pavement components, volume change characteristics, and the season of the year, are some of the important factors that affect surface deflection. For example, natural variation in moisture contents from one location to another could cause different deflections, regardless of the cracking that had occurred in the pavement surface.

Another important result of this study is the relationship found between rutting and total deflection. Wheel track rutting reflects the permanent changes in elevation of the pavement layers and subgrade. In this case subgrade type was shown to be a statistically significant factor affecting the amount of rutting. The largest rutting values were associated with the fine-grained subgrades. A good correlation was established between surface deflection and rutting.

Layered System Deflections

The deflection of a component layer of the pavement structure depends on the physical properties of the layer in question and on the stresses imposed upon the layer. Hence, it becomes necessary in the analysis of layer deflections to take into account the stress distribution through the pavement. Use was made of the Boussinesq solution in this analysis to calculate a relative modulus for the pavement layers. The limitations of this analysis should be recognized (that is, homogeneity, elasticity, tire imprint shape, etc.).

Stress computations for the two- and three-layer problem have been proposed by Burmister (12, 13) and others. However, use was made of the homogeneous problem in this study because relative stresses at offset distance from the centerline of each tire of the dual wheel could readily be computed.

Observation of the deflection data in Table 14 and the modulus computations immediately indicate the interesting point that the deflection in the subbase was disproportionately larger in many cases than the deflection in the subgrade.

The subbase as used in this test pavement has two primary functions. First, it is a drainage layer which permits escape of water through the shoulders. Second, it is a transitional layer between the subgrade and base course. To fulfill this second purpose, the subbase ideally must not deform as much, for the same imposed stresses as the subgrade.

The subbase in this road consisted of a relatively clean, cohesionless sand. This satisfied the aforementioned drainage criterion; however, there was difficulty encountered in supporting construction traffic during construction due to the noncohesive nature of the material.

The fact that the subbase moduli were found to be related statistically to crack frequency is considered to be important. Even though the relationship was statistically significant only at the 0.1 level, this information, coupled with the lack of correlation between cracking and the other factors (as evidenced by very low F ratios in the analysis of variance concerning total deflection, subgrade modulus, and base course modulus), indicates that high deformation in the subbase regardless of seasons contributed to the occurrence of surface cracks. However, the spring measurements showed a large increase in deflections on the waterbound macadam base and sizeable increases in the A-6 subgrades and significant increases in the other subgrade types.

Ductility and Penetration Tests

When the deflection holes were drilled in the test pavement, cores of the bituminous layers were removed. Penetration and ductility tests were made on asphalt extracted from these cores. The results of these tests are given in Table 15.

It should be noted that the penetration and ductility values are the lowest for the surface course and the highest for the base course due undoubtedly to oxidation of the upper layer. Both the penetration and ductility values are rather low, particularly for the surface. This reflects conditions of the surface conducive to pavement cracking.

Evaluation of Test Pavement

On the basis of the findings from the crack survey, surface deflection, rutting studies, and the layered system deflection analysis, it is believed that, regardless of the cause of initial cracking, greater than normal deflection in the subbase is an important factor in the progression of cracking that is occurring in the test pavement. This is based on the observation that areas of high crack frequency were associated statistically with the low values of subbase modulus and vice-versa (see Table 10) and crack frequency was not found to be associated with type of subgrade nor with the relative modulus values of either the subgrade or base.

Cracking in a pavement surface can be caused by many factors including (a) shear

TABLE 15

AVERAGE DUCTILITY (cms) AND PENETRATION (0.1 mm) CORE LAYER

Station	Crack Frequency	Core Component					
		Surface		Binder		Base	
		Pen.	Duct.	Pen.	Duct.	Pen.	Duct.
347	High	29	8	39	22	42	34
249	Low	27	7	30	12	35	22
304	High	28	7	35	29	41	39
275	Low	28	6	34	14	41	30
460	High	33	12	40	24	41	36
453	Low	29	7	29	9	32	14
426	High	22	5	28	10	31	19
438	Low	22	6	28	13	33	17

stresses, (b) tensile stresses induced by volume changes in any of the pavement components, (c) tensile stresses caused by deflection of the pavement structure, and (d) bending stresses due to repeated loads which, when few in number are not destructive, but when repeated in numbers commensurate with high traffic volumes can be detrimental.

Shear stresses in the pavement surface can be assumed to be a major factor contributing to cracking where rutting, upheaval outside the loaded area, and other permanent differential settlements are evident. In the case of this road, rutting and cracking were found to be unrelated (Table 6). The cracks that did occur were quite smooth and lacked the evidence of a shear type of failure.

Effectiveness of Evaluation Methods

The procedures used in this study provided a basis on which to develop answers to the question of what was causing the cracking and rutting of the test pavement. However, the problem is of such complexity as to make impossible complete explanations of all behavior of the pavement structure. For example, if the subbase course is partly responsible for the cracking, why do not the cracks resemble map-type cracking more than they do? Also, if the primary cause is shrinkage, why are there so few transverse cracks? Most of the initial cracks were essentially longitudinal with some of the latter cracks tending to be diagonal in direction. A reason for the direction of crack formation could not be obtained from any of the data obtained in this study and at this point can only be presented as conjecture. Inasmuch as one would normally expect shrinkage cracks to be transverse in direction as well as longitudinal and fatigue cracks to be "map cracking," it appears reasonable to assume a combination of causes. It is pertinent to note that because the heaviest loads are on tandem axles, shorter radii of curvature are produced in the transverse direction (across the dual wheels) than in the longitudinal direction. These shorter radii would cause transverse bending stresses greater than longitudinal stresses, thus encouraging longitudinal cracks.

By showing that there was no relationship between total deflection and crack frequency, greater emphasis is placed on the need of measuring deflections in each pavement layer.

Deflection Measurement Procedure

The method of making the surface deflection measurements with the Benkelman beam differs from that used by many engineers. It is common practice to place the probe of the Benkelman beam between the dual wheels at a distance of 4.5 ft under the truck. The truck then pulls forward and initial and maximum dial readings are recorded. This puts the dual wheels initially about 3 ft from the reference feet of the beam. Data obtained during the surface deflection study of this report indicate that in most instances movement of the reference feet would have occurred if this procedure had been used. The procedure used in this study, wherein the dual wheel comes no closer to the feet than 7.5 ft, is recommended.

SUMMARY OF CONCLUSIONS AND RESULTS

Concerning the study of the pavement reported in this paper the following conclusions are drawn:

1. Total deflections, by themselves, were not effective in determining the entire cause of the distress. Surface deflections were correlated with rutting but no correlation was found between cracking and surface deflection.
2. Deflection measurements of the individual layers of a flexible pavement structure were useful in showing the relationship between the pavement cracking and properties of each pavement layer.
3. Determination of relative modulus values were used satisfactorily in an evaluation of the relationship of deflection of one layer to another.
4. The procedure of backing the truck so that the dual wheel just passes over the probe end of the Benkelman beam was found to be preferable to the procedure where the truck begins only 3 ft from the reference feet of the beam.

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Discussion

W. H. CAMPEN, Omaha Testing Laboratories — The authors are to be commended for conducting an extensive investigation in a systematic manner.

The writer has had considerable experience in conducting deflection or deformation tests in connection with test sections on airport runways.

It will be noted in Figure 1 that for each load the total deformation or settlement can be divided into permanent deformation and elastic deformation. The permanent deformation represents consolidation or plastic flow in any or all of the components of the layered system including the subgrade. The elastic deformation or rebound is caused by the compressibility of entrapped air or other gases.

The data in Table 1 show that with any one load, elastic deformation, deflection or rebound, whichever it is called remains practically constant when the application of the load is repeated.

In discussing the paper, first, the significance of the deflection test results depends on the age of the pavement. If the tests are made at the time of construction or soon thereafter, they might reveal both permanent deformation and elastic rebound. On the other hand, if they are made after the pavement has been in use for some time, the tests will indicate only elastic deformation. The reason lies in the fact that pavements which handle satisfactorily the loads for which they were originally designed, will become truly elastic in a comparatively short time.

The writer's second point pertains to the effects of the types of deformation. Consolidation or plastic flow will cause rutting in the traffic lanes regardless of the magnitude of the elastic deflection but does not usually cause cracks of any kind. Cracks of the type that cause break-up are produced by excessive elastic deformation. The excessive deformation bends the surface beyond its flexing limits and, thus, literally shatters the surface.

TABLE 1

EFFECT OF REPETITIVE LOADING ON ELASTICITY

Project	Layer Tested	Plate Area (sq in.)	Load Used (psi)	Elastic Deformation (in)				
				Load Applications				
				1	2	3	4	5
Omaha	12-in. sand gravel base	432	88	0.1475	0 1425	0 1525	0 1400	0.1475
		432	65	0.100	0 095	0 100	0 095	0 100
	12-in. rock base	800	19	0 045	0 045	0 0475	0 0425	0 045
		800	56	0 1225	0 1225	0 1225	0 1275	0 1275
	3½-in. asphaltic concrete wearing surface	800	49	0.220	0 2275	0 220	0 225	0 2275
Dubuque	12-in subbase	432	92	0 1625	0 1675	0 170	0 170	0 1725
		800	62	0 140	0 145	0.1475	0 145	0 145
Waterloo	6-in. base	216	46	0.065	0 0625	0.0675	0 065	0 0675
		216	93	0 1325	0 1275	0 130	0 1375	0 1325

Applying the basic reactions revealed by deflection tests to the results obtained by the authors the writer comes to the following conclusions:

First, that the deflections measured were all elastic because the highway had been in use for two or three years. The fact that the pavement continued to be of service even though it contained large footage of longitudinal cracks shows that the magnitude of the elastic deformation is low.

Second, that the rutting was caused by consolidation in some portion or all of the layered system. It is possible that the bituminous layers alone might have caused all of the rutting.

Third, that the longitudinal cracks are not related to either consolidation or elastic deformation. However, the writer has no explanation for their occurrence.

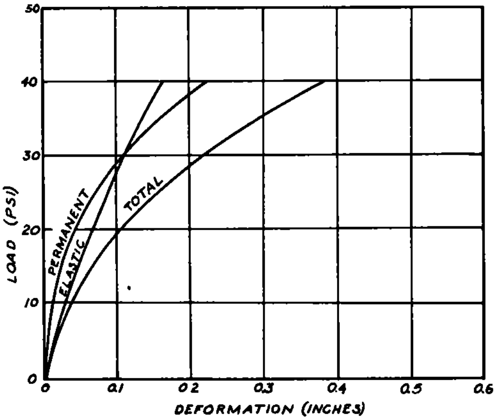

Figure 1. Waterloo Airport test section, 800 sq in. plate on top of subbase.

Fourth, that the apparent correlation of rutting with the magnitude of elastic deformation is no proof that such correlation is sound for the reason that rutting is not related to elastic deformation.

It is evident from the foregoing that deflection tests made after a pavement has been in use for a considerable time do not reveal the cause of rutting. The cause, no doubt, lies in consolidation. This could be proved by making density tests on the components of the layered system and on the subgrade, and then comparing them with densities obtained at the time of construction.