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H-2-49

MEMORANDUM TO: J. R. Harbison
State Highway Engineer
Chairman, Research Committee

SUBJECT: Research Report No. 415; "Deflection Behavior of Asphaltic Concrete Pavements;" KYHPR-70-49; HPR-PL-1(10), Part II; Interim Report on Experimental Construction.

Report No. 340 (September 1972) and W. B. Drake's report to the Kentucky Highway Conference (UK Bulletin No. 99, June 1972) related the construction and early testing of experimental, full-depth asphaltic concrete pavement sections on US 60 between Ashland and Cannonsburg. This report relates the continuation and progress of the testing and evaluation program. Several observations and apparent relationships developed in the interim seemed worthy of reporting at this time. However, the information and data may be of more interest to the mechanists than to designers.

Respectfully submitted,

Jas. H. Havens
Director of Research

JHH/sh
Attachment

cc's: Research Committee

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16. Abstract Deflection responses of a series of experimental test sections were obtained layer by layer during construction, upon completion of construction, and subsequent to construction. Deflections were obtained by use of Benkelman beams, the Road Rater, and the Dynaflect. Test results from one location within each test section were analyzed to determine which relationships were, or were not, meaningful. This was done as a pilot study and as a preliminary step toward final analysis of the data bank. The analyses are presented in this report.			
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Research Report
415

**DEFLECTION BEHAVIOR OF
ASPHALTIC CONCRETE PAVEMENTS**

INTERIM REPORT
KYHPR-70-49, HPR-PL-1(10)

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in cooperation with the
U. S. DEPARTMENT OF TRANSPORTATION
Federal Highway Administration

The contents of this report reflect the views of the authors who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Bureau of Highways of the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

January 1975

INTRODUCTION

The most meaningful, externally measurable structural response of a pavement is the deflection and rebound of the surface under known loading conditions. Measurements have advanced from plate-bearing tests to the Benkelman beam, vibrators, the Dynaflect (1-5), and the Road Rater (6). Interpretations have advanced through two-layer and multilayer elastic and visco-elastic theories. Test values varied with pavement temperature. Methods of estimating temperatures at depth and temperature-modulus relationships have been developed (7). It is now possible to analyze pavement structures very mechanistically.

This report relates test results obtained from a series of experimental pavement sections on US 60, near Ashland, Kentucky, as built, layer by layer, from the ground up and at intervals after opening to traffic (6). The site is shown in Figure 1; test sections are shown in Figure 2. Tests included (1) nuclear moisture-density and asphalt content tests, (2) Benkelman beam measurements, (3) Road Rater measurements, (4) Dynaflect measurements, (5) in-place CBR determinations, and (6) measurements of pavement temperatures. A previous report (6) contained the paving schedule, test schedules, and some preliminary test results and data. Some tests were not performed as planned because the progress of construction did not match the testing plan. Some limitations on testing were:

1. The paving contractor was able to prepare the subgrade for paving in relatively short lengths such as 300 to 600 meters (1000 to 2000 feet) at a time.
2. Such relatively short lengths permitted the contractor to pave one layer and to start placing the next layer over the same length in the same day.
3. Layers which were overlaid in less than a 3-day period prevented Benkelman beam testing because the probe point indented the pavement surface and gave unsteady and unreliable readings. Tire marks and dents were also imprinted by the 80-kilometer (18-kip) axleload. The Road Rater bearing area also left indentations if the surface was too tender.
4. The first layer of the sections having a 50.8-mm (2-inch) thickness laid on the subgrade were observed to deflect under the tires of the construction trucks as they backed slowly over the first layer to the paver. The paver was a 7.3-meter (24-foot) wide Barber-Greene SP-50. This construction process caused additional compaction of the inner wheel tracks and has caused some confusion in subsequent analyses.
5. Road Rater tests on asphaltic concrete layers less than 3 days old were virtually meaningless for long-term analyses of future pavement behavior. Such testing can be analyzed in terms of relative constancy and uniformity of the layer. Testing of the individual layers became meaningful only when there was a minimum of 3 days before the paving of the next layer.

ANALYSES

Selection of Test Stations

One station from each design thickness section was chosen randomly for successive testing during and subsequent to construction. Unless otherwise noted, the data for the same 11 test stations were used in the remainder of this paper and provides continuity for investigations of the effects of the variables. Table 1 summarizes pertinent details.

Time Effects

Road Rater test results on a total of 203 mm (8 inches) of bituminous concrete pavement are shown for one station in Figure 3a. The weather and testing conditions for these first 80 hours were very nearly the same. The weather was warm and clear. The air and pavement temperatures were almost identical on each day, and testing was performed at the same hour. Figure 3b shows the Road Rater response for the final 406-mm (16-inch) thickness in terms of days after compaction was completed. The Road Rater test values for the first 80 hours after compaction of the 203-mm (8-inch) layer of Figure 3a were replotted in Figure 3b in terms of days. Data points for both the 203-mm (8-inch) and 406-mm (16-inch) thicknesses can be connected by a smooth curve. Thus, the magnitudes of Road Rater test responses apparently were not definitively related to thickness during the first few days. Further, there are strong resemblances to soil consolidation curves with time. While there are insufficient data to be conclusive, Figure 3b suggests that, during the early days and first few weeks, increases in strength might be separated into primary, secondary, and tertiary stages.

Figure 4 illustrates the variations of deflections with time as additional thicknesses of bituminous concrete were placed and as the seasons changed. The highest equivalent deflection at the standard temperature occurred in September. Seasonal variations appeared to be less than the repeatability of the Road Rater measurements -- some variation can be attributed to the inability to precisely position the test head in exactly the same spot each time. The decrease in the average measured deflection over the long term indicated an increase in the stiffness of the total structure.

Temperature Effects

Changes in temperature cause changes in pavement stiffness and output responses from Benkelman beam and Road Rater tests. Test data should be adjusted to a standard or reference average pavement temperature.

Benkelman Beam -- Deflection measurements in each wheel track of both eastbound lanes, pavement surface temperatures, time of day, and the date were recorded. Figure 5 is typical and shows the effects of average pavement temperatures (temperatures at depth were either recorded or estimated from the surface pavement temperature (7)). The average pavement temperature was defined as the average of the temperatures at the top, middle, and bottom of the asphaltic concrete. While there is scatter of 2

data, a reasonable trend line could be drawn. The ratio of deflections at 15.6 C (60 F) temperature to the deflection at a given temperature produces a smooth curve, such as is shown in Figure 6 (curves for inner wheel tracks at seven test stations). Figure 6 indicates that there might be a relationship between thickness of asphaltic concrete and in-place CBR's. The seven curves were averaged and the average curve transferred to Figure 7. Similar curves were obtained for the outer wheel tracks at the same test stations, and the average of these curves is also shown in Figure 7. The average inner and outer wheel track curves were so close that an average curve was drawn.

Superimposed on Figure 7 are (1) curves for AASHO Road Test pavements (8) having 76-mm (3-inch) and 152-mm (6-inch) crushed stone bases, (2) curves for the three-layered control sections with 305-mm (12-inch) and 483-mm (19-inch) crushed stone bases on the US 60 road test, and (3) Kingham's (9) "A" and "B" curves. Kingham's "A" curve was based upon Benkelman beam test experience with Canadian pavements consisting of approximately 76 mm (3 inches) of asphaltic concrete on 610 mm (24 inches) of crushed stone. Kingham's curve "B" was based upon tests on full-depth asphaltic concrete pavements in Colorado placed directly on weak subgrade.

The deflection-temperature adjustment factor curves have several positions which appeared to be a function of subgrade support. While the average in-place CBR value for US 60 was 18, Kingham's curve "B" has the position of a weak subgrade. This conclusion is supported by the AASHO Road Test pavements. The curve for the AASHO sections having 76 mm (3 inches) of crushed stone base lies closest to the full-depth curves while the 152-mm (6-inches) crushed stone base sections were on a subgrade having a 305-mm (12-inch) improved layer and is closer to Kingham's "A" curve. Thus, the adjustment factor curves for the three-layered pavements on US 60 fall between Kingham's "A" and "B" curves and are in the proper relative positions. The positions of the temperature adjustment factor curves may, therefore, be a function of equivalent substructure support. Closer inspection of Figure 7 suggested that the relative positions of the curves can be expressed on a logarithmic scale of crushed stone base thickness. The scale increases from Kingham's "B" curve for full-depth pavements to his "A" curve for thick crushed stone bases. Thus, apparent discrepancies between Kingham's "A" and "B" curves and Southgate and Deen's (7) temperature adjustment factor curve, based on AASHO Road Test data, now seem to be resolved. The present analyses were insufficient to determine the proper equivalencies and relationships. However, the thickness of the asphaltic concrete pavement did not appear to affect the positions of the temperature adjustment factor curves.

Road Rater – Figure 8 is a typical illustration of the relationship between average pavement temperatures and Road Rater deflections. Analyses such as Figure 8 were made for the 11 test stations. The ratio of the deflection at 15.6 C (60 F) to a deflection at another temperature produced another

set of adjustment factor curves, which are shown in Figures 9 and 10 for frequencies of 20 and 25 cps, respectively. There, too, the positions of the adjustment factor curves appeared to be a function of in-place CBR; but there is also a frequency effect. Additional in-place CBR and Road Rater tests are needed to develop the inter-relationships more fully.

Subgrade Effects

At fourteen stations, both Road Rater and nuclear density-moisture tests were performed on the finished subgrade just prior to paving. Figure 11 shows the relationship between wet and dry densities and Road Rater deflections measured by the sensor located at the center of the loading head. While the correlation appears to be better in terms of wet density, the trend lines indicated an approximate increase of dry density of 56.8 kg/m^3 per 0.01 mm (9 pcf per 0.001 inch) decrease on the Road Rater meter and an increase in wet density of 67.8 kg/m^3 per 0.01 mm (10.8 pcf per 0.001 inch). Attempts were made, without success, to correlate surface deflection with percent compaction.

Wheel Track and Pavement Thickness Effects

Benkelman Beam – Deflections in the inner wheel tracks were generally less than those in the outer wheel tracks. Pavement sections having 76 mm (3 inches) or greater thickness for the first layer produced deflections in the inner paths which were 20 to 25 percent less than those in the outer tracks; those sections with a first layer 51 mm (2 inches) thick produced inner wheel track deflections approximately 40 percent less than those for the outer wheel tracks. These differences might be attributed to drying due to crown and(or) increased compaction of the subgrade in the central portion of the pavement due to the construction trucks backing to the paver.

Road Rater – Figure 12 shows the dynamic surface deflections obtained soon after paving and after about 18 months. Table 1 contains pertinent identification information for Figure 12. While there was a trend of reduced deflection with an increase in pavement thickness, the initial stiffness of the subgrade appeared to have a persisting influence.

Figure 13 illustrates observed differences between deflections in the wheel tracks for the subgrade and asphaltic concrete layers. The lower response magnitudes of the inner wheel tracks during the construction period were thought to be a result of compaction by construction trucks during the paving process. It has been noted that the wide differences between wheel tracks tend to disappear when the thickness of asphaltic concrete reaches approximately 356 mm (14 inches) on the weaker subgrades and 254 mm (10 inches) on the stronger subgrades.

The average deflections for the respective layers at each of the 11 test stations were combined to prepare Figure 14. The heavy smooth curve is an approximation of a best-fit line for all of the data. For a fixed dynamic input force, measured deflections decreased as the structural stiffness increased.

Generally, as the thickness of asphaltic concrete increased, the measured deflections decreased. For thicknesses greater than 102 mm (4 inches), measured deflections decreased at an approximate meter reading rate of 0.000965 mm (0.000038 inches) per 25.4-mm (1-inch) increase in thickness of asphaltic concrete.

The variation in dynamic deflection for a given thickness was dependent upon the stiffness of the supporting structure beneath the newest layer. Deflections of succeeding pavement layers at a given location tended to remain in the same relative, offset position from the mean curve of Figure 14 as the value measured on the subgrade prior to paving. This suggested that improving the subgrade improves the overall pavement structural stiffness and that a greater thickness of pavement is required over a weak subgrade to achieve the structural stiffness desired.

The age of the newest layer at the time of testing directly affected the measured deflections. Figure 14 indicated that there was a greater decrease in measured deflection per unit pavement thickness increase for the third layer than for the fourth layer. The third layer was tested the 6th day after being compacted, but the fourth layer was tested the next day after compaction. The fifth layer was tested 10 days after compaction and showed the greatest reduction in measured deflection per unit increase in thickness.

Deflections of the third layer decreased at approximately the same unit rate as that for the first and second layers, yet the degree of compaction of the third layer was less. Deflections of the fourth layer were almost the same as that for the third layer, yet the degree of compaction of the fourth layer was higher than the third layer. Deflections of the fifth layer decreased at the same unit rate as that of the first to third layers. This suggested that responses to Road Rater inputs are more a function of the stiffness of the total structure beneath the most recently constructed layer and are not influenced nearly as much by the most recent increase in pavement thickness. Also intertwined in this relationship is the effect of the age of the newest layer prior to the Road Rater test. Thus, the relatively high stiffness of Layer 2 overshadowed the relative weakness of Layer 3.

Extrapolation of the best-fit average curve of Figure 14 indicated that a near-zero deflection would be obtained for a full-depth asphaltic concrete pavement of 584-mm (23-inch) thickness for the given dynamic and static forces at the reference average pavement temperature. If the subgrade stiffness is greater than the average value, the "zero" deflection would occur at thicknesses less than 584 mm (23 inches) and vice versa. Had the percent compaction of the third layer remained at a minimum of that of the second layer, the zero deflection would have occurred at an approximate thickness of 483 mm (19 inches).

The inter-relationships discussed above would be modified significantly if construction procedures could be scheduled so that each new pavement layer was allowed to "cure" for 20 to 30 days before

placing the next layer. The average curve of Figure 14 would have a much flatter slope. There are indications that the decrease in measured deflection might be as much as 0.00127 to 0.00152 mm (0.00005 to 0.00006 inch) per 25.4 mm (1 inch) of pavement thickness. Though there is insufficient data to provide a firm conclusion, there were indications that stiffness would increase significantly if the final surface layer had been allowed to "cure" for 30 days prior to the opening of the pavement to traffic.

Effects of Static Preloads

Dynamic Deflections -- The static load is applied by the Road Rater to the pavement through the hydraulic cylinders that lower the dynamic head. As the hydraulic pressure is increased, the cylinders push downward with more force, raising the front of the truck and transferring more of the truck weight from the front springs to the pavement. Analysis of one series of tests where the static weight was varied showed that increases in static load increased dynamic deflections measured by the sensors. However, the influence of this effect diminishes with increasing distance from the loading head and with increasing frequencies. The effect of additional static load diminishes as the frequency increases. Additional testing is needed to develop this relationship.

Static Deflections -- The Kentucky Road Rater is the only one manufactured to date which has the capability of measuring static deflections with linear variable differential transformers, LVDT's. This system has been used very little because it is awkward to handle. The Road Rater is mounted on the front of an International Travelall, but the vehicle weight is insufficient to cause the thick pavement sections on US 60 to deflect measurably. The LVDT system has been used on relatively thin pavements with success. The LVDT system was used once where the LVDT reference support beam was placed under the differential of an 80-kilonewton (18-kip) single axle while Benkelman beams were placed between the tires on both ends of the axle. The Benkelman beams measured 0.38 mm (0.015 inch) rebound and the LVDT's measured 0.076 mm (0.003 inch) rebound deflection between the wheel tracks. This test was performed on a pavement consisting of 165 mm (6.5 inches) asphaltic concrete on 305 mm (12 inches) of crushed stone base.

Road Rater-Dynalect-Benkelman Beam Concurrent Tests

In October 1973, Ohio State University and the Kentucky Division of Research conducted a concurrent series of tests using the Benkelman beam, Road Rater, and Ohio State University's Dynalect on the US 60 pavement sections. The tests were conducted as quickly as possible in succession at each station so that pavement temperature would not be a factor. Thus, direct comparison could be made of each test value at each test station. Another warm-weather series would be needed to define inter-relationships more completely. Figures 15 and 16 illustrate the test results.

CLOSURE

Several possible and probable relationships between test methods are suggested; peculiarities of materials have been identified; and some effects attributable to construction practices have been indicated. Hopefully, this report will invite study and perhaps provide a reference for ensuing correlation investigations.

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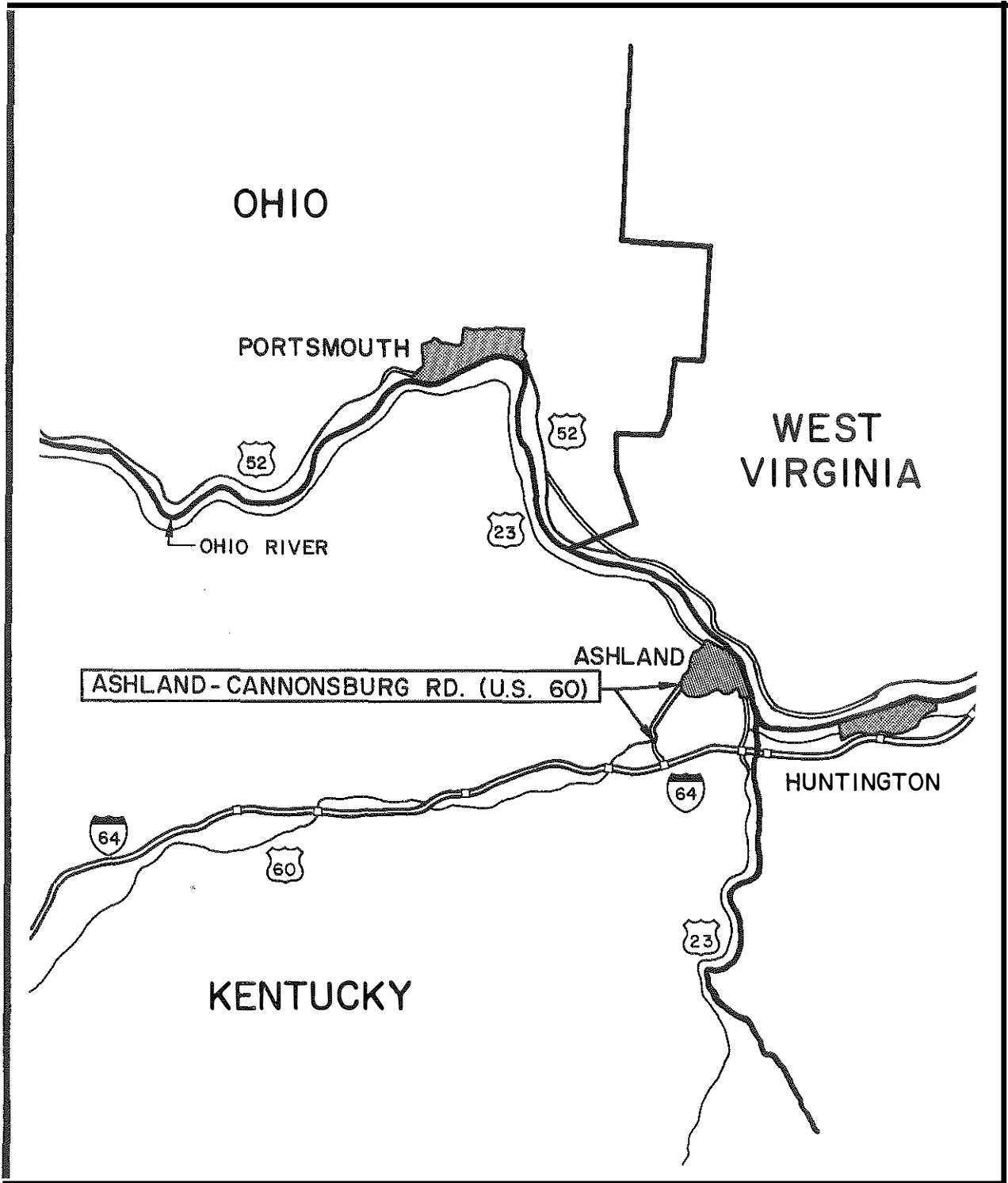


Figure 1. Project Location

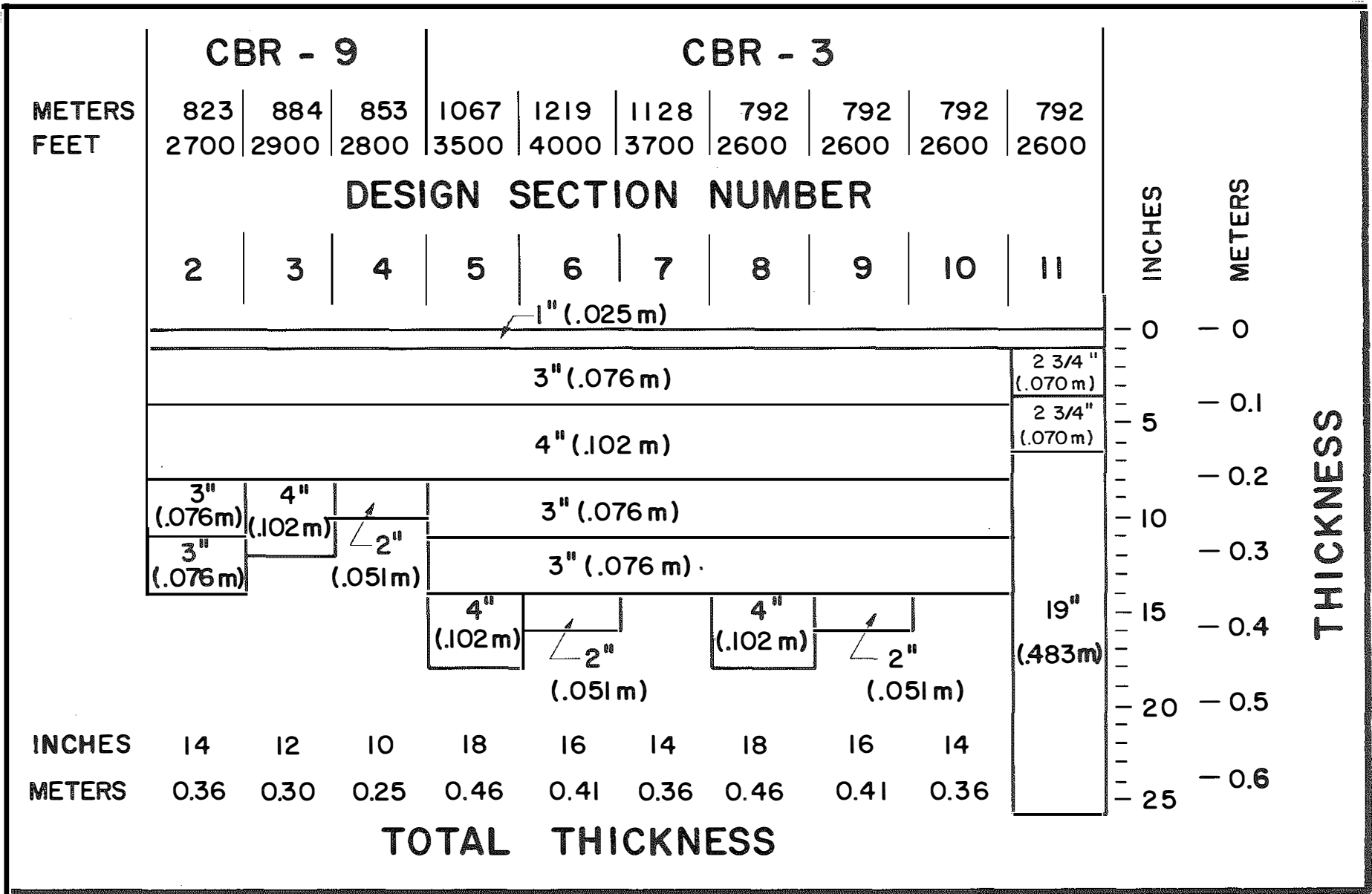


Figure 2. Pavement Section Design Thicknesses and Lengths.

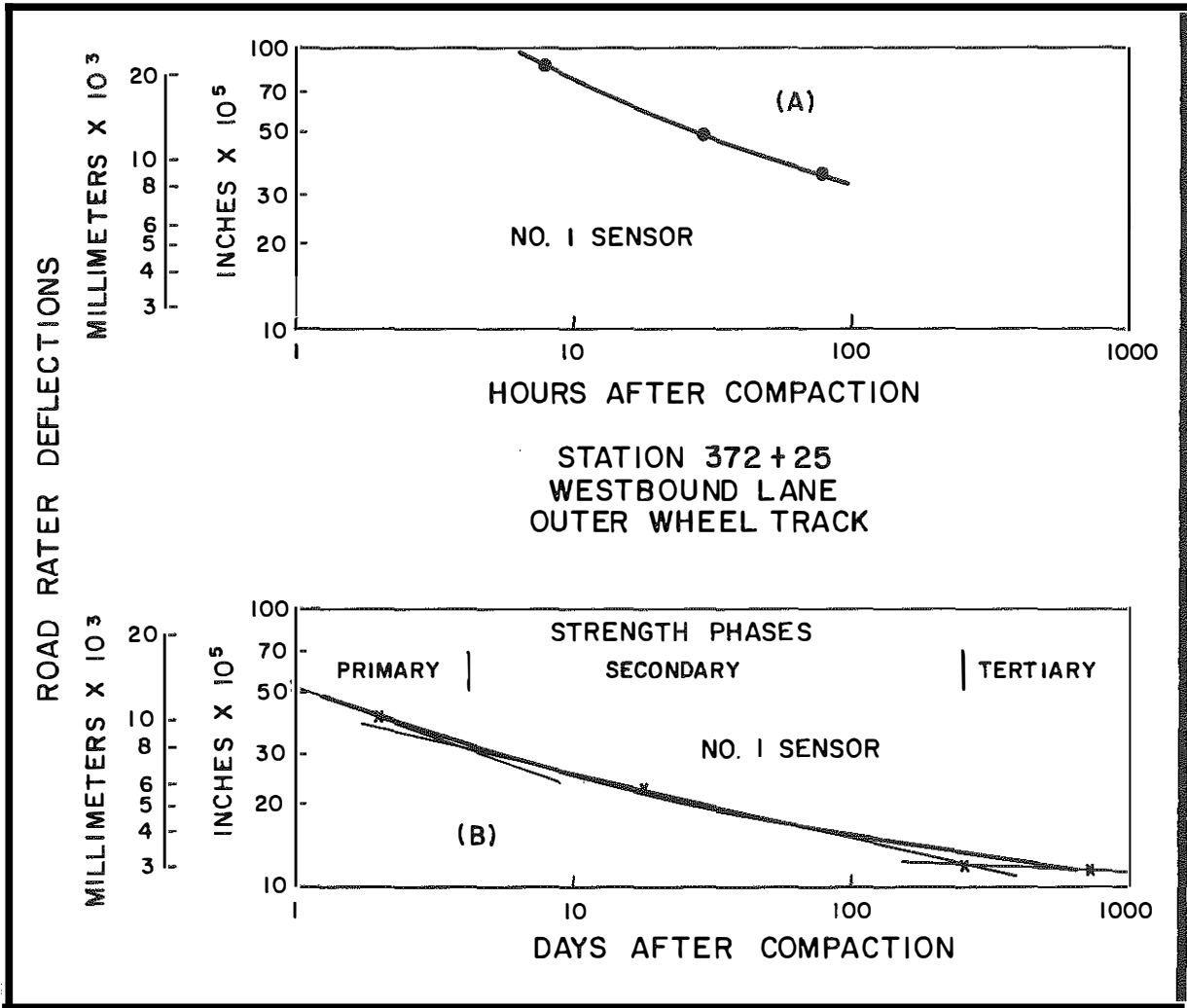


Figure 3. Road Rater Deflection Tests on Asphaltic Concrete Starting 8 Hours after Compaction.

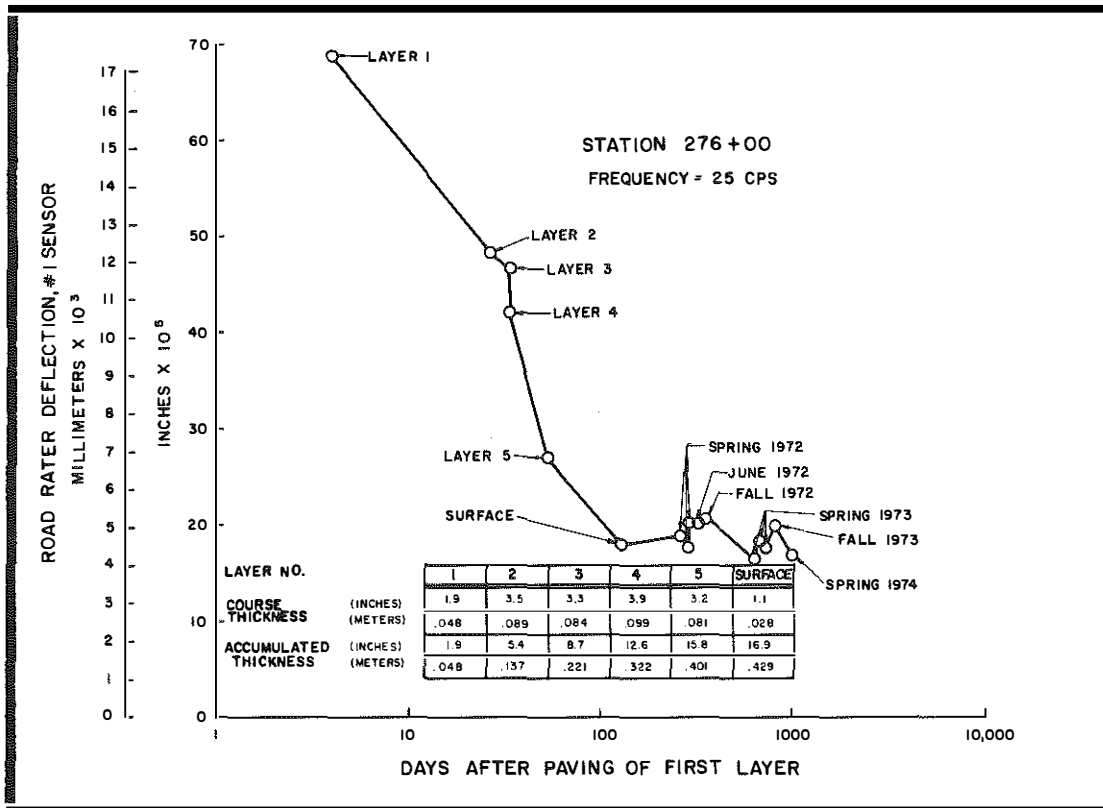


Figure 4. Road Rater Deflection Tests Illustrating Thickness, Season, and Age Effects at Reference Pavement Temperature.

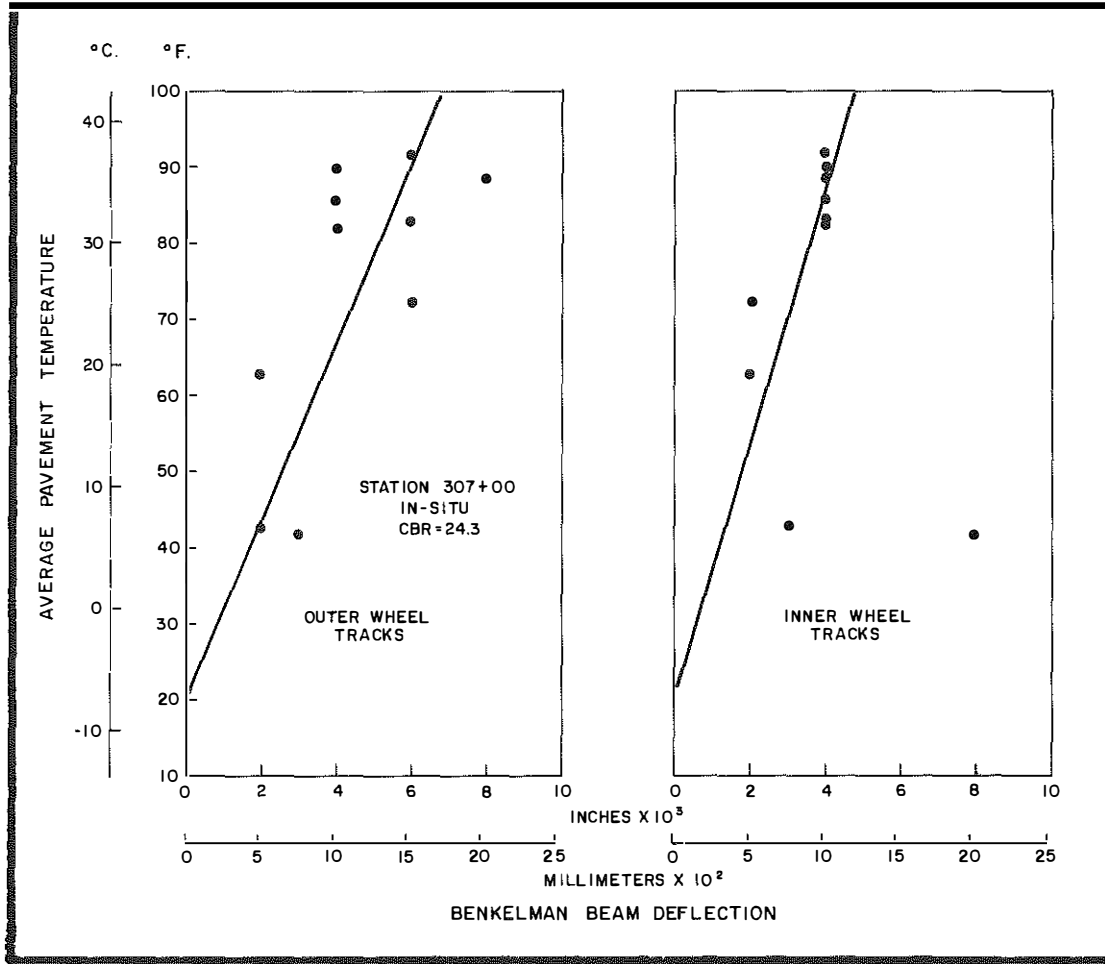


Figure 5. Average Pavement Temperature vs Benkelman Beam Deflections for Inner and Outer Wheel Tracks.

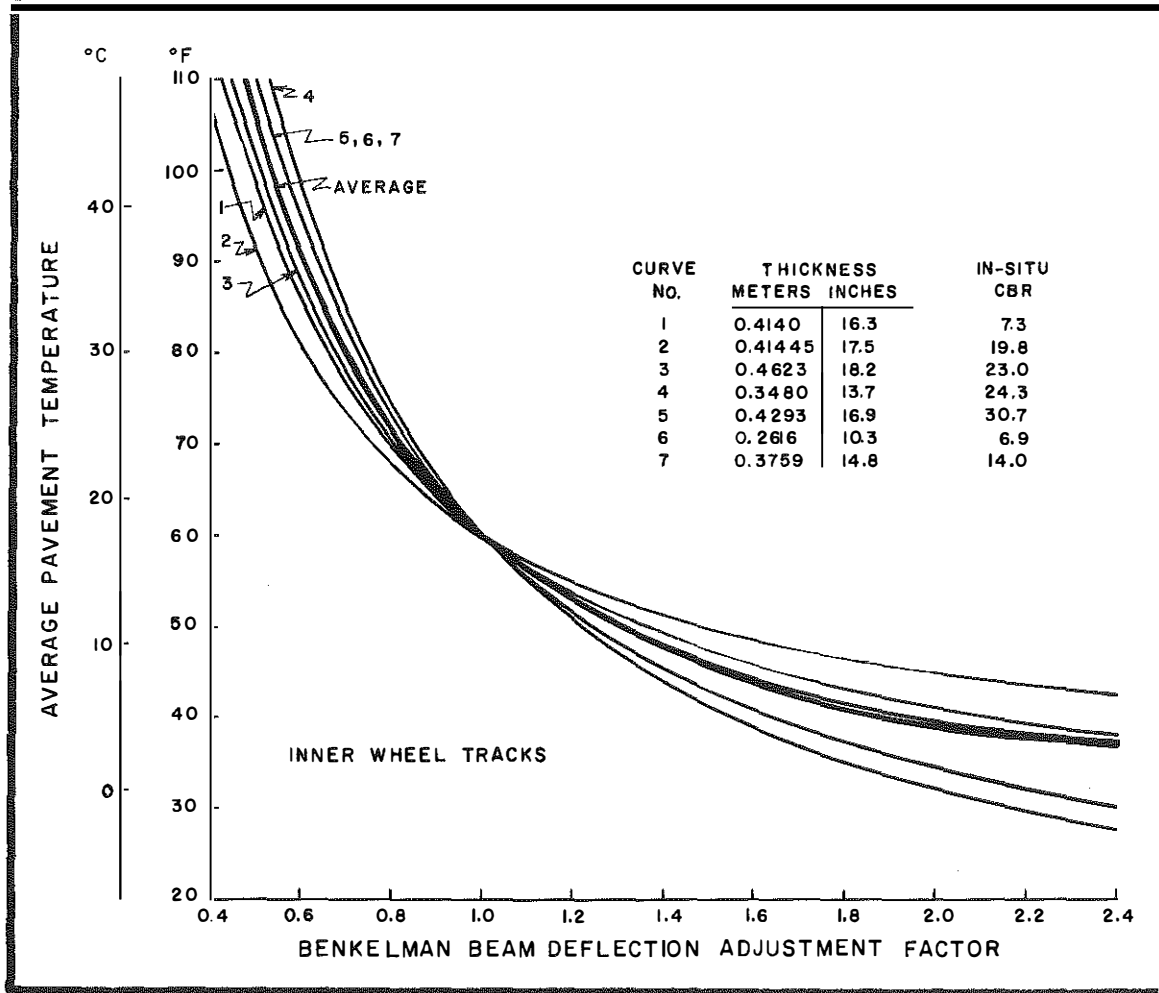


Figure 6. Average Pavement Temperature vs Benkelman Beam Adjustment Factor for Inner Wheel Tracks.

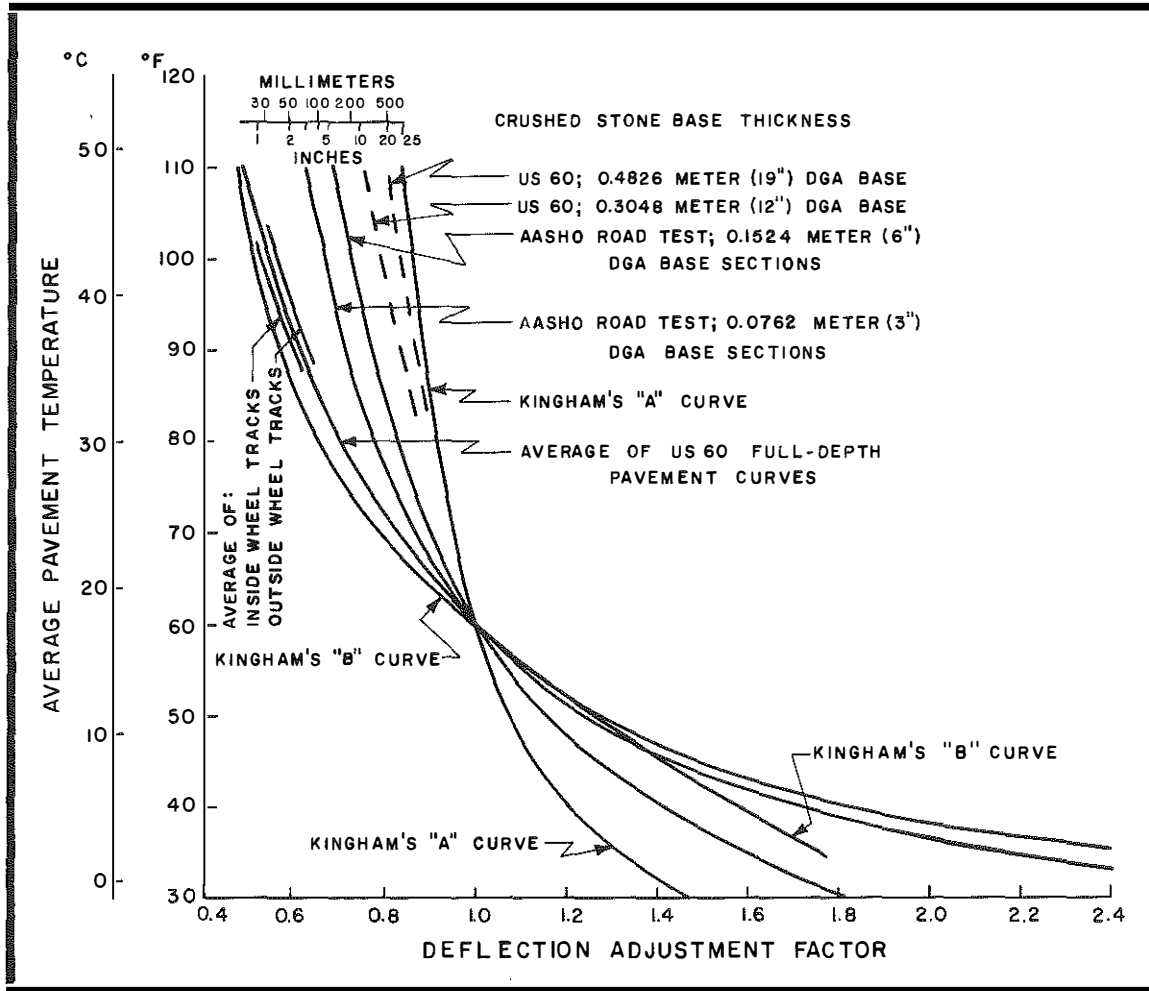


Figure 7. Average Pavement Temperature vs Benkelman Beam Deflection Adjustment Factors for Full-Depth Asphaltic Concrete Pavements.

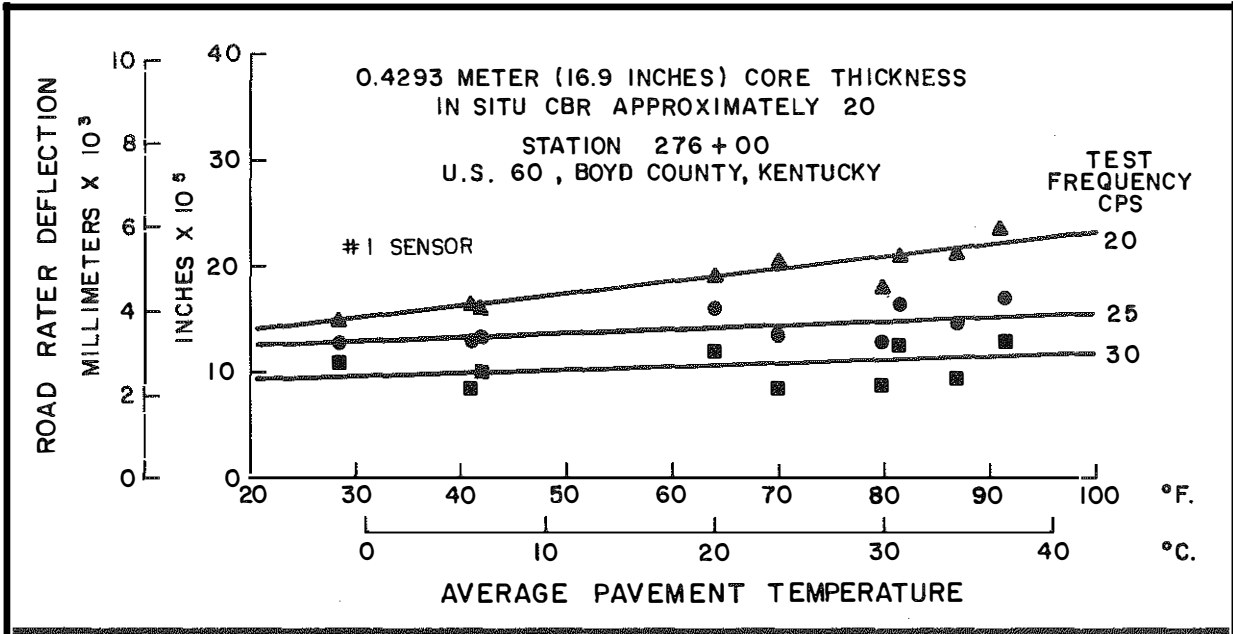


Figure 8. Effects of Average Pavement Temperature and Road Rater Test Frequencies upon Deflection.

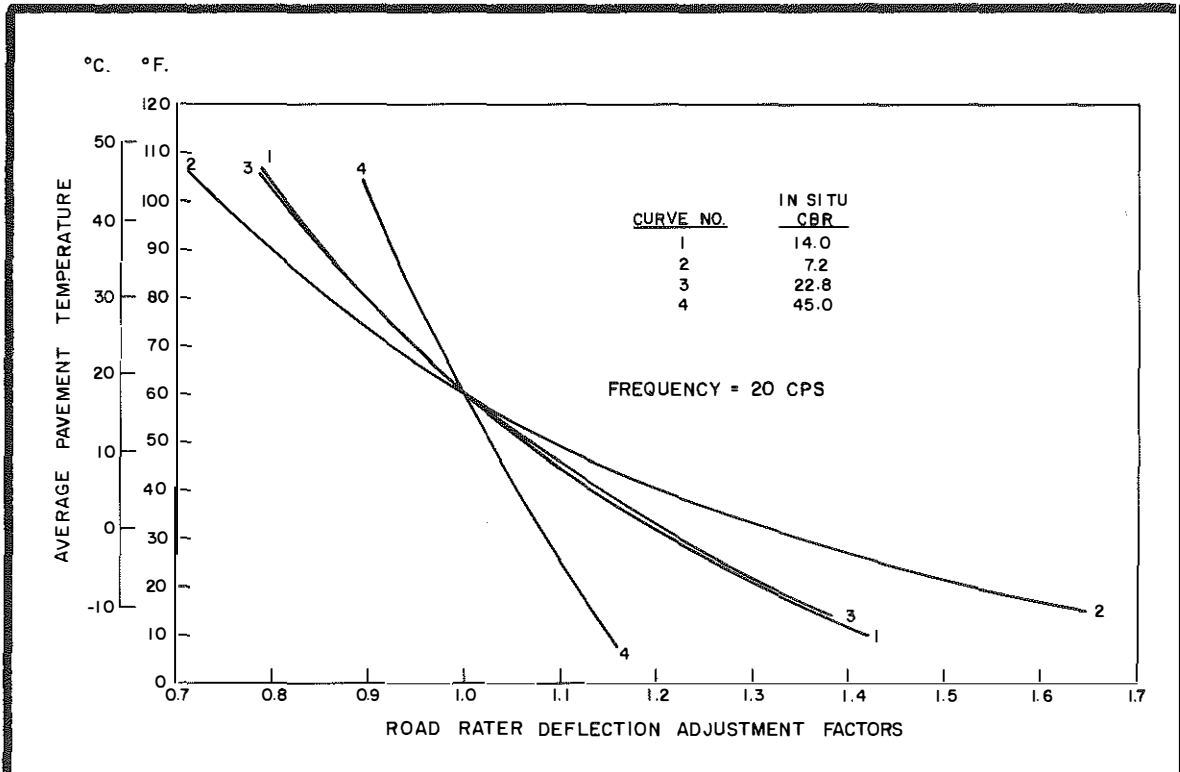


Figure 9. Average Pavement Temperature vs Road Rater Deflections at 20 CPS.

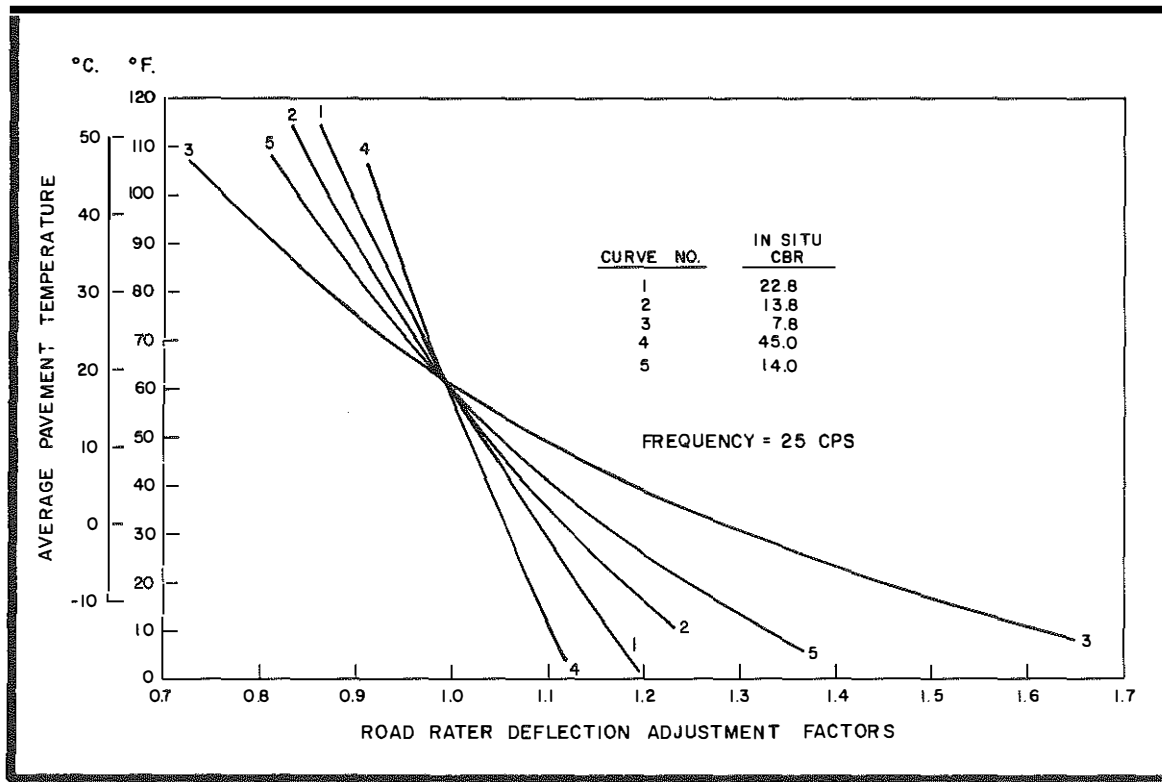


Figure 10. Average Pavement Temperature vs Road Rater Deflections at 25 CPS.

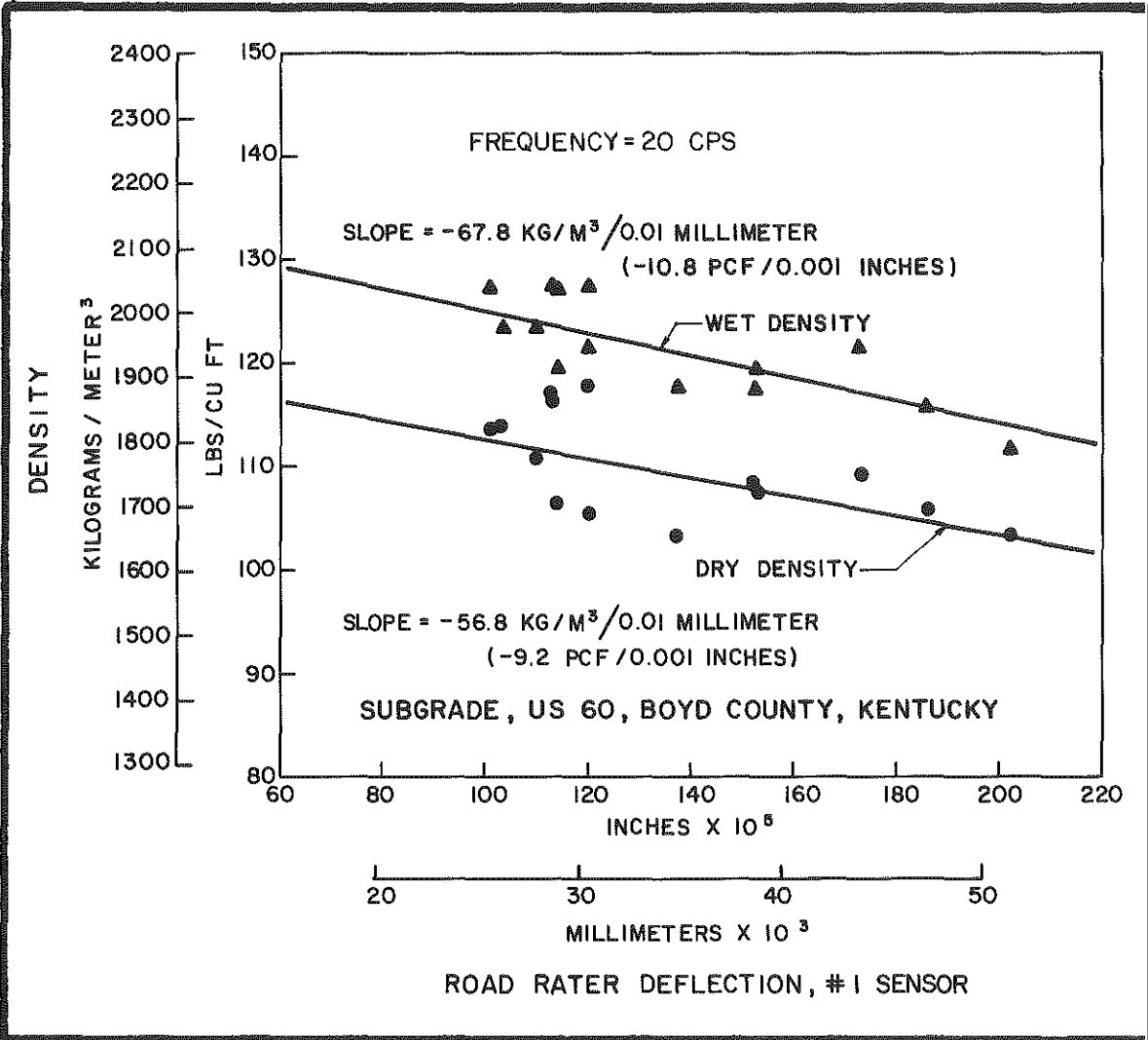


Figure 11. Nuclear Density Test Values of Asphaltic Concrete vs Road Rater Deflection.

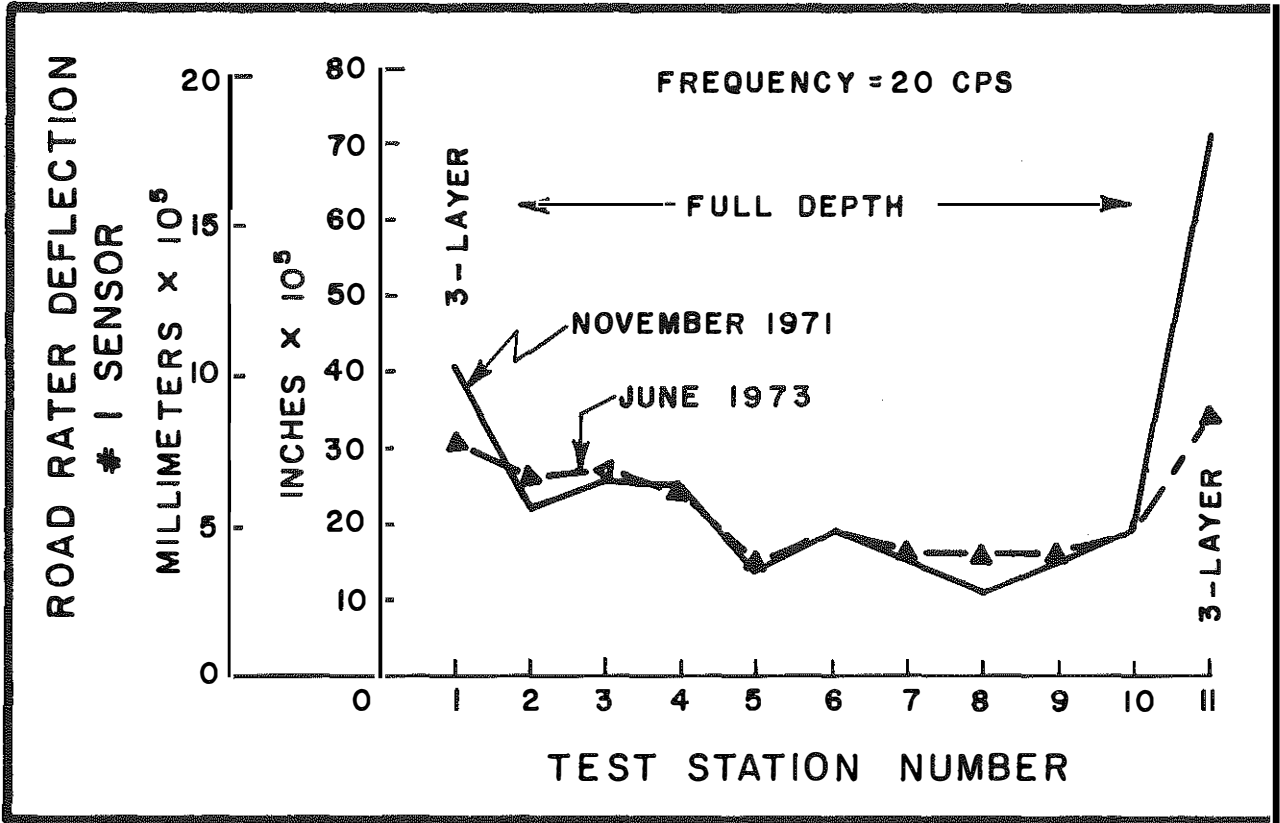


Figure 12. Effects of Time and Pavement Thickness on Road Rater Deflections.

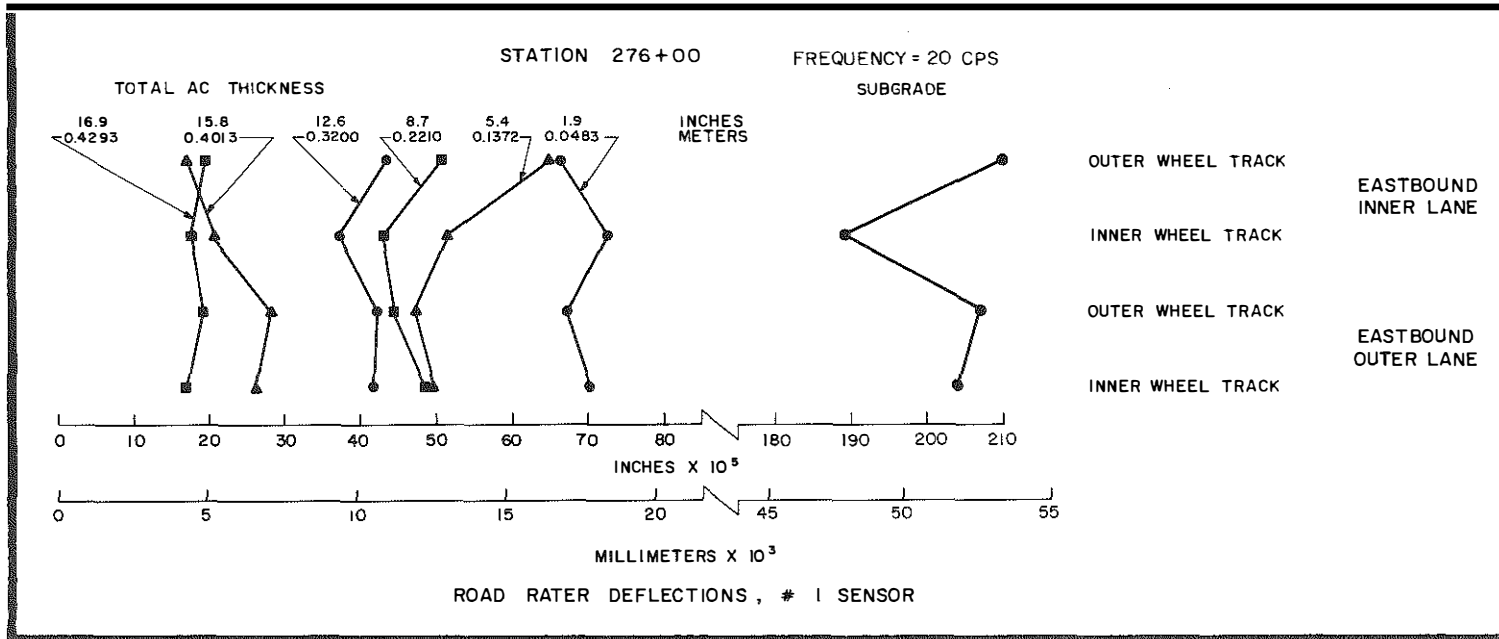


Figure 13. Road Rater Deflections as a Function of Increasing Pavement Thickness and Wheel Track Location.

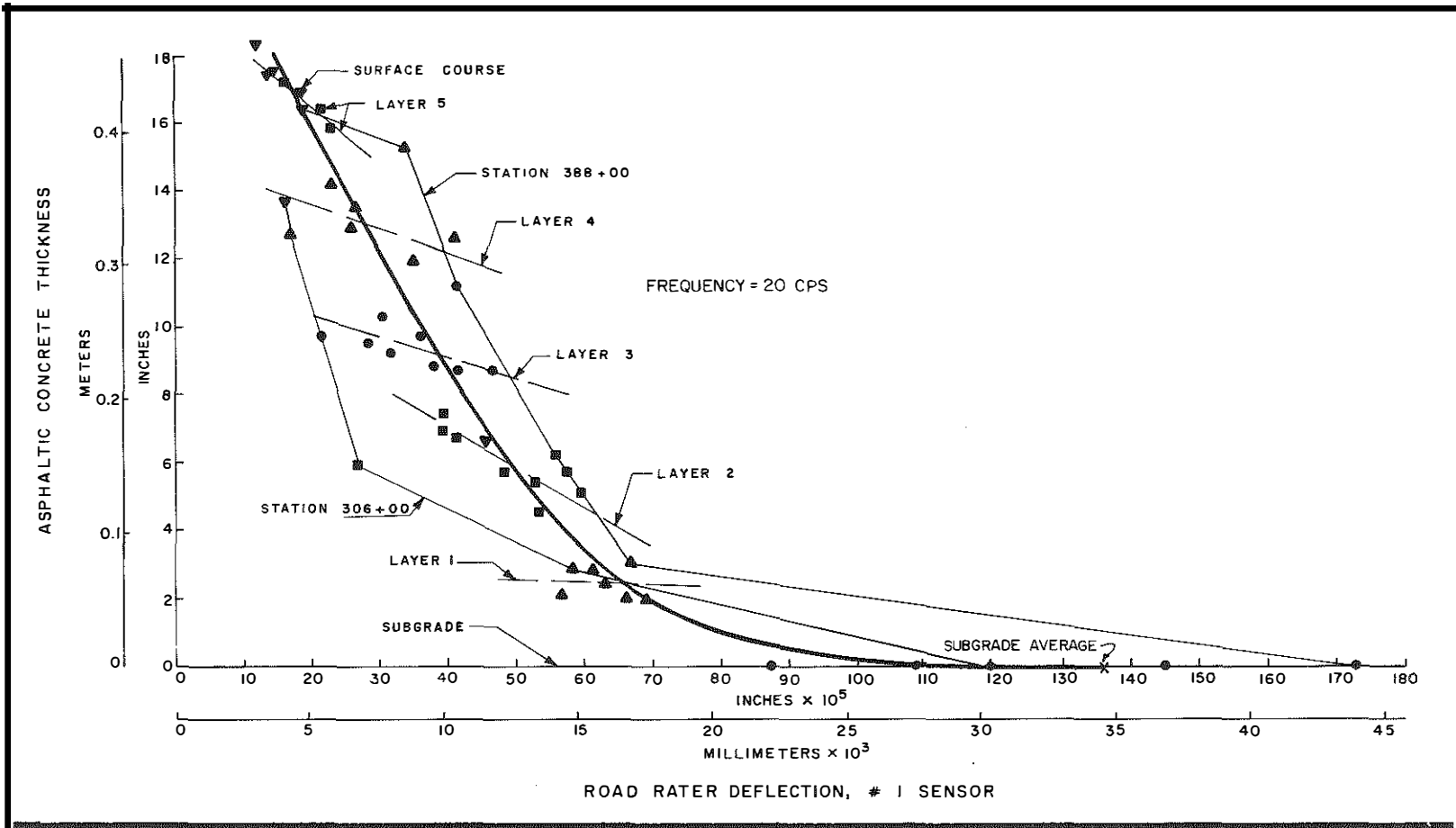


Figure 14. Road Rater Deflections vs Asphaltic Concrete Thickness.

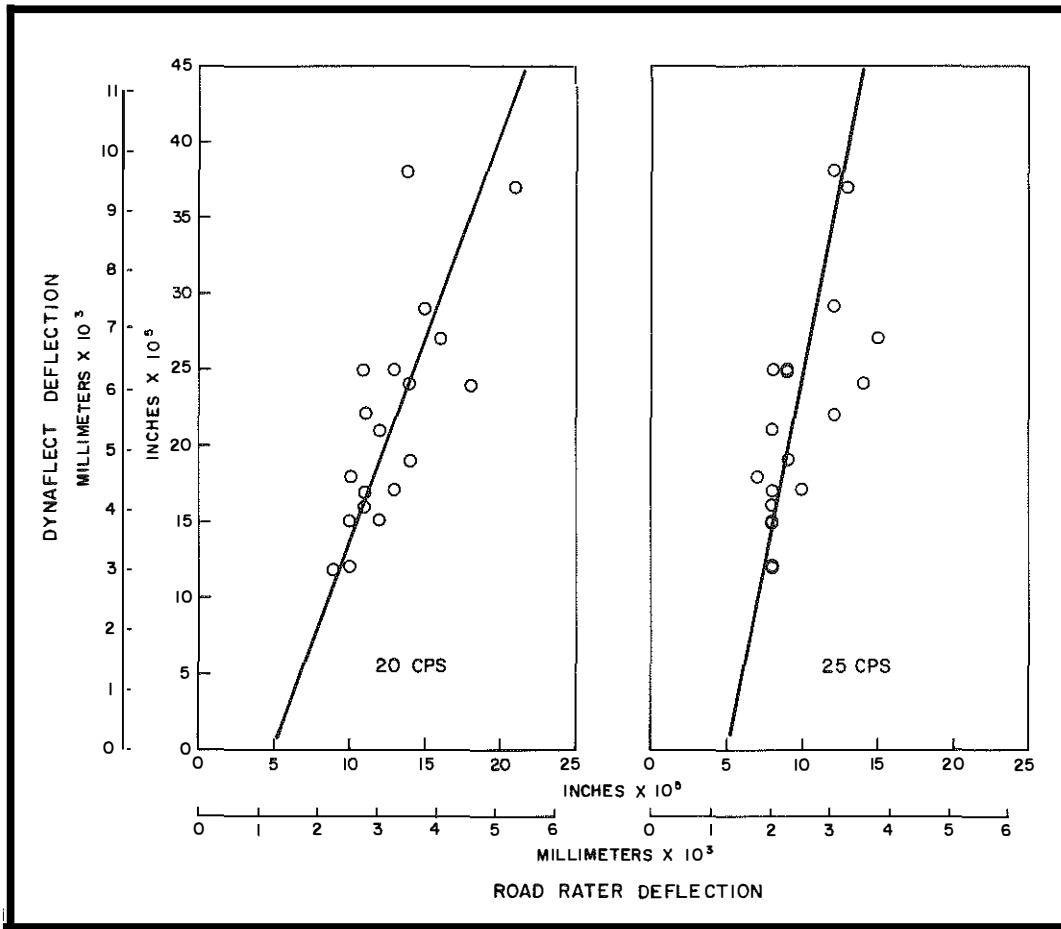


Figure 15. Dynaflect Deflection vs Road Rater Deflection.

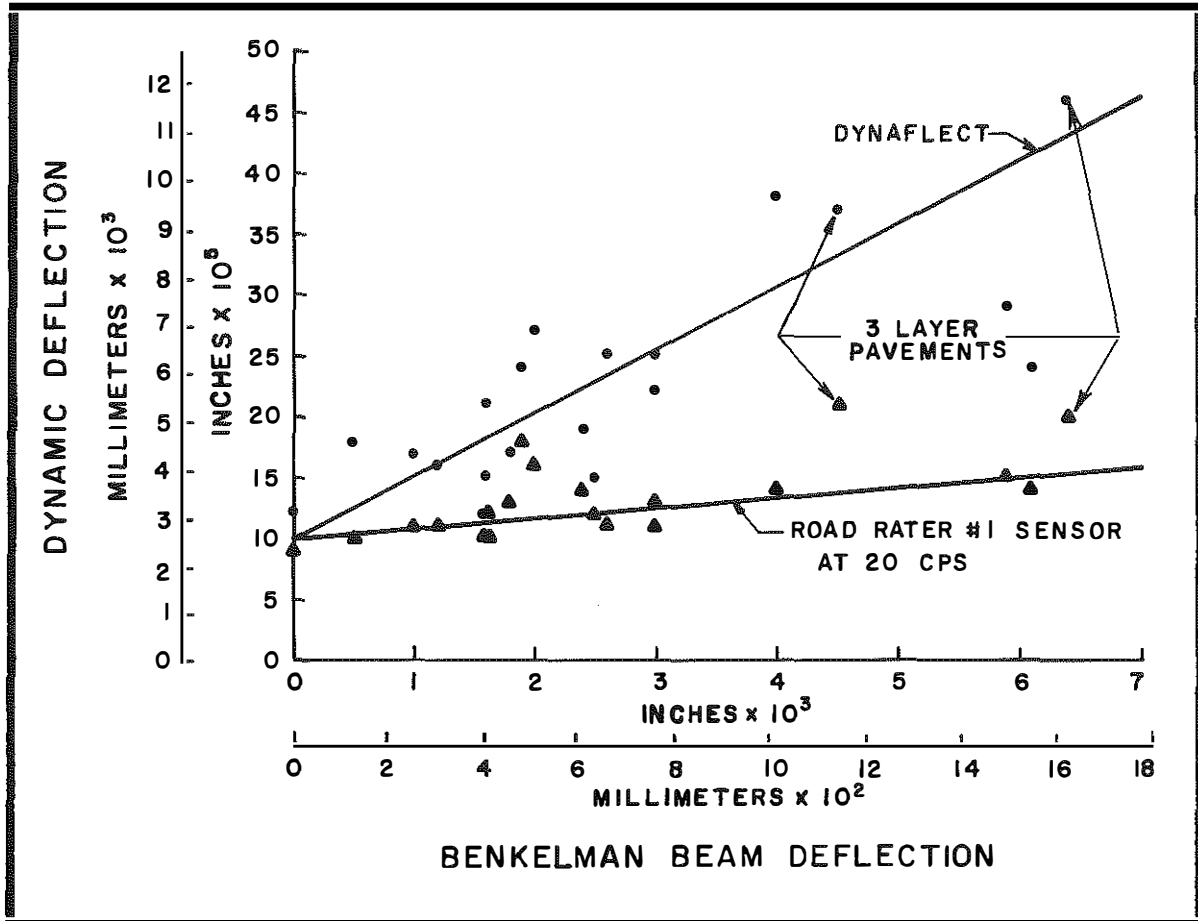


Figure 16. Dynaflect and Road Rater Deflections vs Benkelman Beam Deflections.

TABLE 1
DESIGN AND CORED THICKNESSES

TEST SECTION	TOTAL THICKNESS		LAYER THICKNESSES												IN-PLACE CBR		
			LAYER 1		LAYER 2		LAYER 3		LAYER 4		LAYER 5		SURFACE				
			METERS	INCHES	METERS	INCHES	METERS	INCHES	METERS	INCHES	METERS	INCHES	METERS	INCHES		METERS	INCHES
Design	1	0.165	6.5	0.071	2.8	0.071	2.8							0.025	1.0		
		0.305*	12.0*														
	2	0.356	14.0	0.076	3.0	0.076	3.0	0.102	4.0	0.076	3.0			0.025	1.0		
	3	0.305	12.0	0.102	4.0	0.102	4.0	0.076	3.0					0.025	1.0		
	4	0.254	10.0	0.051	2.0	0.102	4.0	0.076	3.0					0.025	1.0		
	5	0.457	18.0	0.102	4.0	0.076	3.0	0.076	3.0	0.102	4.0	0.076	3.0	0.025	1.0		
	6	0.406	16.0	0.051	2.0	0.076	3.0	0.076	3.0	0.102	4.0	0.076	3.0	0.025	1.0		
	7	0.356	14.0	0.076	3.0	0.076	3.0	0.102	4.0	0.076	3.0			0.025	1.0		
	8	0.457	18.0	0.102	4.0	0.076	3.0	0.076	3.0	0.102	4.0	0.076	3.0	0.025	1.0		
	9	0.406	16.0	0.051	2.0	0.076	3.0	0.076	3.0	0.102	4.0	0.076	3.0	0.025	1.0		
	10	0.356	14.0	0.076	3.0	0.076	3.0	0.102	4.0	0.076	3.0			0.025	1.0		
11	0.165	6.5	0.071	2.8	0.071	2.8							0.025	1.0			
	0.483*	19.0*															
In Place	1	0.142	5.6	0.053	2.1	0.061	2.4							0.028	1.1		
		0.305*	12.0*														
	2	0.376	14.8	0.066	2.6	0.078	3.1	0.078	3.1	0.078	3.1	0.046**	1.8**	0.028	1.1	14	
	3	0.305	12.0	0.089	3.5	0.086	3.4	0.066	2.6	0.036**	1.4**			0.028	1.1	8	
	4	0.262	10.3	0.056	2.2	0.097	3.8	0.069	2.7					0.041	1.6	7	
	5	0.442	17.4	0.091	3.6	0.078	3.1	0.076	3.0	0.097	3.8	0.071	2.8	0.028	1.1	14	
	6	0.429	16.9	0.048	1.9	0.089	3.5	0.084	3.3	0.099	3.9	0.081	3.2	0.028	1.1	31	
	7	0.348	13.7	0.071	2.8	0.078	3.1	0.097	3.8	0.076	3.0			0.025	1.0	24	
	8	0.462	18.2	0.112	4.4	0.076	3.0	0.074	2.9	0.099	3.9	0.076	3.0	0.025	1.0	63	
	9	0.445	17.5	0.051	2.0	0.078	3.1	0.104	4.1	0.094	3.7	0.089	3.5	0.028	1.1	20	
	10	0.414	16.3	0.076	3.0	0.081	3.2	0.127	5.0	0.104	4.1			0.025	1.0	7	
11	0.173	6.8	0.071	2.8	0.074	2.9							0.028	1.1	7		
	0.483*	19.0*															

*Dense Graded Aggregate Base Thickness

**Extra lift required to obtain design thickness