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EVALUATION OF THE DYNAFLECT FOR THE NON-DESTRUCTIVE TESTING OF PORTLAND CEMENT CONCRETE PAVEMENTS

by

GEORGE M. PACE

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DEPARTMENT OF THE ARMY
OHIO RIVER DIVISION LABORATORIES, CORPS OF ENGINEERS
CINCINNATI OHIO, 45227

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SUMMARY

This report presents the results obtained from portland cement concrete pavement testing with the Dynaflect, an apparatus developed by the Lane-Wells Company, for the deflection testing of pavements under dynamic load. Essentially the device was tested to determine if deflection measurements from dynamic loading could be correltated with deflection measurements from static loadings, and thereby relate to allowable loadings on portland cement concrete pavement. Also of interest during the investigation was the performance of concrete pavement at joints to determine load transfer between slabs. The detection of cracking where not visible on the pavement surface, and the extent of pavement deterioration where visible cracks existed were matters for investigation.

The results of the investigation as described herein indicated that:

1. The deflection measurements obtained with the 1000 pound peak to peak dynamic load at a frequency of 8 cycles per second were found to correspond within reasonable tolerances to theoretical deflections that would be expected from static loads of 500 pounds on a range of portland cement concrete pavement thicknesses varying from 6 inches to 24 inches on clay subgrades.

2. Deflection measurements on the only pavement tested on a sand subgrade were not consistent with theoretical deflections based on the Westergaard analysis.

3. Differences in load transfer at joints could be detected with the Dynaflect.

4. A more accurate method of obtaining allowable loadings on rigid pavements was indicated by use of the Dynaflect apparatus through the obtaining of better data in regard to variations in subgrade moduli.

5. Dynamic deflection measurements obtained on cohesive subgrades indicated that a correlation with plate bearing test results could be obtained by means of the Dynaflect apparatus.

6. Indications of slab integrity can be obtained by use of the Dynaflect apparatus.

PREFACE

The study reported herein was made by the Special Projects Branch, Construction Engineering Laboratory, Ohio River Division Laboratories, for the Civil Engineering Branch, Engineering Division, Military Construction, Office, Chief of Engineers. The field testing was accomplished by Messrs. G. M. Pace, G. M. Schanz, and E. M. Cundiff. Dr. Walter E. Fisher participated in the analysis of data. This report was prepared by Mr. G. M. Pace.

Authority for the performance of this work is contained in the "Instructions and Outline for the Evaluation of Equipment for the Non-Destructive Testing of Portland Cement Concrete, FY 1967", and is in accordance with the approved "Long-Range Program - Investigations for Development of Engineering Criteria - Army, FY 1967".

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PART I: INTRODUCTION

Background

1. A means for the non-destructive testing of portland cement concrete pavements to determine such physical properties as strength, thickness, load carrying ability, and the location of cracks or flaws, has long been needed. Most of the work along these lines has been conducted using sonic pulse velocity measurements and attempting, through correlation, to determine the quality of the concrete. Consequently, it seems appropriate that other approaches to this problem be investigated, and this report is presented as an attempt to explore other types of non-destructive tests.

2. As a departure from sonic pulse velocity tests, it was decided to attempt the non-destructive testing of a concrete pavement system by a study of deflection measurements. In this study, it was not contemplated that the flexural strength of the concrete would be obtained, but that the bearing capacity of the pavement system as a whole (i. e. concrete and foundation acting together) would be sought. Previous work on deflection measurements as compared with applied loads had been performed and reports made by Philippe and Mellinger(1), (2)*. Also, deflection measurements have been made on concrete airfield pavements, resulting from loadings by B-52 aircraft(3).

3. The study reported herein is an evaluation of the dynamic deflection device, Dynaflect (trade name) as developed by the Lane-Wells Division of Dresser Industries. The tests were performed during a two month rental period, during which all the deflection measurements with the Dynaflect were made. The deflections of various pavements under standard loadings were observed and an attempt made to evaluate allowable loadings, condition of joints, cracking in the bottom of slabs, and other aspects of rigid pavement performance. This study of the capabilities of the Dynaflect must be considered as preliminary since the length of time that the apparatus was available did not permit complete evaluation of all phases of its performance on concrete pavement.

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* Numerals in parentheses refer to references.

4. Deflection measurements performed on the surface of flexible pavements using a Benkelman beam for comparison with Dynaflect measurements have been performed at the Texas Transportation Institute and satisfactory correlation obtained(4). Insofar as is known this study is the first attempt to correlate Dynaflect deflection measurements with theoretical deflections for rigid pavements. Practically all deflection tests performed in connection with the present study were performed with the Dynaflect apparatus on the surface of concrete pavement. A few tests were performed on flexible pavement and subgrade to observe performance on these materials.

Purpose and Scope

5. The purpose of this study is to determine the applicability of the Dynaflect apparatus to the evaluation of rigid pavements. Since more variety in pavement thicknesses is afforded by a study of airfield pavements, this study has been conducted almost entirely on airfield pavements, the only exception being test pavements at Sharonville, Ohio. Incidental to the airfield pavement tests, a few tests were performed on the prepared subgrade for Interstate Highway 71. This report presents the results of tests performed at five airfields and at Sharonville. Included is a description of the apparatus, test procedures, discussions, conclusions and recommendations in regard to the desirability of future work on this method of rigid pavement evaluation.

PART II: THE DYNAFLECT

General

6. The Dynaflect is a trailer mounted device (Plate 1) which induces a dynamic load and measures the deflections therefrom in pavements. A force generator subjects the pavement to a 500 pound dynamic load at a frequency of 8 cycles per second. The 500 pound load is produced by the counter rotation of two unbalanced flywheels, the generated cyclic force being transmitted vertically to the pavement through two steel wheels spaced 20 inches center to center. The horizontal reactions cancel by virtue of the opposing rotations.

7. The dynamic force varies in sine wave fashion from 500 pounds upward to 500 pounds downward during each rotation. The entire force applied to the pavement consists of the weight of the trailer, about 1600 pounds, together with the dynamic force which alternately adds to and subtracts from the static weight. Thus the peak to peak variation of force during each rotation of the flywheels at the proper speed is 1000 pounds(4).

8. The deflection of the pavement is sensed through a series of geophones spaced as shown in Figure 1 and Plates 1 and 2. A description of the deflection measuring apparatus and calibration of the geophones is contained in Appendix A. A departure from normal procedure was the use of the extension cord at geophone position No. 5 to obtain deflection readings at 7 and 10 feet from the load in addition to the normal readings at 0, 1. 2, 3, and 4 feet. Deflection measurements are expressed in terms of mils (thousandths of an inch)*.

9. Operation. A lift mechanism in the trailer moves the force generator in or out of contact with the ground. When lifted, the trailer is supported on rubber tires for travel at legal driving speeds. With the force generator in contact, (Plate 1b) the unit may be moved on its steel wheels from one measuring point to another at speeds below 5 mph. To enable such moves to be made rapidly, the geophones are raised and lowered by remote control. A complete description of the operation of the Dynaflect is contained in the Operator's Manual issued by the Lane-Wells Company, 1965(5). Operating characteristics are discussed in Appendix A of this report.

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* 1 mil = 25.4 microns

PART III: THEORETICAL CONSIDERATIONS

The Westergaard Analysis

10. Because Corps of Engineers pavement design is based on the Westergaard concept, it was desirable to determine the theoretical deflections, based on Westergaard equations, that would result through loadings of the type applicable to the Dynaflect. Accordingly, plots were made of theoretical deflections of concrete pavement in slab interiors for thicknesses ranging from 6 inches to 24 inches, and subgrade moduli, k, from 50 pci to 500 pci(6). Examples of these plots are shown on Figures 2-7. The Westergaard equations are based on the concept of a dense liquid subgrade. Comparison with actual test results are given in Part VI of this report. The theoretical deflections were obtained from the formula:

$$z = \frac{cp}{k \ell^2}$$

where

p = load (250 lbs per wheel at 20 in. c to c)

k = subgrade modulus in pci

ℓ = radius of relative stiffness = $\sqrt[4]{\frac{Eh^3}{12\,(1-\mu^2)\,k}}$

c = coefficient obtained from plots for various values of spacing in terms of ℓ (Reference 5), e.g. an ℓ of 20 = a spacing of 1 - ℓ, an ℓ of 40 = a spacing of 0.5 ℓ etc. for wheels spaced 20 in. c to c.

E = 4,000,000 psi, modulus of elasticity of the concrete

μ = 0.15, Poisson's ratio for the concrete

z = deflection, in.

h = thickness of slab

The Elastic Solid Concept

11. It was considered that theoretical deflections based on the elastic solid concept for the subgrade would be applicable in making test result comparisons. Accordingly, deflections at the load have been computed using the methods set forth

in Kansas State College EES Bulletin No. 65(7). Comparisons with the Dynaflect test results in slab interiors are given in Part VI herein. The theoretical deflections, using this concept, were obtained from the formula:

$$z = 0.0005 \frac{q\ell^4 N}{D}$$

where

z = deflection, in.

q = intensity of load $= \dfrac{500 \text{ lbs*}}{\text{area of circle of 10'' radius (1/2 - 20'' c to c spacing)}}$

$$\ell = \left(2 \frac{D}{C}\right)^{1/3}$$

$$D = \frac{E_c h^3}{12\,(1-\mu_c^2)}$$

$$C = \frac{Em}{1-\mu_m^2}$$

N = number of blocks on deflection chart(6)

E_c = 4,000,000 psi, modulus of elasticity of concrete

h = thickness of concrete

μ_c = 0.15, Poisson's ratio for concrete

E_m = 15,000 psi, modulus of elasticity for clay subgrade

μ_m = 0.4, Poisson's ratio for subgrade

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* See Paragraph 16 and Appendix B for discussion of intensity of load.

Systems of Elastic Layers

12. Considerable work has been done by Heukelom and others(8) in regard to deflection measurements and vibrations with variable frequencies and wave lengths in order to determine moduli of elasticity of foundation materials in layered systems to considerable depths*. The complexity of this work is beyond the scope of the testing reported herein since the Dynaflect has been designed with only one frequency in an attempt to achieve simplicity and to correlate with static load tests. However, theoretical deflections for slab interior loading, where only one subgrade layer is involved, have been computed using the Heukelom formula:

$$z = \frac{1.5\,pf}{\pi a E_m}$$

where

z = deflection, in.

p = load in pounds

a = radius of loaded area

E_m = modulus of elasticity of subgrade

f = a factor dependent on the ratios of:

$$\frac{E_s}{E_m} \quad \text{and} \quad \frac{h_s}{a}$$

E_s = modulus of elasticity of the slab

h_s = thickness of the slab

Comparisons with actual Dynaflect test results are given in Part VI herein with E_s assumed at 4,000,000 psi, E_m assumed at 15,000 psi for clay, $a = 10$ inches for the radius of loaded area of 2 steel wheels 20 inches c to c.

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* In 1958 this system was used in making dynamic tests for the pavements at the Sharonville Test Track, and E_m for the sandy clay was found to be 18,500 psi. Typical values for E_m according to Heukelom(8) are:

Clay	6,300	-	17,000 psi
Sandy Clay	17,000	-	31,000
Sand	11,400	-	25,600

PART IV: TEST PROCEDURES

General

13. In preparing for the tests with the Dynaflect, it was recognized that deflections obtained at joints would be different in magnitude from those obtained at the midpoint in the interior of slab except in unusual cases. This would also be true at cracks. A test procedure was therefore set up to systematically measure deflection on both sides of a joint or crack as well as in the slab interior (See Figures 8 and 9).

14. The repeatability of the deflection measurements was also of interest. Steps were made to repeat tests at certain locations under varying climatic conditions. Occasionally holding a test in a given location for ten minutes or more to observe any change in readings was also considered desirable.

15. In order to make comparisons between measured and theoretical deflection basins*, an extension of readings to ten feet or more from the point of load application was considered desirable, and as previously stated, an extension cord was attached to the equipment to permit deflection measurements in addition to the standard four feet usually obtained (See Figures 1, 8, and 9).

16. Previous to the testing performed for this study, results for various testing with the Dynaflect apparatus were observed at a number of locations. In considering the peak to peak variation of 1000 pounds of force, it became apparent that the material to which the dynamic force is applied, does not deflect to the full extent corresponding to a static load of 1000 pounds. The dynamics of the pavement system apparently do not permit full depression and rebound during the short period of one-eighth second. Rather, the observed amplitudes of the vibrating movement corresponded to deflections that would be expected with a 500 pound static load, and it was therefore decided to compare Dynaflect deflection measurements with theoretical deflections for a 500 pound static load. As the tests progressed it became apparent that this equivalency to a 500 pound static load, while reasonably suitable for clay subgrades, was not applicable to cohesionless sand subgrades. A discussion of variations in equivalent loadings, with changes in the subgrade, is contained in Part VI and Appendix B.

17. It was also considered desirable to examine the shape of the deflection basins, i.e. whether the basins are circular and symmetrical throughout an expanse of 360°. To do this, it was decided to rotate the deflection measuring devices in several directions using a common point in the pavement for the load application. The use of the extension cord at geophone position No. 5 would also facilitate obtaining the deflection contours for the basins.

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* A deflection basin is defined as the depression formed in the surface of the pavement due to the application of the dynamic load.

18. Other considerations in the testing were:

- a. Variety in the type of subgrade tested
- b. The age of the pavements
- c. Variation in the thickness of pavements
- d. Variable weather conditions.

Program of Tests

19. A program embracing all the test conditions in paragraphs 13 through 18 during the interval of two months for which the rental of the Dynaflect was made, was not considered possible on a comprehensive basis. It was therefore decided to perform as many tests as possible on as large a variety of pavement thicknesses and subgrade conditions as could be scheduled in the time allotted. It turned out that practically all test considerations were included in the program, although some aspects were performed only briefly. However, a preliminary evaluation for more extensive tests in the future was made. The program included testing pavements at four United States Air Force Bases, one Municipal Airport, the Sharonville, Ohio Test Track, and subgrade tests of the pavement foundation for Interstate Highway No. 71, Sycamore Township, Hamilton County, Ohio. The location and general physical properties of these pavements are as follows:

Location of Test Pavements	PCC Thickness, in. Including Overlays	Type of Subgrade	k value, pci, from Plate Bearing Tests
Clinton County AFB, Ohio	7-21 Various Overlays	Sandy Clay (CL)	50-75
Wurtsmith AFB, Michigan	7-21 Various Overlays	Sand (SP)	250
Bakalar AFB, Indiana	6-11	Silty, Clayey Sand (SC-SM)	80
Wright-Patterson AFB, Ohio	10-25 Various Overlays	Clayey Sand and Gravel (SC-GC-GM)	200-350
Lunken Airport Cincinnati, Ohio	7-8	Sandy Clay (CH)	40
Sharonville, Ohio Test Track	12-28 Various Overlays 9" Prestressed	Sandy Clay (CL)	45-85 Varies Higher
Interstate Highway #71 Subgrade Test Only	---	Clay (CL)	---
Various Flexible Pavements at the Above Locations	Various		

Performing the Tests

20. The standard procedure used in performing the Dynaflect tests on concrete pavements included deflection tests at both joints and slab interiors. Typically, the steel load wheels were positioned about 6 inches from a joint in adjacent slab prior to entering a slab for interior tests. In the initial position, geophones 1 and 2 were on opposite sides of a joint with geophones 3, 4, and 5 continuing in the direction of travel toward the interior of the unloaded slab. Figure 8 shows the wheel and geophone positions for this type of test which was designed to measure the vertical displacement at the joint between geophone positions 1 and 2 (Plate 3a). In visualizing this displacement, it may be thought of as a "step up" in the deflection basin. Varying amounts of

"step up" are illustrated in plots on Figures 28 through 30. This "step up" is an indication of load transfer at the joint, large "step up" indicating loose joint continuity and thus poor load transfer.

21. The next typical test was performed with the steel wheels moved across the joint and positioned about 6 inches away with all geophones now in the same slab. Thus the total movement in direction of travel would be about one foot as shown on Figure 9. This test along with the previous test is an indication of total deflection at the joint, which normally would be expected to be greater than the deflection at the interior due to the combined effect of differences in bending, possible loss of subgrade support at the joint, and incomplete load transfer.

22. The third typical test was the normal deflection measurement test performed in the slab interior (Plate 1b) with geophones positioned as in Figure 1. For ease of notation, tests in the interior were designated as "mid slab" or simply "mid". The form for note keeping was the same as designated by the Lane-Wells Company in the 1965 Operator's Manual(5).

23. Tests at cracks were conducted in the same manner as tests at joints. If considerable "step up" was found, cracks were considered as extending completely through the slab. Otherwise the cracks were considered as shallow cracks or surface defects. Tests on flexible pavements or on prepared subgrade were conducted similarly to the slab interior tests.

PART V: TEST RESULTS

Airfield Tests

24. Lunken Municipal Airport, Cincinnati, Ohio. Deflection measurement tests were performed at this airfield on 7 and 8-inch reinforced portland cement concrete pavements. The 7-inch pavements were constructed during the period 1930-32 and were therefore in service about 35 years prior to the Dynaflect tests. The 8-inch pavements of Taxiway A were constructed in 1960 and were in service about 6 years. The other 8-inch pavements varied in construction dates from about 1951 to 1964. All of the pavements except the Proctor and Gamble (P and G) Apron Extension were reinforced. Maximum deflections produced in these pavements during the Dynaflect tests on slab interiors are shown in Table 1. Typical plots of deflection basins are shown on Figures 10-12, and data in regard to deflection tests at joints are shown in Table 7. In this table and in other tables (8-12) depicting joint information of the deflection at the joints is given in terms of the deflection at the slab interior. Thus a figure of 2 in the sixth column of these tables denotes that the deflection at the joints is approximately twice the deflection in the slab interior; a figure of 3 indicates three times the deflection in the slab interior, etc.

25. At Lunken Airport, deflection tests were made weekly for a period of 9 weeks to attempt to find out if any decided trend of variation in deflection occurred with changes in temperature. The range of deflections during the period September-November 1966 is shown in Table 15. The two areas selected for these weekly tests were the 7-inch Municipal Apron and the 8-inch Taxiway A pavements. Plots of the test results are shown on Figures 33 and 34.

26. Clinton County AFB, Ohio. Deflection tests were made at this airfield on rigid pavements, ranging from 7 to 23 inches in thickness. Tests were also performed on several overlays and on a flexible shoulder pavement consisting of 2 inches of asphaltic concrete on a 6-inch base. The subgrade at this airfield consists of sandy clay (CL). Deflection measurements on these pavements at slab interiors and at joints are shown on Tables 3 and 9. Typical plots of deflection basins are shown on Figures 16-18.

27. Most of thes tests at Clinton County AFB were made on 15-16 September 1966, but repeat tests were made in several areas on 8 November 1966 to observe the effect of temperature on the Dynaflect measurements. A tabulated comparison of these tests is shown on Table 17.

28. Wurtsmith AFB, Michigan. The principal reason for the performance of Dynaflect tests at this airfield was to observe the results on a cohesionless (sand) subgrade, as compared to cohesive soil (clay) subgrades at the other airfields.

Pavement thicknesses ranged from 7 inches to 21 inches. Tests were also performed on a 6-inch rigid pavement overlay of a 6-inch soil cement base and on the flexible pavements of the runway overrun. Deflection measurements on these pavements at slab interiors and at joints are shown on Tables 4 and 10. Typical plots of deflection basins are shown on Figures 22-24.

29. Bakalar AFB, Indiana. Deflection tests with the Dynaflect were performed on the rigid pavements at this airfield. Thicknesses of the pavement where tests were performed were 6, 8, and 11 inches where the concrete was non-reinforced, and 10 inches on the reinforced pavement. A few tests were also performed on flexible pavements. The subgrade at this airfield consists of silty, clayey sand (SC-SM) and sandy clay (CL). Deflection measurements on these pavements at slab interiors and at joints are shown on Tables 5 and 11. Typical plots of deflection basins are shown on Figures 19-21.

30. Wright-Patterson AFB, Ohio. Deflection tests were made on rigid pavements ranging from 10 to 25 inches in thickness. Tests on overlays including tar rubber overlays were also made. The subgrade at this airfield is variable but in general, is a cohesive clayey sand or gravel (SC, GC) with some cohesionless silty gravel (GM). Deflection measurements on these pavements at slab interiors and at joints are shown on Tables 6 and 12. Examples of plots of deflection basins are shown on Figures 25-27.

31. Sharonville Test Track Tests. Tests were conducted at the Sharonville, Ohio Test Track on a variety of rigid pavements including overlays and a 9-inch prestressed pavement. The subgrade is generally a lean clay (CL) but with some fat clay (CH). A 12-inch lean mix concrete was used as a base course for two sections of pavement. Tables 2 and 8 show deflections in the interior of slabs and at joints. Plots of typical deflection basins are shown on Figures 13-15.

32. Similar to the Lunken Airport tests, deflection tests were made weekly at the Sharonville Test Track to observe variation in results with changes in temperature. The range of deflections during the period September-November 1966 is shown in Table 16. Plots of test results are shown on Figures 35-38.

Deflection Basin Contours

33. The shape of the deflection basins was examined as cited in paragraph 17, principally through the use of the extension cord for geophone No. 5. Measurements were taken in all radial directions from the point midway between the load wheels of the Dynaflect on various concrete pavements. It was found that the contours of deflections were circular at one foot radial intervals and symmetrical throughout, with only minor deviations.

Subgrade Tests

34. Deflection measurement tests were conducted with the Dynaflect on prepared subgrade during the construction of Interstate Highway 71, in Sycamore Township, Hamilton County, Ohio. This highway pavement was designed to provide a 9-inch reinforced concrete pavement on a 6-inch granular base course (1/2 in. maximum) on a compacted, lean clay subgrade. Tests were first conducted on the compacted lean clay subgrade which was at final grade. A plot of the average of 5 tests on the clay subgrade is shown on Figure 45 showing the deflection basin extending to 10 feet from the center of the loaded area.

35. The second group of tests was conducted on the granular base course (principally sand) which had been rolled and was prepared for concrete pavement placement. These tests did not give consistent results but fell generally into two groupings. Plots of these two groupings are also shown on Figure 45. Deflection readings on the geophones could not be obtained beyond 4 feet from the center of the loaded area.

PART VI: DISCUSSION OF TEST RESULTS ON CONCRETE PAVEMENTS

Comparison of Theoretical Deflections with Actual Deflections, Slab Interiors

36. As previously stated, Figures 2-7 are typical plots of theoretical deflection basins for a concrete slab interior on a dense liquid subgrade for several thicknesses of slabs and values of the subgrade modulus, k, as computed from the Westergaard equations(6). Actual test results were plotted and attempts were made to fit the basins obtained to the theoretical basins for slab interiors using a 500 pound equivalent static load (See Figures 10-27). Deflection comparisons at free edges were not generally made, since many thickened edges for the pavements were found at the airfields making such comparisons infeasible. Also, at small distances in from a free edge the magnitude of deflection changes fairly rapidly, and it was difficult to position the wheels of the Dynaflect at the exact free edge. However, when free edge readings were obtained, they were usually found to be about twice the deflection in the slab interior. This checks previous results obtained on small model studies (See Plates 1b and 3b for views of interior and free edge positions).

37. It was found that for cohesive soil subgrades, the Westergaard theoretical deflection basins for interior loading, were generally consistent with actual deflection basins obtained from the Dynaflect tests. However, for the one cohesionless soil subgrade tested at Wurtsmith AFB, Michigan, deflection basins were not consistent with the theoretical Westergaard deflection basins based on the dense liquid subgrade concept. When arriving at the indicated k values shown in Tables 1-6 from the Westergaard deflection basins, the values are abnormally low at Wurtsmith AFB by comparison with results of previously performed plate bearing tests. Since deflection tests on pavement located on a cohesionless subgrade were made at only one location, it is evident that more data in regard to tests for pavements on cohesionless subgrades at other locations are required before the subject can be adequately treated.

38. When it is stated that the Dynaflect deflection test results were consistent with the Westergaard deflection basins, it is meant that the indicated k values were roughly equivalent to results previously obtained with plate bearing tests. At most airfields about 5 to 15 plate bearing tests have been performed as prescribed by Corps of Engineers' procedures(9), and k values are arrived at from these test results. In many instances test results are averaged and one or two k values are used for the entire airfield area. This is the case at Clinton County AFB, where k values of 50 to 75 pci were used in the evaluation of all the airfield pavements except one overlay. In comparing these k values with the k values indicated by the Dynaflect tests, Table 3, it is seen that most of the k values fall within this range. However, several of the tests indicate the k values to be much higher in some areas, and it is believed that this variation may better represent the actual supporting quality of the subgrade than the overall average. In any event, when most of the indicated k values from the Dynaflect

tests fall within the range of the plate bearing test results, the actual and theoretical deflection basins are considered to be consistent. As stated in the previous paragraph, all deflection basins actual and theoretical, were found to be consistent at all the airfields except Wurtsmith AFB. A comparison of the range of k values obtained with plate bearing tests and with the Dynaflect is given below for the various test locations.

Comparison of Plate Bearing Test Results and Dynaflect Test Results

Location of Test Pavements	PCC Thickness, in. Includes Overlays	Type of Subgrade	k values, pci, Plate Bearing Tests	k values, pci, Dynaflect Tests 500-lb. Equiv. Load
Clinton County AFB, Ohio	7-21 Various Overlays	Sandy Clay, (CL)	50-75	50-150
Wurtsmith AFB, Michigan	7-21 Various Overlays	Sand (SP)	250	50-125
Bakalar AFB, Indiana	6-11	Silty, Clayey Sand (SC-SM)	80	65-150
Wright-Patterson AFB, Ohio	10-25 Various Overlays	Clayey Sand and Gravel (SC-GC-GM)	200-350	130-350
Lunken Airport Cincinnati, Ohio	7-8	Sandy Clay (CH)	40	65-90
Sharonville, Ohio Test Track	12-28 Various Overlays 9" Prestressed	Sandy Clay (CL)	45-85 Var. Higher	60-150

39. In reviewing the above tabulation and considering reasons for the low k values obtained at Wurtsmith AFB with the Dynaflect tests compared to results with the plate bearing tests, the difference in the type subgrade at Wurtsmith AFB compared with the subgrade at the other locations is significant. As previously stated, at Wurtsmith AFB the subgrade is a cohesionless sand while clayey materials in several

forms exist at the other locations. It was surmised that the 500 pound equivalent force attributed to the Dynaflect loading, which produced reasonable results for pavements on clay subgrades, might not be applicable for pavements on cohesionless sand subgrade. An examination of the aspect of a variable equivalent force with variations in the subgrade was made and is included in Appendix B. After some study, it was decided to use an appreciably higher equivalent load at Wurtsmith AFB than at the other locations and observe the results when replotted. This was done and plots are shown on Figures 46-48 for 10, 14, and 21-inch pavements where the dynamic load produced by the Dynaflect is considered to be equivalent to an 850 pound static load. These plots are directly comparable to Figures 22-24 where a 500 pound equivalent load was used.

40. In comparing the two sets of plots (Figures 22-24 with Figures 46-48), it is evident that the higher equivalent load of 850 pounds produces an effect whereby the maximum deflections, which occur at the loaded area, are indicative of k values approximately comparable to the values obtained from the plate bearing tests. However, the shape of the deflection basin as it extends out 10 feet from the load does not follow the normal pattern for the Westergaard theoretical deflections. For example, the basin for the 10-inch pavement shown on Figure 46 begins at a k value of about 250 but cuts across the 200, 150, and 100 lines as it extends toward 10 feet from the load. A similar pattern is shown on Figures 47 and 48. From this, it appears that this method of estimating k values by means of the Dynaflect tests may not be applicable to pavements built on a cohesionless sand subgrade since this type of subgrade does not appear compatible with the dense liquid concept. A preliminary check of theoretical deflection basins computed by the elastic solid concept indicates more compatability with the Dynaflect readings, but further study is required in this regard.

41. In considering another aspect, that of a weak subgrade, and referring again to the tabulation in paragraph 38, the weakest subgrade is shown to be at Lunken Airport where the plate bearing tests indicated a k value of 40 pci. Similar to the method described in paragraph 36, an equivalent static load of less than 500 pounds could be used at Lunken Airport resulting in reduced k values as estimated from the Dynaflect tests. However, very little practical benefits would result from this adjustment since reducing the k value by the small amounts indicated (from about 75 to 40 pci) would have little effect on pavement evaluation.

42. Other comparisons of deflection test results with theoretical values were made using the elastic solid concept(7) and the Heukelom formula(8). To do this, the modulus of elasticity of the clay soil was assumed at 15,000 psi. Only the maximum deflections were obtained for each formula, so the shapes of the theoretical deflection basins were not determined. Clinton County AFB, Ohio was assumed as a typical location with a clay subgrade k value of 100 pci. A comparison of actual with theoretical deflections at Clinton County AFB is given in Table 13, considering the Dynaflect loading equivalent to a static load of 500 pounds. This table shows that the actual

deflections, obtained with the Dynaflect, agree with results calculated theoretically within reasonable amounts for tests on a cohesive subgrade. For tests on the cohesionless subgrade at Wurtsmith AFB, a comparison between the Dynaflect readings and theoretical values is given on Table 14. In this case, the modulus of elasticity for the sand subgrade was assumed at 25,000 psi and the equivalent static load for the Dynaflect at 850 pounds. A plot of these values is shown on Figure 49 which shows the departure of the dense liquid subgrade theoretical deflections from the others, again indicating that this concept of subgrade is not applicable to cohesionless sand. However, further deflection testing on rigid pavements placed on cohesionless subgrades is required before this aspect can be properly evaluated.

Deflections at Joints

43. When a load is placed on one side of a joint (Plate 3a), the joint deflects downward by an amount dependent on the load transfer between slabs at the joint and the subgrade support at the joint. Dynaflect readings taken at a joint with the load applied on one side, with geophone No. 1 showing readings on the loaded slab, and geophone No. 2 showing the first reading on the unloaded slab, produce the amount of vertical displacement or "step up" between the slabs. This is shown on Figures 28-30, with Figure 28 showing a large displacement due to poor load transfer, Figure 29 showing medium displacement, and Figure 30 showing small displacement.

44. Figures 28, 29, and 30 are for illustration of load transfer between slabs and do not depict the relative efficiency between different types of joints. A short study of the relative efficiency of joint types was made, and data are shown in Tables 7-12. More data are required to make firm conclusions, but from the limited amount of information obtained, dowel joints seemed to be performing slightly better than key joints, and key joints slightly better than dummy joints. It seems clear that climatic conditions would also have to be considered in the performance of joints, since joints would be closed during hot weather, when the slabs are in an expanded condition, and the load transfer would be better than during cold weather.

45. In addition to load transfer at joints, subgrade support at the joints was also studied. A large amount of deflection at the joints, even though load transfer between slabs was good, indicated a loss of subgrade support at the joints through pumping or other causes. As stated previously, the sixth column on Tables 7-12 indicates the deflection at the joints in terms of deflection in the slab interior. Where the deflection at the joint was only 1 to 2 times the deflection at mid slab, subgrade support was considered good. Where the deflection at the joints reached greater amounts, subgrade support was not so satisfactory, and where the amount was 3 or 4 times the deflection at mid slab (exceeding theoretical free edge deflection) subgrade support was considered poor at the joints.

Deflection at Cracks and Crack Detection

46. Where cracks were found in slabs, deflection tests were conducted in a similar manner to tests at joints. With the load on one side of a crack, "step up" was observed and conclusions drawn as to whether the crack extended completely through to the bottom of the slab or not. If considerable "step up" was encountered the crack was considered to be completely through the slab; if no "step up" was encountered, the crack was evidently shallow. The amount of deflection was also a factor. If the deflection was greater at the crack than at the joint, the slab was considered cracked through. But if the deflection at the crack did not differ appreciably from deflections in other slab interiors, where no cracks existed, the crack was considered not to have progressed through the slab.

47. At a few locations, deflections in slab interiors were observed to be greater than deflections at the joints. This was evidently a departure from normal. In all such cases it was found that cracking was occurring in the area, and the pattern of deflections for the cracked slabs corresponded to that of the uncracked slabs. It was concluded that cracking existed in the bottom of the slabs even though cracks were not visible at the surface. Several plots of deflections showing such departures from normal, where cracking was presumed to exist even though no cracks were observed on the surface, are shown in Figures 31-32 for pavements at Bakalar AFB. Although these departures from normal are shown in comparison with normal deflections at the interior of the slabs, in all cases the deflections were greater in the slab interiors than at the joints. Another instance of this condition occurred on the 15-inch SAC Apron at Wright-Patterson AFB. Here deflections at mid slab were in the order of 0.16 mils and at the joints 0.12 mils. Cracking existed in this area and it was assumed that it had not progressed to the surface on the slabs tested, which were free of cracks on the surface.

Repeatability of Deflection Measurements and Variations with Temperature Change

48. Excellent repeatability of the test results with the Dynaflect was obtained on a short term basis, i.e., tests repeated after short intervals during the same day produced the same readings. Also testing held in position at the same location for ten minutes or more did not alter the deflection readings. However, it was decided to make repeat tests at approximate weekly intervals to observe variation in test results with temperature. These weekly tests were performed at Lunken Municipal Airport on 7 and 8-inch reinforced concrete pavements and at the Sharonville Test Track on non-reinforced pavement varying in thickness from 11 to 24 inches, a 9-inch prestressed concrete pavement and several overlays.

Repetitive Tests at Lunken Airport

49. The tests at Lunken Airport showed generally a slight decrease in the magnitude of the deflection readings in slab interiors with decrease in temperature, but fluctuations occur which may be connected with periods after rainfalls (See Figures 33 and 34). Tests were conducted 12 September-14 November 1966 and generally dry weather prevailed until October 15 when about 0.5-inch of rainfall occurred; after that, variable weather conditions prevailed. Overall, fluctuations in deflection readings were in the order of 0.2 mils which were within tolerances for expected results for 7 and 8-inch pavements. Where load transfer was good, tests at joints showed very little variation, but where load transfer was poor, variations in vertical displacement (step up) occurred up to about 0.9 mils (See Table 15 for test results).

Repetitive Tests at Sharonville Test Track

50. For the weekly tests at Sharonville, where thicker pavements were tested, variations for slab interior tests were very small, the maximum variation being 0.07 mil for the 12-inch pavement. For these small variations, no trend with temperature change was discernable (See Figures 35-38). Similar to Lunken Airport pavements, when load transfer was good, tests at joints showed very little variation (See Table 16 for test results). The 9-inch prestressed concrete pavement deflection tests also showed very little variation from week to week (See Figure 39 for the deflection basin for the prestressed pavement).

Clinton County AFB Tests

51. Repeat tests were made at Clinton County AFB at an interval of approximately two months. These test results are shown on Tables 9 and 17 for the dates of 16 September 1966 and 8 November 1966. Slab interior deflection tests showed no variation for pavements 17 inches or greater in thickness. However, for the 7 and 11-inch pavements the variation was 0.20 mils and 0.12 mils, respectively. More data are required for the study of deflection test variation with climatic changes, but it seems probable that corrections for temperature and possibly precipitation may be required for pavements below 12 inches in thickness. Again, it may be that for operations in the summer season, no corrections will be required.

Strength of Concrete

52. The determination of the flexural strength of concrete is not feasible from deflection tests at present. However, any decided irregularity in a deflection basin, as compared to basins which would normally be expected, may indicate differences in the bending characteristics of the concrete (See Figure 25). Of course, the differences in

curvature of the basins may also be due to differences in compaction of the subgrade.

53. In general, a flat deflection basin indicates a strong pavement while a steep one indicates a weak pavement. The relative slope of the deflection basin on similar subgrades may therefore be an indicator of pavement strength.

Elasticity of the Pavement System

54. An examination of test results in the 1944 report(1) for the static loading of pavements and the 1951 report(2) for dynamic loadings leads to an inference in regard to deflection measurements. The 1944 tests were conducted with static loadings to failure on 6, 8, and 10-inch portland cement concrete pavement on cohesive subgrades. Later, tests were conducted with traffic tests of known loadings on 12, 15, and 20-inch portland cement concrete, also on cohesive subgrades. Some sections of the pavements were constructed on base courses and some on the natural subgrade. In considering the deflections produced by the static loadings, it was found that although the pavement system, consisting of concrete and foundation, is not a perfect elastic medium, the system acts somewhat elastically until a deflection of about 0.05 inch (50 mils) is reached. After that, a different rate of deflection vs load takes place with failure usually between 0.1 and 0.2 inch deflection. This was also apparent in the traffic testing results in the 1951 report where the statement was made that "where the design thickness is just adequate for the loading, transient interior deflections were about 0.05 inch, as indicated by the 15-inch slabs."

55. Since the deflections on concrete pavements produced by the Dynaflect tests were less than 1 mil, usually in the range of 0.1 to 0.5 mil, the tests are all performed in the range of the presumed elastic pavement system. By projecting the load-deflection diagram, it was considered possible that projected points of pavement failure could be estimated.

Depth of Penetration

56. The depths into the subgrade to which the effects of testing with the Dynaflect penetrate are not known. The Dynaflect is not presumed to be capable of detecting weaknesses in layers several feet below the surface, but is designed to measure the bearing qualities of the pavement system as a whole. However, a reduction in exploratory drilling in the foundation for the design of airfield pavements might be possible as a result of the surface deflection measurements after considerable experience with the equipment.

Effect of Pavement Thickness

57. Dynaflect deflection measurements were made on a range of thickness of portland cement concrete pavement varying from 6 to 28 inches. Deflection readings were obtained throughout this range. A plot of the slab interior deflections vs the pavement thicknesses is shown on Figure 50. The deflections plotted are for all six locations and are not modified by type of subgrade on which the pavements were located. The effect of this plot is to show that even on very thick pavements on strong subgrades, measurements of deflections with the Dynaflect are possible.

PART VII: EVALUATION OF PORTLAND CEMENT CONCRETE PAVEMENTS

Determination of Allowable Loadings

58. Normal Method. The normal Corps of Engineers method for the determination of allowable loadings(10) on rigid pavements is contained in TM 5-827-3. This method proceeds from basic properties of the pavement, namely; the thickness, the flexural strength of the concrete, and the modulus of foundation reaction, k. In making use of the Dynaflect tests in this system, the k values would be verified or new values obtained for various areas of pavement, and the evaluation would proceed in the same manner using measured flexural strength test results and thicknesses of the concrete.

59. The principal using aircraft at Clinton County AFB and Bakalar AFB is the C-119, with twin wheel main gear, 28.5 inches c to c, and 203 sq in. contact area, each tire. Referring to Tables 3 and 5, examples of pavement evaluation comparing the present method of average plate bearing test k values with the Dynaflect test method of k value determination, evaluations would be as follows:

Clinton County AFB

Allowable Loadings for C-119 Aircraft

Pavement Location	Concrete Flexural Strength psi	PCC Thickness, in.	Avg. k Value Plate Bearing Tests, pci	Allowable Load lbs.	Indicated k Value Dynaflect Tests, pci	Allowable Load lbs.
Parking Apron A	750	11	50	113,000	40	109,000
Parking Apron B	750	11	50	113,000	75	117,000
Op. Apron A	740	11	50	110,000	150	130,000
Op. Apron B	740	11	50	110,000	200	137,000
Taxiway B	750	8.5	75	82,000	60	79,000
Runway 14-32 Interior	800	7	75	90,000	100	95,000
Bakalar AFB Allowable Loadings for C-119 Aircraft						
Apron	800	6	80	56,000	125	60,000
Runway Interior 04-22, 13-31	800	6	80	74,000	150	80,000
Apron Taxiway	720	8*	80	73,000	65	70,000
Taxiway No. 1	720	8*	80	73,000	100	77,000
Op. Apron	740	11	80	117,000	60	113,000
Op. Apron Ext.	740	11	80	117,000	40	106,000

* Replaced Slabs

60. From the preceding tabulations, differences in allowable loadings by the two methods of k value determinations vary from about 3 to 25 percent for the C-119 aircraft. The differences result from the averaging of a few plate bearing tests and assigning overall k values, as against k values derived from each pavement facility based on pavement deflection in the particular area. Although differences in allowable loads are not large in most cases, it is believed the pavement deflection method more accurately determines allowable loadings for individual cases.

61. At Wright-Patterson AFB the most severe loadings on the airfield pavements occur as a result of operations by the B-52 aircraft with a twin-twin bicycle main landing gear, 267 sq in. contact area, each tire. Referring to Table 6, comparisons of evaluations using the two methods for the determination of k values for two SAC pavements follows:

Wright-Patterson AFB

Allowable Loadings for B-52 Aircraft

Pavement Location	Concrete Flexural Strength, psi	PCC Thickness, in.	Average k Value Plate Bearing Tests, pci	Allowable Load, lbs.	Average k Value Dynaflect Tests, pci	Allowable Load, lbs.
SAC Op. Apron	760	15	350	440,000	150	316,000
Nose Dock Apron Stubs	760	13	350	363,000	350	363,000

The above difference in allowable loadings by the two methods of evaluation is appreciable for the SAC Operational Apron, and the fact that considerable cracking has taken place on this apron, requiring the replacement of many slabs, may be of significance.

62. At Wurtsmith AFB, the most severe loadings on the pavements are also by B-52 aircraft. However, since this airfield is on a cohesionless subgrade, the dense liquid concept of subgrade does not appear applicable, and the indicated k values shown in Table 4 also not applicable. More data are required on other cohesionless subgrades before proceeding on the basis of revised k values from pavement deflection tests.

63. Deflection Comparison Method. This method consists essentially of comparing the deflections on the strongest, weakest, and intermediate pavements on an

airfield, and formulating curves for allowable loads vs deflections. Allowable loadings on an airfield are usually obtainable from previous computations for many pavements by the normal method(10). By comparing deflections for pavements where allowable loadings are known with deflection test results, allowable loads for a particular gear configuration may be estimated to some extent from the deflections obtained on pavements where load computations have not been made. For example, deflections for individual pavements in type B traffic areas may be plotted against allowable loads computed by the Corps of Engineers' method for 5000 coverages, which take into account the fatigue effect for this amount of traffic. Figure 40 shows a curve for deflection vs allowable load for the C-119 aircraft at Clinton County AFB and Bakalar AFB. Figure 41 shows a similar curve for the B-52 aircraft at Wright-Patterson AFB. This method would usually be applicable to only one airfield whereby the relative strengths of various pavements would be compared. Later, observations at similar airfields in the same vicinity might produce results permitting limited comparisons between airfields as at Clinton County AFB and Bakalar AFB.

64. Direct Proportion. By this method, the pavement system (pavement and foundation) would be considered essentially in the elastic range until a deflection of 0.05 inch or 50 mils is reached. By direct proportion from the deflections produced by the equivalent 500-pound Dynaflect load for a cohesive subgrade to a deflection of 50 mils, a corresponding critical load is reached. This result must then be corrected to gear load on the proper tire contact area, from interior load to edge load where the critical stresses occur, for fatigue effect, and from a gear load to gross load. Results are usually within 20 percent of the allowable loads obtained by normal means, but the method does not appear to be promising due to the many complications and correction factors involved.

Integrity of Pavements

65. Cracking. By making deflection tests on each side of a crack in concrete pavement, and noting the relative vertical displacement (step up) and magnitude of the deflection, determination of the depth of cracking can often be made. As discussed briefly in Part V, where large deflections occur in the slab interior in comparison to deflections at the joints, it is the writer's opinion that cracking almost certainly exists in the bottom of the slab. Also, where appreciable vertical displacement exists between the pavement on each side of a crack, load transfer is at a minimum and the crack extends full depth. However, it should be recognized that in warm periods of the year, the crack may be tightly held together through normal expansion of the slab and vertical displacement may be minimal. Even so, a slab with a crack extending full depth will exhibit a larger than normal deflection. An evaluation of cracking can therefore be made noting not only the quantitative amount of the cracking, but also an indication of the relative severity, whether surface or full depth cracking.

66. Joints. Similar to the cracking information, an evaluation of the joints can be made by deflection testing. Load transfer and the magnitude of deflections can be determined. If deflections at joints are more than three times the deflection in slab interiors accelerated cracking near the joints can probably be expected under continuing traffic. This information can be supplied along with other evaluation data for the airfield pavements.

67. Slab Interiors. Evaluation of the quality of slab interiors can be made by means of deflection testing. As previously cited in paragraph 47, where cracking exists in the general vicinity, deflections in the interior of uncracked slabs which exceed the deflections at joints indicate cracking at the bottom of the slabs even though such cracking does not appear on the surface.

PART VIII: MISCELLANEOUS TEST RESULTS

Overlays

68. Rigid Pavement Overlays. A few deflection tests were made on rigid pavement overlays but not in sufficient amounts to make an adequate analysis. Test results in Table 2 for the Sharonville Test Track on rigid overlays of rigid pavements tend to show the same deflections as for uniform pavements of the total thickness for both layers. The same is true for two overlays of this type at Clinton County AFB shown on Table 3. Three tests on a 16-inch rigid overlay of 3-inch flexible pavement were performed and are also shown in Table 3. No firm conclusions on the basis of this one pavement can be made, but it is to be noted that deflections were consistent with results that would be expected from a 16-inch rigid pavement on a modulus of reaction, k, of 110 pci or a 19-inch rigid pavement on a modulus of reaction, k, of 70 pci. In this case, the 3-inch flexible pavement was on a 6-inch base course of water bound macadam which in turn was on a subbase course of 22 inches of pit run gravel.

69. Flexible Pavement Overlays. Overlays of about 1/2 inch of asphaltic concrete on old 8 1/2-inch rigid pavement were used to improve surfacing at Clinton County AFB. Deflection tests shown in Table 3 show that no appreciable effect on test results was experienced from the overlay. However, the effect of the 2 and 2 1/2-inch asphaltic concrete and tar rubber overlays of 10-inch rigid pavement, at Wright-Patterson AFB, shown in Table 5 was to produce deflections similar to what would be expected from 12-inch rigid pavements.

Flexible Pavements

70. Deflection measurements on flexible pavements are not pertinent to the work reported herein. Studies of this type are being performed at the Texas Transportation Institute, the Saskatchewan Highway Department, and possibly others. However, for comparative purposes, a few tests were performed at two airfields and results are shown on Tables 4 and 5. The shapes of deflection basins for two types of flexible pavement, one consisting of a double bituminous surface treatment on an 8 and 9.5-inch base course, and the other 2 to 3-inch asphaltic concrete pavements on various thicknesses of base course, are shown on Figures 42-44.

Prestressed Concrete Pavement

71. Deflection measurements were made on one prestressed concrete pavement at the Sharonville Test Track and are shown on Figure 39 as a matter of interest. The pavement was 9 inches thick, with prestressing both 200 psi and 400 psi longitudinally and 200 psi transversely. Very little difference in deflection was noted between the 200 psi and 400 psi prestressed pavement (See Table 2).

Subgrade Tests

72. Clay. Deflection tests were performed with the Dynaflect on the prepared subgrade of Interstate Highway 71 in Sycamore Township, Hamilton County, Ohio, just prior to the placing of the 6-inch base course during construction. The subgrade had been proof rolled and was at final grade. This area of the highway was a fill section, and the embankment was a gravelly, lean clay with a k value probably in the order of 75 to 125 pci. A plot of the deflection basin for an average of six test areas is shown on Figure 45.

73. Sand. Deflection tests were also performed on the prepared gravelly sand base course of Interstate Highway 71. The 6-inch layer of base course had been rolled and was at final grade just prior to the placing of the 9-inch concrete pavement. Plots for deflection basins for this material are also shown on Figure 45. The deflection basins for this granular base course are not consistent and extend only 3 to 4 feet from the load before reaching zero deflection. This compares to the readings at 10 feet from the load on the cohesive subgrade. Maximum deflections vary from 0.43 to 1.08 mils in the plots shown. Two groups with data fairly close were averaged in each case, and these are the two plots of deflections on sand shown in Figure 45. One test showed a maximum deflection 1.98 mils and is not shown in the Figure.

74. From the inconsistency of results with the deflection tests on sand, it appears that correlation of the Dynaflect tests with plate bearing test results to arrive at a modulus k value is not feasible. However, such a correlation may be possible for a cohesive subgrade. For example, the area above the curve for the clay subgrade on Figure 45 may be related to the k value of the subgrade.

PART IX: FUTURE WORK

Studies to be Performed with Dynaflect or Similar Devices

75. Subgrade Variables. The present study was performed in a limited time, and it was possible to make deflection measurements at only six locations. All tests were conducted in Ohio and Indiana, in areas where cohesive soil predominate, except for one location, Wurtsmith AFB, Michigan where a sand subgrade exists. Future tests should try to embrace more variety in subgrade conditions. It is suggested that for poor subgrade conditions, tests could be performed at Blytheville AFB, Arkansas and Scott AFB, Illinois, where Mississippi River alluvium subgrade prevails. For intermediate subgrade, tests at Florida, Michigan, and Minnesota airfields could be made. Strong subgrades exist at Griffiss AFB, New York where pavements are on glacial till, and at Loring AFB and Dow AFB, Maine, where due to frost considerations, pavements are placed on 5 feet of base course on a sand subgrade. Tests at airfields are preferred to tests on highways because a greater variety of pavement types and thicknesses exist on airfields.

76. Types of Pavement. More deflection tests are needed on overlays, reinforced pavements, and possibly prestressed pavements to compare and correlate with deflection test results on plain concrete pavements.

77. Deflection Basin Studies. Future work could contemplate studies of deflection basins to observe the steepness of slopes and change of slopes. The shape of the basin may possibly indicate remaining pavement life.

78. Subgrade Modulus, k, and CBR. Correlation of Dynaflect or similar deflection tests with plate bearing test results needs to be undertaken to determine if a simplified procedure for determining k values can be found. Correlation with CBR readings might also be undertaken.

79. Modifications to Equipment. It may be desirable to procure a dynamic testing device which would produce larger loads on the pavement for testing thick portland cement concrete pavements while still retaining the mobility and automatic features of the present Dynaflect. More than one frequency of operation may also be desirable as a check on test results.

80. Proof Roller Aspects. Similar to proof rolling, to determine weaknesses in a prepared subgrade prior to paving operations, it appears that the Dynaflect could be used for a subgrade check for weak spots. Detrimental crushing and unnecessary displacement of some materials may take place as a result of proof rolling, whereas this would not occur with Dynaflect testing.

81. Pavement Evaluation. Continued work on the evaluation of the functioning of joints and cracks in pavements as well as the load carrying ability of the pavements could be carried on.

82. Type of Joints. A study of the relative efficiency of key, dummy, and dowel joints could be undertaken by measurements of total deflections, and displacement on each side of a joint.

83. Effect of Temperature Changes. Studies of the effect of seasonal variations in temperature on deflection measurements should be made including frost melting periods.

PART X: CONCLUSIONS

84. Deflection measurements and basins obtained with the Dynaflect on rigid pavements were consistent with computed deflections, within reasonable tolerances, for pavements on cohesive subgrade.

85. Deflection measurements and basins obtained with the Dynaflect on rigid pavements lying on a granular subgrade were not consistent with theoretical deflections based on the dense liquid concept of subgrade.

86. On the basis of comparison of actual and theoretical deflections, the dynamic loading produced by the Dynaflect was considered reasonably compatible with a 500-pound static load with the same points of application for pavement on cohesive subgrades.

87. So far as could be determined, through the limited number of comparisons available, the modulus of reaction, k, obtained with deflection measurements on the surface of the rigid pavements was consistent with plate bearing test results for cohesive soil subgrades.

88. Deflection measurements at joints appeared to indicate the amount of load transfer at a joint, and whether loss of subgrade support had been experienced.

89. Determination of whether a crack on the surface of a slab is a serious structural break or only a minor crack in the slab can be made by Dynaflect measurements.

90. An indication of initial cracks starting in the bottom of slabs, but which have not yet appeared on the surface, can be made by comparing deflection measurements at the joints with deflection measurements in the slab interior. Where the deflections in the slab interior are greater, initial cracking is indicated, or can be expected to occur shortly.

91. Deflection measurements obtained with the Dynaflect were found to be repeatable when made on the same day.

92. When the effect of seasonal temperature changes from week to week or month to month were considered, pavements 12 inches or greater in thickness showed little variation in measured deflections. For thinner slabs more variation was found, and corrections for temperature may be required.

93. The computation of allowable loads on rigid pavements was improved by the use of k values as indicated by the Dynaflect deflection measurements, using the normal Corps of Engineers' system of evaluation. This was shown at Wright-Patterson AFB where a large difference in k value in one pavement area apparently accounted for the cracking that had occurred in that pavement.

94. The determination of allowable loads by comparison of deflections on one pavement with deflections on another and estimating differences in capability of the pavements requires more study before feasibility can be determined.

95. The determination of allowable loadings by projecting a load-deflection diagram to a point of presumed pavement failure did not appear promising on the basis of the tests performed.

96. Future work involving deflection testing on overlays is required before conclusions can be made in regard to overlays.

97. The correlation of plate bearing test results and Dynaflect deflection test results on compacted cohesive subgrade appears feasible from the preliminary data.

PART XI: RECOMMENDATIONS

98. Continued studies of pavement deflection measurements with the Dynaflect are recommended.

99. The study of Dynaflect deflection measurements on compacted subgrades is recommended to determine a possible relationship between these test results and plate bearing test results.

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Table 1

Dynaflect Tests - Slab Interior

Lunken Municipal Airfield, Cincinnati, Ohio

12-14 September 1966
$70^{\circ} - 85^{\circ}$ F

Test Area	Location	PCC Thickness in.	Average Maximum Deflection mils	Indicated* k Value pci	No. Tests
1	Municipal Apron	9-7-9 Reinforced	0.70	65	4
2	Taxiway A (South)	8 Reinforced	0.52	70	3
3	P&G Apron	8 Reinforced	0.38	130	3
4	P&G Apron Extension	8	0.44	90	3
5	Taxiway A (North)	8 Reinforced	0.43	90	5
6	Runway 15-33	9-7-9 Reinforced	0.55	90	3
7	Taxiway B	8 Reinforced	0.49	80	6

*From plots of deflection basins

PCC (Portland Cement Concrete)

Table 2

Dynaflect Tests - Slab Interior

Sharonville Test Track, Sharonville, Ohio

13 September 1966

65° F

Test Area	Location	PCC Thickness in.	Average Maximum Deflection mils	Indicated* k Value pci	No. Tests
Item 72	Track A	28	0.09	**	3
Item 71	Track A	11/17	0.07	**	2
Item 69	Track A	15/17	0.10	**	2
Item 68	Track A	18/8 AC/12	0.10	**	2
Item 78	Track B	24/12 Lean Mix	0.08	150	1
Item 77	Track B	28/12 Lean Mix	0.07	**	1
Item 85	Track C	13 Reinforced/11	0.13	70 (1)	1
Item 83	Track C	17 Reinforced/11	0.10	**	1
West Lane	Prestressed	9 (200 psi)	0.46	75	1
East Lane	Prestressed	9 (400 psi)	0.50	75	1

Table 2 (cont)

Dynaflect Tests - Slab Interior

Sharonville Test Track, Sharonville, Ohio

11 October 1966
60° F

Test Area	Location	PCC Thickness in.	Average Maximum Deflection mils	Indicated* k Value pci	No. Tests
1	Channelized Track	16	0.21	75	1
2	Channelized Track	12	0.24	125	1
3	Overlay Track	16/6	0.14	75 (1)	1
4	Track A	24	0.13	60	2
5	Overlay Track	15/17	0.18	**	3
6	Overlay Track	6/10	0.20	75 (1)	1
7	Overlay Track	9/8	0.22	65 (1)	2
20 October 1966 60° F					
8	Overlay Track	10/6	0.28	50 (1)	2

(1) Considering pavement thickness as total of both sections

* From plots of deflection basins

** Theoretical curves not constructed for these thicknesses

PCC (Portland Cement Concrete) AC (Asphaltic Concrete)

Table 3

Dynaflect Tests - Slab Interior

Clinton County Air Force Base, Ohio

15-16 September 1966
60^{o} - 75^{o} F

Test Area	Location	PCC Thickness in.	Average Maximum Deflection mils	Indicated* k Value pci	No. Tests
1	SAC Operational Apron Ext.	17	0.18	75	5
2	Taxiway Widening	23	0.13	60	4
3	Parallel Taxiway N-End	23	0.13	60	1
4	ADC Dispersal Area (New)	11	0.30	75	4
5	Runway-NE End (22)	21	0.15	50	2
6	Runway-NE End	21	0.11	100	2
7	Runway-NE End, 2nd 500'	19	0.12	125	2
8	Runway-Interior	17	0.19	75	2
9	Runway-Interior	15/7	0.14	60	2
10	Runway-SW End (04)	19/7	0.13	50	2
11	SAC Operational Apron Extension Taxiway	23	0.15	50	2

Table 3 (cont)

Dynaflect Tests - Slab Interior

Clinton County Air Force Base, Ohio

15-16 September 1966

60° - 75° F

Test Area	Location	PCC Thickness in.	Average Maximum Deflection mils	Indicated* k Value pci	No. Tests
12	SAC Operational Apron Txy.	21	0.10	150	2
13	SAC Operational Apron	17	0.13	150	4
14	Hangar Aprons	17	0.13	150	2
15	Hangar Access Taxiway	18	0.11	175	2
16	Op. Apron A (Cracked)	11	0.24	150	2
17	Op. Apron B	11	0.19	200	2
18	Parking Apron D	1/2 AC/8 1/2	0.49	60	2
19	Parking Apron D Finger	11	0.33	75	2
20	Parking Apron C	1/2 AC/8 1/2	0.34	100	2

Table 3 (cont)

Dynaflect Tests - Slab Interior

Clinton County Air Force Base, Ohio

15-16 September 1966

60^{o} - 75^{o} F

Test Area	Location	PCC Thickness in.	Average Maximum Deflection mils	Indicated* k Value pci	No. Tests
21	Taxiway B	8 1/2	0.51	60	2
22	Parking Apron B	11	0.31	75	2
23	Parallel Taxiway	19-21-19	0.15, 0.14-, 0.14+	75	3
23A	Parallel Taxiway	19-21-19	0.13	75	3
24	Closed Runway 14-32	7	0.50	100	4
25	Parking Apron A	11	0.45	40	3
26	Parallel Twy. South End	16 PCC/3 AC/6 W. B. Macadam/22 Pit Run Gravel	0.16	110	3

*From plots of deflection basins

PCC (Portland Cement Concrete) AC (Asphaltic Concrete)

Table 4

Dynaflect Tests - Slab Interior

Wurtsmith Air Force Base, Michigan

28-29 September 1966

45° - 55° F

Test Area	Location	PCC Thickness in.	Average Maximum Deflection mils	Indicated* k Value pci	No. Tests
1	Blast Pavement	2 AC/6 Base	0.82	--	2
2	Hangar Apron 5060	14	0.245	75	2
3	Hangar Apron Taxiway	14	0.26	75	3
4	Hangar Apron	14	0.25	75	2
5	Cracked Area Hangar Apron Taxiway	14	0.35	75	1
5A	Cracked Area Hangar Apron Taxiway	14	0.29	60	2
6	SAC Operational Apron	17	0.215	90	2
7	SAC Operational Apron Taxiway	17	0.185		2
		Transition	0.165		2
		21	0.155	100	2
8	SAC Operational Apron Access Taxiway	21	0.165	50	2

Table 4 (cont)

Dynaflect Tests - Slab Interior

Wurtsmith Air Force Base, Michigan

28-29 September 1966

$45^{o} - 55^{o}$ F

Test Area	Location	PCC Thickness in.	Average Maximum Deflection mils	Indicated* k Value pci	No. Tests
8A	SAC Operational Apron Access Taxiway	21	0.15	60	3
9	NE Connecting Taxiway	21	0.17	50	6
10	NE Warmup Apron	20	0.18	75	3
11	ADC Alert Apron Access Txy.	10	0.36	90	3
12	ADC Alert Apron Access Txy.	7	0.52	100	4
13	Subgrade		1.80	--	1
14	NE-SW Parking Apron	6/6 Soil Cement	0.46	--	2
15	ADC Operational Apron Access Taxiway	10	0.34	90	2
16	SAC Hangar Apron Txy. 5066	14	0.23	75	4

Table 4 (cont)

Dynaflect Tests - Slab Interior

Wurtsmith Air Force Base, Michigan

28-29 September 1966
45^{o} - 55^{o} F

Test Area	Location	PCC Thickness in.	Average Maximum Deflection mils	Indicated* k Value pci	No. Tests
17	ADC Operational Apron Access Taxiway	10	0.29	125	5
18	ADC Operational Apron Access Taxiway	10	0.35	90	3
19	ADC Operational Apron Access Taxiway	7	0.47	125	4
20	ADC Operational Apron Access Taxiway	7	0.45	125	3
21	Maintenance Hangar Apron Taxiway	14	0.23	75	3
22	Maintenance Hangar Apron	14	0.22	75	3
23	Taxiway F	9	0.36	100	3

Table 4 (cont)

Dynaflect Tests - Slab Interior

Wurtsmith Air Force Base, Michigan

28-29 September 1966

45° - 55° F

Test Area	Location	PCC Thickness in.	Average Maximum Deflection mils	Indicated* k Value pci	No. Tests
24	ADC Alert Apron Access Taxiway	7	0.39	150	3
25	NE-SW Parking Apron	6/6 Soil Cement	0.53 0.43	--	2 2
26	SAC Operational Apron Access Taxiway	21	0.16**	50	3
27	Overrun 24 End	Double Bituminous Surface Treatment/ 9 1/2 Base	1.00	--	2
28	Overrun 24 End	3 AC/8 Base	0.88	--	2
29	SAC Alert Taxiway	20	0.17	60	2
30	Runway End (24)	20	0.155	60	2
31	Runway End (24) 1st 500'	21	0.15	50	2

Table 4 (cont)

Dynaflect Tests - Slab Interior

Wurtsmith Air Force Base, Michigan

28-29 September 1966

$45^{o} - 55^{o}$ F

Test Area	Location	PCC Thickness in.	Average Maximum Deflection mils	Indicated* k Value pci	No. Tests
32	Runway End (24) 2nd 500'	20	0.15	60	2
33	Runway Interior (24)	17	0.19	75	2
34	Runway Interior (24) Edge Lanes	15	0.22	75	2
35	Runway Interior (24) Edge Lanes	15	0.20	90	3
36	Runway Interior	17	0.185	75	2
37	Runway Interior Edge Lanes	15	0.21	75	2
38	Runway Interior Edge Lanes	15	0.21	75	3
39	Runway Interior Edge Lanes (06)	15	0.225	60	2
40	Runway End and Taxiway (06)	21	0.145**	50	2
41	Taxiway B	17	0.23	50	3

* From plots of deflection basins based on 500-pound equivalent static load.

** High strength concrete may be indicated by flat curve of deflection basin.

Table 5

Dynaflect Tests - Slab Interior

Bakalar Air Force Base, Indiana

6 October 1966

$65^{o} - 70^{o}$ F

Test Area	Location	PCC Thickness in.	Average Maximum Deflection mils	Indicated* k Value pci	No. Tests
1	Apron	6 (12 1/2'x15' Slabs)	0.62	125	4
2	Apron	6	0.49	150	1
2A	Apron	6	0.61	125	1
3	Apron	6	0.69	100	3
4	Apron (Flexible Pavement)	Seal Coat and Base 10	1.60	--	5
5	Apron	6	0.64	125	5
6	Apron Taxiway	8 Replaced Slabs	0.55	65	4
6A	Apron Taxiway	8 Replaced Slabs	0.93	--	1
6B	Apron Taxiway	6	0.64	120	1

Table 5 (cont)

Dynaflect Tests - Slab Interior

Bakalar Air Force Base, Indiana

6 October 1966
65° - 70° F

Test Area	Location	PCC Thickness in.	Average Maximum Deflection mils	Indicated* k Value pci	No. Tests
6C	Apron Taxiway	8	0.48	90	1
6D	Apron Taxiway	8	0.58	70	1
7	Apron Taxiway Widening	6	0.90	70	3
7A	Apron Taxiway Widening	6	1.29	--	1
8	Intersection 27-31 Runways	6	0.68	100	6
9	Runway End 31, 2nd 500'	6	0.50	150	2
10	Runway 13-31, Interior	6	0.54	150	2
11	Runway 13-31, Interior	6	0.51	150	4
11A	Runway 13-31, Interior	8 Replaced Slabs	0.50	75	3
12	Runway End 13, 2nd 500'	6	0.51	150	2
13	Runway End 13, 1st 500'	6	0.56	140	3

Table 5 (cont)

Dynaflect Tests - Slab Interior

Bakalar Air Force Base, Indiana

6 October 1966

$65^{o} - 70^{o}$ F

Test Area	Location	PCC Thickness in.	Average Maximum Deflection mils	Indicated* k Value pci	No. Tests
13A	Runway End 13, 1st 500'	6	0.73	90	2
14	Overrun	Double Bitum. Surface Treat. 8" Base	1.86	--	2
14A	Overrun	Double Bitum. Surface Treat. 8" Base	1.86	--	2
14B	Overrun	2 AC/6 Base	1.10	--	2
15	Runway End 04, 1st 500'	6	0.59	125	3
15A	Runway End 04, 1st 500'	6	0.84	70	1

Table 5 (cont)

Dynaflect Tests - Slab Interior

Bakalar Air Force Base, Indiana

7 October 1966

40^{o} - 70^{o} F

Test Area	Location	PCC Thickness in.	Average Maximum Deflection mils	Indicated* k Value pci	No. Tests
16	Runway End 04, 1st 500'	6	0.55	150	3
16A	Runway End 04, 1st 500'	6	0.62	120	1
17	Runway End 04, 2nd 500'	6	0.52	150	4
18	Runway 04-22, Interior	6	0.51	150	2
19-21	Not Used - Questionable Readings				
22	Overrun, 22 End	Double Bitum. Surface Treat. 8" Base	1.90	--	2
22A	Overrun, 22 End	Double Bitum. Surface Treat. 8" Base	1.41	--	1

Table 5 (cont)

Dynaflect Tests - Slab Interior

Bakalar Air Force Base, Indiana

7 October 1966

$40^{o} - 70^{o}$ F

Test Area	Location	PCC Thickness in.	Average Maximum Deflection mils	Indicated* k Value pci	No. Tests
23	Overrun, 22 End	2 AC/6 Base	1.59	--	3
24-25	Not Used - Questionable Readings				
26	Taxiway No. 1	8" Replaced Slabs	0.43	100	2
26A	Taxiway No. 1	6	0.61	125	2
26B	Taxiway No. 1	6	0.87	70	2
27	Taxiway No. 1 Widening	6	0.69	100	3
27A	Taxiway No. 1 Widening	6	0.56	140	1

* From plots of deflection basins

PCC (Portland Cement Concrete) AC (Asphaltic Concrete)

Table 6

Dynaflect Tests - Slab Interior

Wright-Patterson Air Force Base, Ohio

13 October 1966
$70^{o} - 75^{o}$ F

Test Area	Location	PCC Thickness in.	Average Maximum Deflection mils	Indicated* k Value pci	No. Tests
1	Apron Area E, PCC Portion	12	0.21	200	5
2	Apron Area E, PCC Portion	12	0.18	200	6
3	SAC Operational Apron (No Cracks)	15	0.16	150	4
4	SAC Operational Apron (No Cracks)	15	0.16	150	5
5	SAC Operational Apron (No Cracks)	15	0.13	150	2
5A	SAC Operational Apron (Crack)	15	0.21	--	2
5B	SAC Operational Apron (Faint Crack)	15	0.16	--	2
6	SAC Operational Apron (No Cracks)	15	0.15	150	4
6A	SAC Operational Apron (Faint Crack)	15	0.16	--	2
7	SAC Operational Taxiway	19	0.10	160	3
8	SAC Operational Taxiway	19	0.10	160	4

Table 6 (cont)

Dynaflect Tests - Slab Interior

Wright-Patterson Air Force Base, Ohio

14 October 1966

$62^{o} - 70^{o}$ F

Test Area	Location	PCC Thickness in.	Average Maximum Deflection mils	Indicated* k Value pci	No. Tests
9	Nose Dock Stub	18	0.10	350	2
10	Nose Dock Stub	13	0.12	350	2
10A	Nose Dock Stub (Cracks)	13	0.22	--	2
11	Nose Dock Stub	13	0.12	350	2
12	Nose Dock Stub	13	0.14	350	3
13	Taxiway 22	18	0.08	300	3
14	Taxiway 22	18	0.07	300	3
15	Taxiway 19	19	0.08	225	4
16	Taxiway 19	19	0.07	225	3
17	SAC Operational Apron Taxiway	19	0.07	225	2
18	SAC Operational Apron Taxiway	19	0.07	225	1

Table 6 (cont)

Dynaflect Tests - Slab Interior

Wright-Patterson Air Force Base, Ohio

14 October 1966
62^{o} - 70^{o} F

Test Area	Location	PCC Thickness in.	Average Maximum Deflection mils	Indicated* k Value pci	No. Tests
18A	SAC Operational Apron Taxiway	15	0.09	--	1
19	Fighter Apron	2 1/2 TR/10	0.24	130	3
20	Taxiway 7	2 AC/10	0.22	130	4
21	Apron F (Edge Portion)	10	**	**	
22	Apron F	2 1/2 TR/10	0.23	130	5
23	Alert Hangar Apron	10	0.25	150	3
24	Alert Hangar Apron	10	0.29	150	3
25	Alert Hangar Apron	10	0.26	150	3
26	Taxiway 10	25	0.08	150	2
27	Taxiway 10	25	0.08	150	2

* From plots of deflection basins
** Marginal area, auto parking - not representative

PCC (Portland Cement Concrete) AC (Asphaltic Concrete) TR (Tar Rubber Concrete)

Table 7

Dynaflect Test Results

Lunken Municipal Airfield, Cincinnati, Ohio

12 September - 15 November 1966

Location	PCC Thickness in.	Construction Year	Avg. Max. Defl. at Mid-Slab mils		Defl. at Joint x Defl. at Mid-Slab Avg.	Approx. Vertical Displacement Between Slab, mils* Avg.	Load Transfer
			Avg.	No. Tests			
			Dummy Joints**				
Municipal Apron	9-7-9 Reinforced	1929-30	0.68	8	2.0	1.11	Poor
Municipal Apron	9-7-9 Reinforced	1929-30	0.70	9	2.0	0.79	Poor
Municipal Apron	9-7-9 Reinforced	1929-30	0.73	6	1.5	0.69	Poor
Municipal Apron	9-7-9 Reinforced	1929-30	0.62	8	2.0	0.99	Poor
Taxiway A (South)	8 Reinforced	1960	0.50	9	1.5	0.17	Fair
Taxiway A (South)	8 Reinforced	1960	0.51	9	1.0	0.10	Good
P & G Apron	8 Reinforced	1951	0.38	2	2.0	0.07	Good
P & G Apron	8	1960	0.44	3	3.0	1.42	Poor
Taxiway A (North)	8 Reinforced	1960	0.44	4	2.0	0.08	Good
Runway 15-33	9-7-9 Reinforced	1932	0.57	2	1.0	0.10	Good
Taxiway B	8 Reinforced	1964	0.54	1	1.0	0.03	Good
Taxiway A (South)	8 Reinforced	1960	0.49	8	1.5	0.24	Fair
			Key Joints**				
Municipal Apron	9-7-9 Reinforced	1929-30	0.66	7	2.0	0.27	Fair
Municipal Apron	9-7-9 Reinforced	1929-30	0.61	8	2.0	0.20	Fair
			Dowel Joints				
Taxiway A (North)	8 Reinforced	1960	0.40	2	2.0	0.07	Good
Taxiway A (South)	8 Reinforced	1960	0.50	8	2.0	0.57	Poor

*Difference in readings between sensors 1&2 when located on opposite sides of the joint (step up).

**Some joints may contain dowels-records not available.

Table 8

Dynaflect Test Results

Sharonville Test Track, Sharonville, Ohio

13 September - 14 November 1966

Location	PCC Thickness in.	Construction Year	Avg. Max. Defl. at Mid-Slab mils Avg.	Avg. Max. Defl. at Mid-Slab mils No. Tests	Defl. at Joint x Defl. at Mid-Slab Avg.	Approx. Vertical Displacement Between Slabs, mils* Avg.	Load Transfer	Remarks
					Dummy Joints			
Item 59	16	1955	0.19	7	2	0.26	Fair	Channelized Test Track
Item 60	12	1955	0.24	7	2	0.29	Fair	Channelized Test Track
Item 50	16/6	1953	0.13	6	2	0.14	Good	Overlay Test Track #2
Item 73	24	1957	0.12	13	2	0.12	Good	Heavy Load Test Track
Item 28	6/10	1953	0.20	6	4	0.21	Fair	Overlay Test Track #2
Item 27	9/8	1953	0.22	7	3	0.33	Fair	Overlay Test Track #2
Item 26	10/6	1953	0.25	5	3	0.48	Poor	Overlay Test Track #2
					**Longitudinal Crack			
Item 69A	15/17	1957	0.16	6	-	0.04	NA	Heavy Load Test Track
Item 69B	15/17	1957	0.17	6	-	0.07	NA	Heavy Load Test Track
					No Joints			
Prestressed	9	1957	0.44	4	-	0.07	NA	----

*Difference in readings between sensors 1 & 2 when located on opposite sides of the joint (step up).

**Tests made on a slab divided by a longitudinal crack. Each half used as a slab and the crack used as the joint.

69A	Readings taken on half slab adjacent to a full slab.
69B	Readings taken on half slab adjacent to the turf.
NA	Not applicable.

Table 9

Dynaflect Test Results

Clinton County Air Force Base, Ohio

16 September and 8 November 1966

Location	PCC Thickness in.	Construction Year	Avg. Max. Defl. at Mid-Slab mils		No. Tests	Defl. at Joint x Defl. at Mid-Slab		Approx. Vertical Displacement Between Slabs, mils*		Load Transfer
			16 Sept.	8 Nov.		16 Sept.	8 Nov.	16 Sept.	8 Nov.	
						Dummy Joints				
Runway B	7	1943	0.50	0.33	13	1.1	2.5	---	0.6	Poor
Parking Apron A	11	1956	0.45	0.33	4	1.5	2.0	0.4	0.5	Poor
SAC Apron Extension	17	1959	----	0.20	6	---	2.0	---	0.3	Poor
Parallel Taxiway	21	1959	0.14	0.14	6	1.0	2.0	Negl.	0.1	Good
						Key Joints				
Parking Apron A	11	1956	----	0.33	2	---	2.5	---	0.6	Poor
SAC Apron Extension	17	1959	----	0.19	3	---	2.0	---	0.3	Poor
						Dowel Joints				
SAC Apron Extension Txy.	17	1959	----	0.23	5	---	1.5	---	0.1	Good
Parallel Taxiway	21	1959	0.14	0.14	6	2.0	2.0	0.11	0.15	Good

*Difference in readings between sensors 1 and 2 when located on opposite sides of the joint (step up).

Table 10

Dynaflect Test Results

Wurtsmith Air Force Base, Michigan

28, 29 September 1966

Location	PCC Thickness in.	Construction Year	Avg. Max. Defl. at Mid-Slab mils Avg.	No. Tests	Defl. at Joint x Defl. at Mid-Slab Avg.	Approx. Vertical Displacement Between Slabs, mils* Avg.	Load Transfer
					Dummy Joints*		
SAC Hangar Aprons	14	1959	0.25	4	4.0	0.8	Poor
SAC Hangar Apron Twy.	14	1959	0.31	3**	4.0	0.7	Poor
Maintenance Hangar Apron	14	1956	0.23	4	3.0	---	Fair
Runway	17	1959	0.19	2	2.0	---	Good
Taxiway B	17	1959	0.23	2	1.5	---	Good
Primary SAC Taxiway	21	1959	0.17	4	2.0	---	Good
					Key Joints		
SAC Hangar Aprons	14	1959	0.25	3	3.0	0.6	Poor
SAC Apron	17	1959	0.21	1	2.0	---	Good
NE Warmup Apron	20	1959	0.18	2	2.0	0.04	Good
					Dowel Joints		
NE Connecting Taxiway	21	1959	0.17	5	1.5	0.06	Good

*Difference in readings between sensors 1 and 2 when located on opposite sides of the joint (step up).

**Tests made on sound pavement, but cracking exists near the tests.

Table 11

Dynaflect Test Results

Bakalar Air Force Base, Indiana

6, 7 October 1966

Location	PCC Thickness in.	Construction Year	Avg. Max. Defl. at Mid-Slab mils Avg.	No. Tests	Defl. at Joint x Defl. at Mid-Slab Avg.	Approx. Vertical Displacement Between Slabs, mils* Avg.	Load Transfer	Remarks
					Dummy Joints			
Operations Apron	11	1957	0.67	2	1.25	0.7	Poor	Probable cracking at bottom of slab.
Op. Apron Ext.	11	1958	0.51	2	Less Than 1.0	0.4	Poor	Probable cracking at bottom of slab.
Operations Apron	11	1957	0.39	1	2.0	0.6	Poor	No cracking
					Key Joints			
Operations Apron	11	1957	0.44	2	1.0	0.15-0.32	Fair	No cracking
Op. Apron Ext.	11	1958	0.46	1	Less Than 1.0	0.06	Good	Probable cracking at bottom of slab.

*Difference in readings between sensors 1 and 2 when located on opposite sides of the joint (step up).

INCLOSURE 5

THE NORTH ATLANTIC REGIONAL WATER RESOURCES STUDY
AND
THE NORTHEASTERN UNITED STATES WATER SUPPLY STUDY

I have been asked to discuss with you today two major water resource investigations which are currently underway and which impinge on the Appalachian Study area. These studies cover the northeastern portion of the United States.

The North Atlantic Regional Water Resources Study, which we call NAR for short, is part of a nation-wide program sponsored by the Water Resources Council.

Slide No. 1

Presented by Burnham H. Dodge, Chief of Planning Division, North Atlantic Division, Corps of Engineers, New York City, to Water Development Coordinating Committee for Appalachia, June 15, 1967.

Table 13

Dynaflect Test Results and Theoretical Deflections

Clinton County Air Force Base, Ohio

Clay Subgrade - Slab Interior

PCC Thickness in.	Theoretical Deflections, mils			Average Deflection at Load Dynaflect mils
	Heukelom Formula	Dense Liquid Subgrade	Elastic Solid Subgrade	
7	0.39	0.53	0.44	0.50
11	0.26	0.27	0.29	0.29
17	0.16	0.15	0.20	0.16
21	0.14	0.11	0.15	0.13

Heukelom formula, $z = \frac{1.5\ pf}{\pi a\ E_m}$

where

z = deflection

f = a factor dependent on ratios $\frac{h}{a}$ and $\frac{E_s}{E_m}$

p = 500 lbs (assumed equivalent static load)

E_s = 4,000,000 psi-assumed

E_m = 15,000 psi-assumed

a = 10 inches (radius = 1/2 of 20" C to C spacing)

h = slab thickness

For dense liquid subgrade
k value assumed at 100 pcf

1 mil = 0.001 inch

Table 14

Dynaflect Test Results and Theoretical Deflections

Wurtsmith Air Force Base, Michigan

Cohesionless Sand Subgrade - Slab Interior

PCC Thickness in.	Theoretical Deflections, mils			Average Deflection at Load Dynaflect mils
	Heukelom Formula	Dense Liquid Subgrade	Elastic Solid Subgrade	
7	0.46	0.56	0.53	0.48
11	0.32	0.29	0.34	0.33
17	0.20	0.14	0.23	0.20
21	0.17	0.12	0.17	0.16

See Table 13 for Heukelom formula

p = 850 pounds (assumed equivalent static load)
E_m = 25,000 psi-assumed

For dense liquid subgrade
k value assumed at 250 pci

Table 15

Dynaflect Test Results - Ranges of Deflection

Lunken Municipal Airfield, Cincinnati, Ohio

12 September - 15 November 1966

Weekly Tests

Location	PCC Thickness in.	Construction Year	Range Average Maximum Deflection at Mid-Slab, mils		Range Approx. Vertical Displacement Between Slabs, mils*		No. Tests
Municipal Apron	9-7-9 Reinforced	1929-30	0.55	0.77	0.88	1.40	8
Municipal Apron	9-7-9 Reinforced	1929-30	0.58	0.78	0.51	1.12	9
Municipal Apron	9-7-9 Reinforced	1929-30	0.61	0.81	0.26	1.21	6
Municipal Apron	9-7-9 Reinforced	1929-30	0.49	0.78	0.70	1.26	8
Taxiway A (South)	8 Reinforced	1960	0.43	0.59	0.10	0.30	9
Taxiway A (South)	8 Reinforced	1960	0.44	0.60	0.04	0.10	9
Taxiway A (South)	8 Reinforced	1960	0.41	0.55	0.06	0.36	8
Municipal Apron	9-7-9 Reinforced	1929-30	0.52	0.78	0.12	0.45	7
Municipal Apron	9-7-9 Reinforced	1929-30	0.51	0.70	0.06	0.39	8
Taxiway A (South)	8 Reinforced	1960	0.42	0.57	0.25	0.91	8

*Difference in readings between sensors 1 and 2 when located on opposite sides of joint (step up).

Table 16

Dynaflect Test Results - Ranges of Deflection

Sharonville Test Track, Sharonville, Ohio

12 September - 14 November 1966

Weekly Tests

Location	PCC Thickness in.	Construction Year	Range Average Maximum Deflection at Mid-Slab, mils		Range Approx. Vertical Displacement Between Slabs, mils*		No. Tests
Item 59 Channelized Test Track	16	1955	0.18	0.20	0.19	0.37	7
Item 60 Channelized Test Track	12	1955	0.20	0.27	0.22	0.39	7
Item 50 Overlay Test Track #2	16/6	1953	0.12	0.14	0.11	0.21	6
Item 73 Heavy Load Test Track	24	1957	0.11	0.15	0.07	0.18	13
Item 28 Overlay Test Track #2	6/10	1953	0.19	0.20	0.15	0.26	6
Item 27 Overlay Test Track #2	9/8	1953	0.19	0.23	0.23	0.96	7
Item 26 Overlay Test Track #2	10/6	1953	0.23	0.28	0.21	0.69	5
			Longitudinal Crack**				
Item 69A Heavy Load Test Track	15/17	1957	0.14	0.18	0.02	0.07	6
Item 69B Heavy Load Test Track	15/17	1957	0.15	0.20	0.03	0.13	6

*Difference in readings between sensors 1 & 2 when located on opposite sides of joint (step up).

**Tests made on a slab divided by a longitudinal crack. Each half used as a slab and the crack used as the joint.

69A Readings taken on half slab adjacent to full slab.
69B Readings taken on half slab adjacent to turf.

Table 17

Comparison of Dynaflect Tests at Varying Temperatures

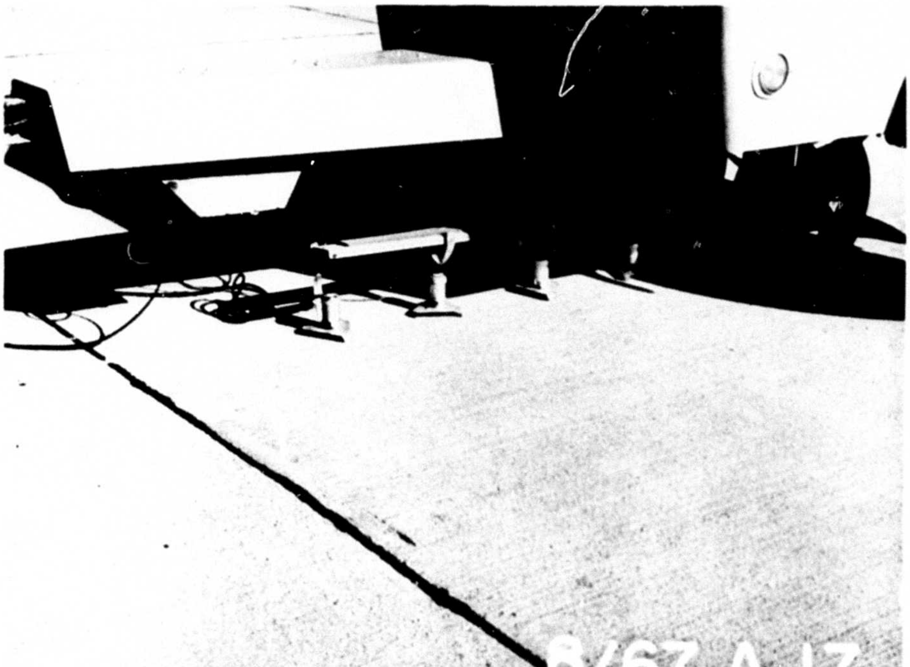
Clinton County Air Force Base, Ohio

Location	PCC Thickness in.	16 Sept. 1966* 67^{o} F @ 1:00 PM Avg. Max. Defl. mils	8 Nov. 1966** 54^{o} F @ 1:00 PM Avg. Max. Defl. mils
Runway B Test Area 24	7	0.50	--
Runway B Test Area 29	7	--	0.30
Parking Apron A Test Area 25	11	0.45	0.33
Operational Apron Ext. (SAC) Test Area 1 and 32	17	0.18	0.19
Parallel Taxiway Test Area 23 (Transverse Direction)	21	0.14	0.14
Parallel Taxiway Test Area 23A (Longitudinal Direction)	19-21-19	0.13	0.13

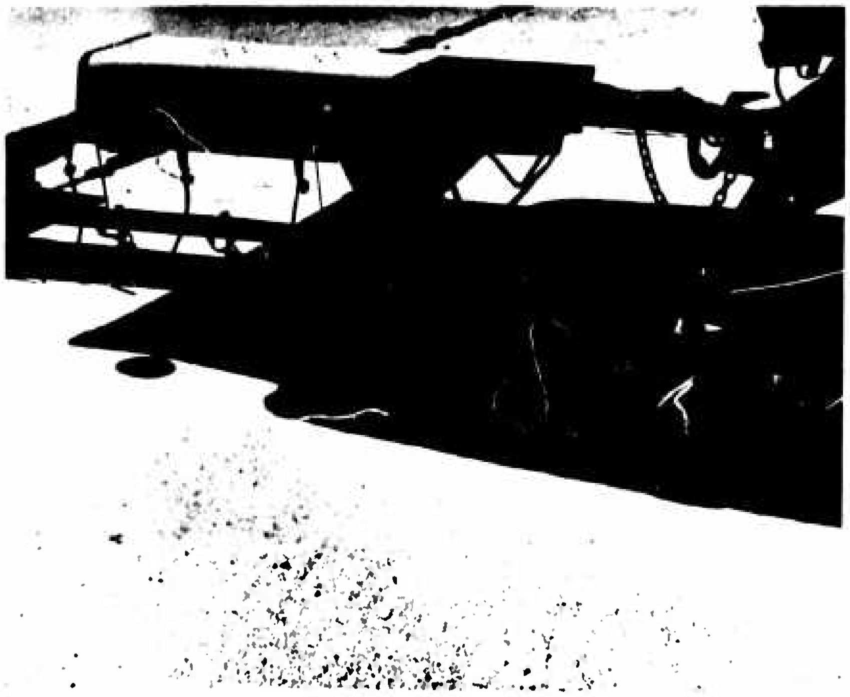
NOTE: All tests were performed at painted marks on the pavement except the Runway B tests where no painting was done and the repeat (Nov.) tests were not in the exact location of the previous (Sept.) tests.

*Average temperature for week ending 16 September 1966 - 64^{o} F.
**Average temperature for week ending 8 November 1966 - 38^{o} F.

a. View of Dynaflect in Road Travel Position



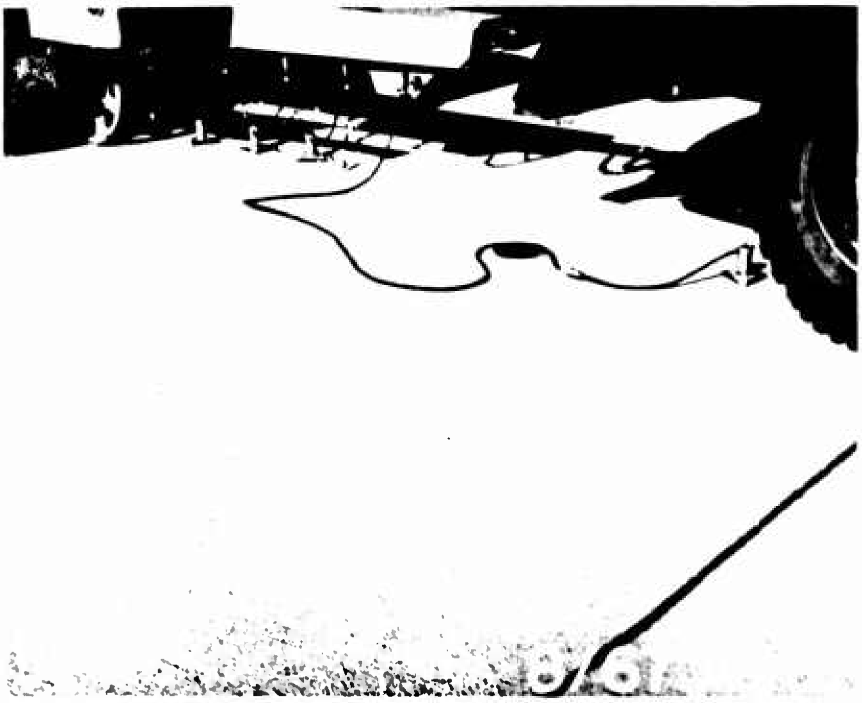
b. View of Dynaflect with Geophones in Normal Position



a. View of Dynaflect with Geophone #5 at 7 foot Extension Cord Position

b. View of Dynaflect with Geophone #5 at 10 foot Extension Cord Position

a. View of Dynaflect with Load Wheels at Joint



b. View of Dynaflect with Load Wheels at Free Edge of Slab and Extension Cord at 10 Foot Position

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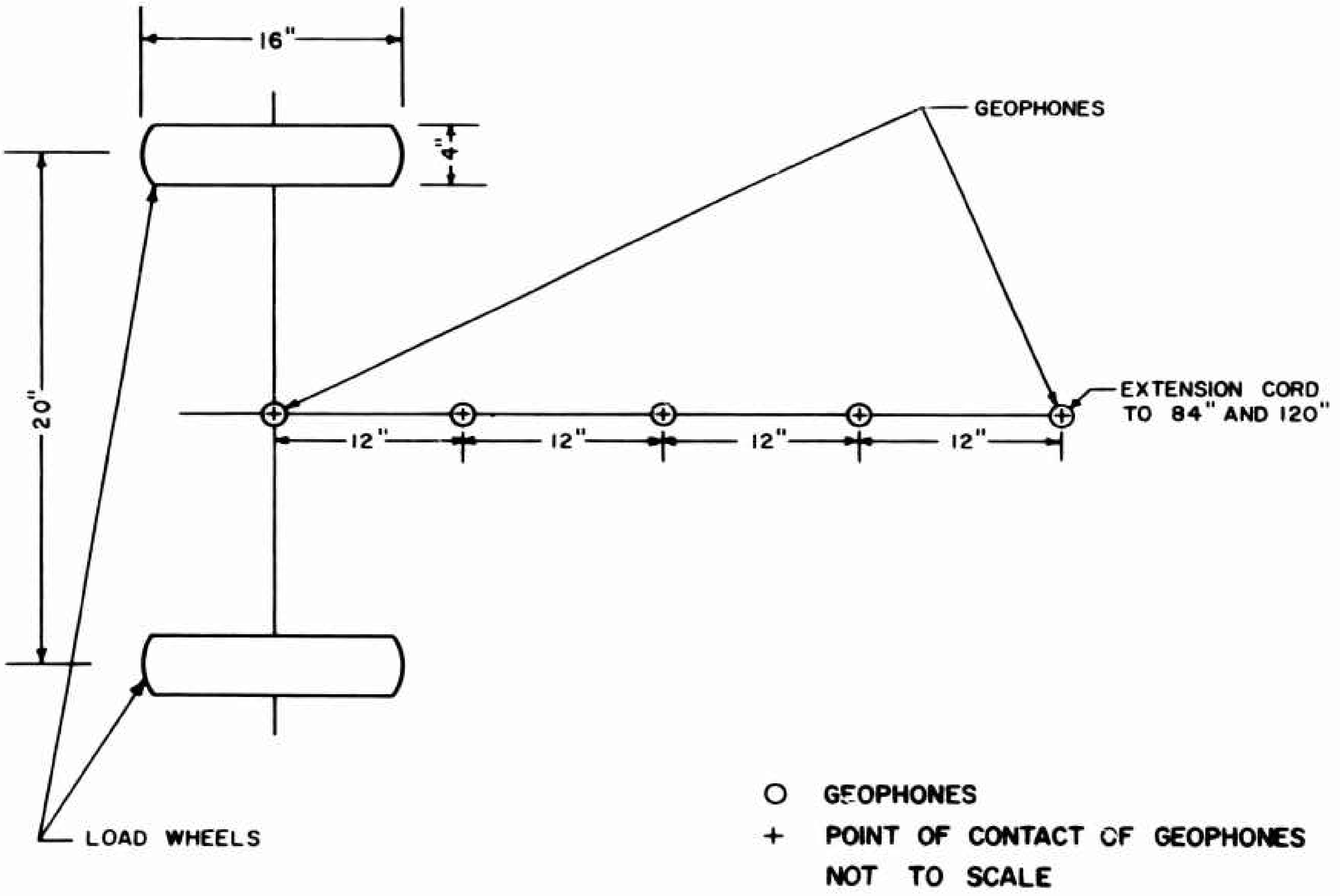
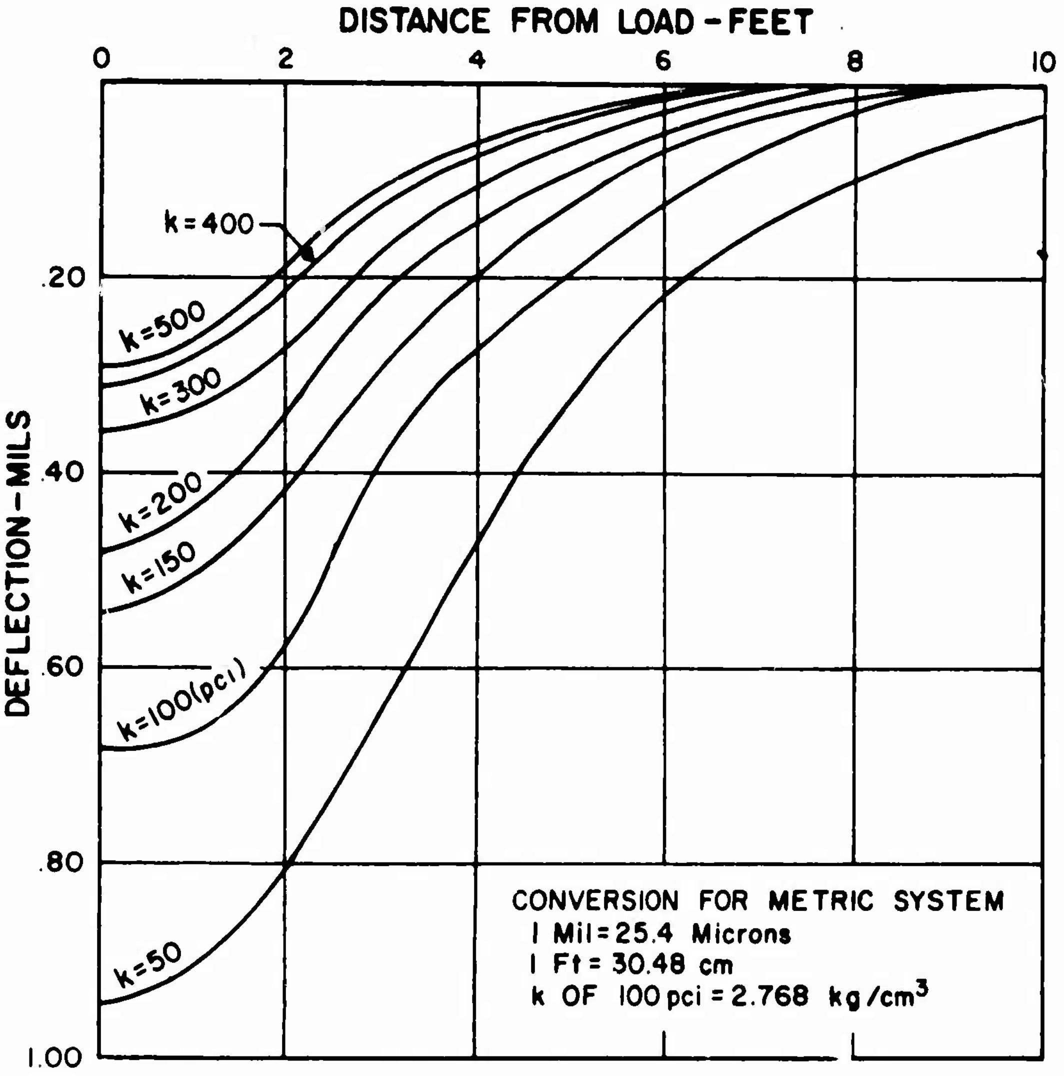


NORMAL ARRANGEMENT OF GEOPHONES USED WITH THE DYNAFLECT

FIGURE 1



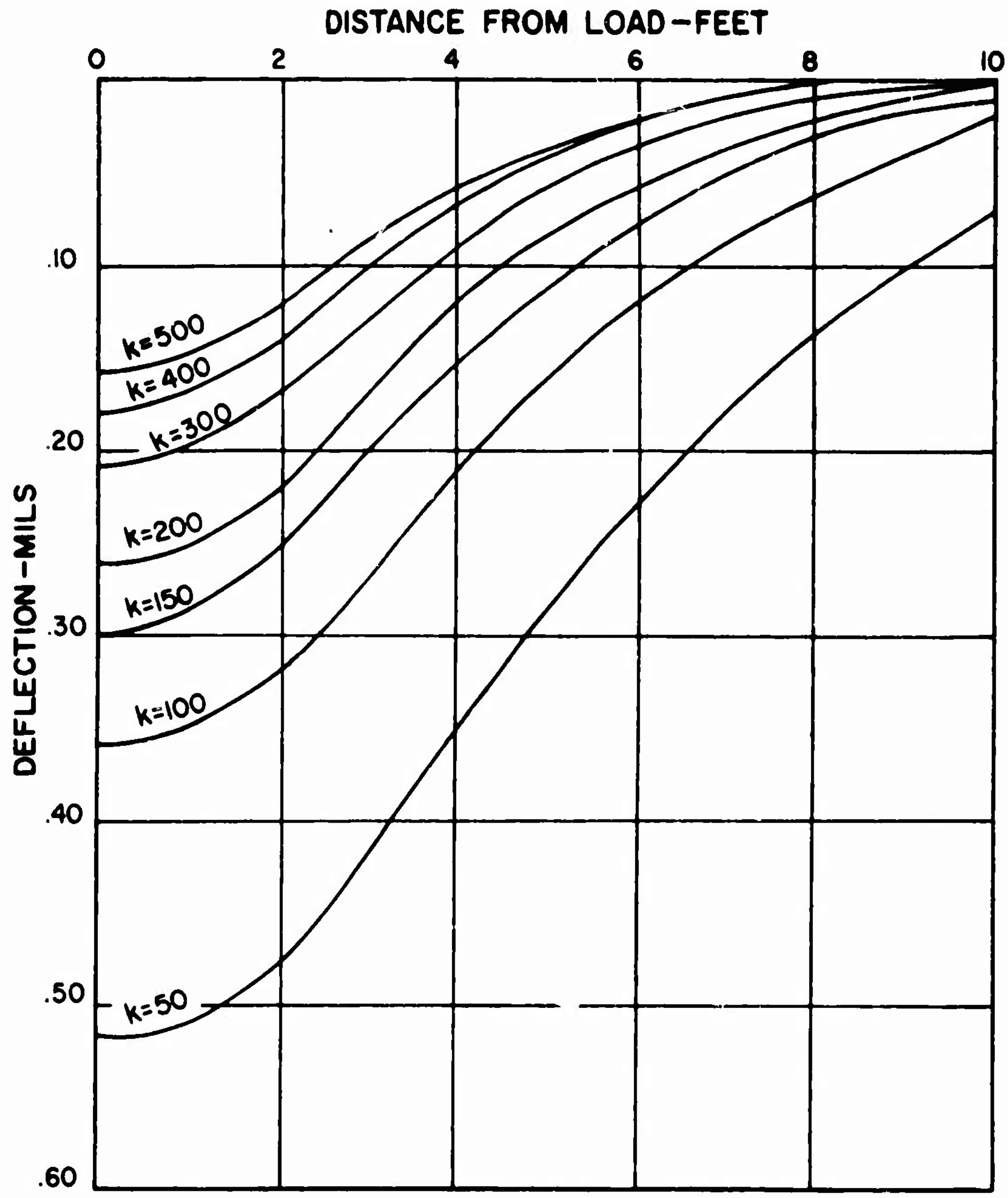
CONVERSION FOR METRIC SYSTEM
1 Mil = 25.4 Microns
1 Ft = 30.48 cm
k OF 100 pci = 2.768 kg/cm^3

REF: WESTERGEARD ANALYSIS,
HIGHWAY RESEARCH BOARD,
VOL. 7, NO. 2, 1926.

NOTE: REFERENCE APPLIES TO
FIGURES 3 THROUGH 7.

THEORETICAL DEFLECTION OF CONCRETE PAVEMENT
UNDER 500 POUND LOAD TWO WHEELS 20" C TO C
250 POUNDS PER WHEEL 6-INCH PAVEMENT (SLAB INTERIOR)

FIGURE 2

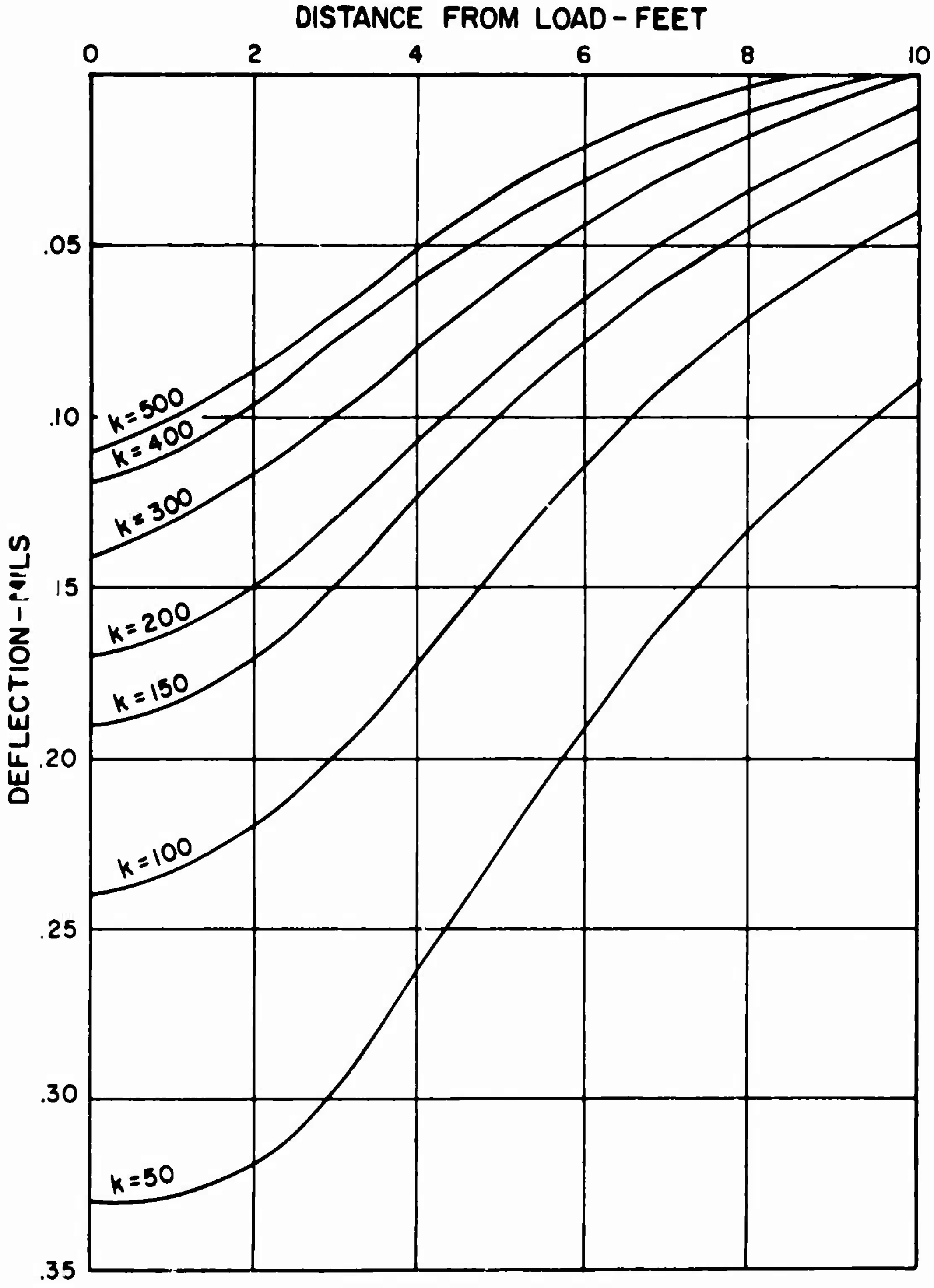


REF: WESTERGEARD ANALYSIS,
HIGHWAY RESEARCH BOARD,
VOL. 7, NO. 2, 1926.

NOTE: REFERENCE APPLIES TO
FIGURES 3 THROUGH 7.

THEORETICAL DEFLECTION OF CONCRETE PAVEMENT
UNDER 500 POUND LOAD TWO WHEELS 20" C TO C
250 POUNDS PER WHEEL 9-INCH PAVEMENT (SLAB INTERIOR)

FIGURE 3

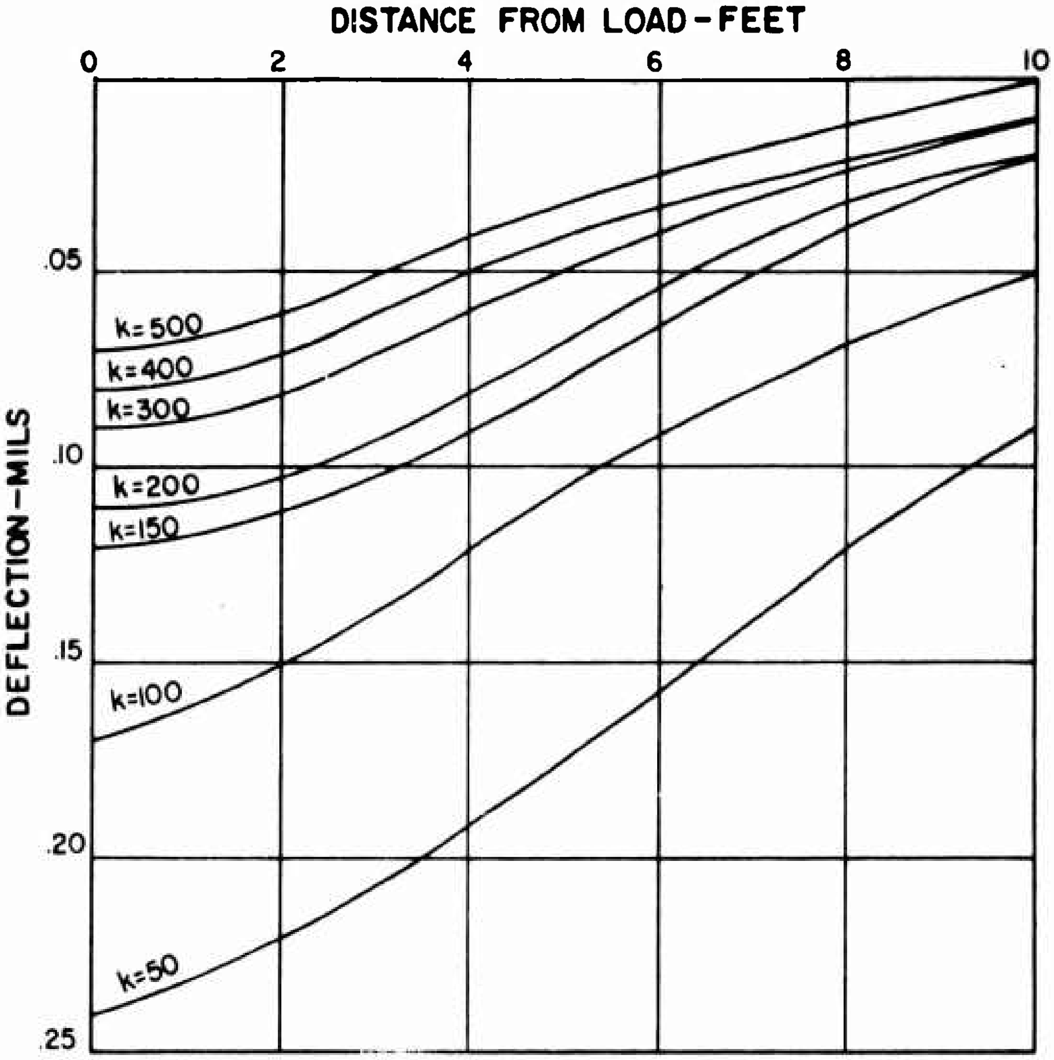


REF: WESTERGEARD ANALYSIS,
HIGHWAY RESEARCH BOARD,
VOL. 7, NO. 2, 1926.

NOTE: REFERENCE APPLIES TO
FIGURES 3 THROUGH 7.

THEORETICAL DEFLECTION OF CONCRETE PAVEMENT
UNDER 500 POUND LOAD TWO WHEELS 20" C TO C
250 POUNDS PER WHEEL 12-INCH PAVEMENT (SLAB INTERIOR)

FIGURE 4

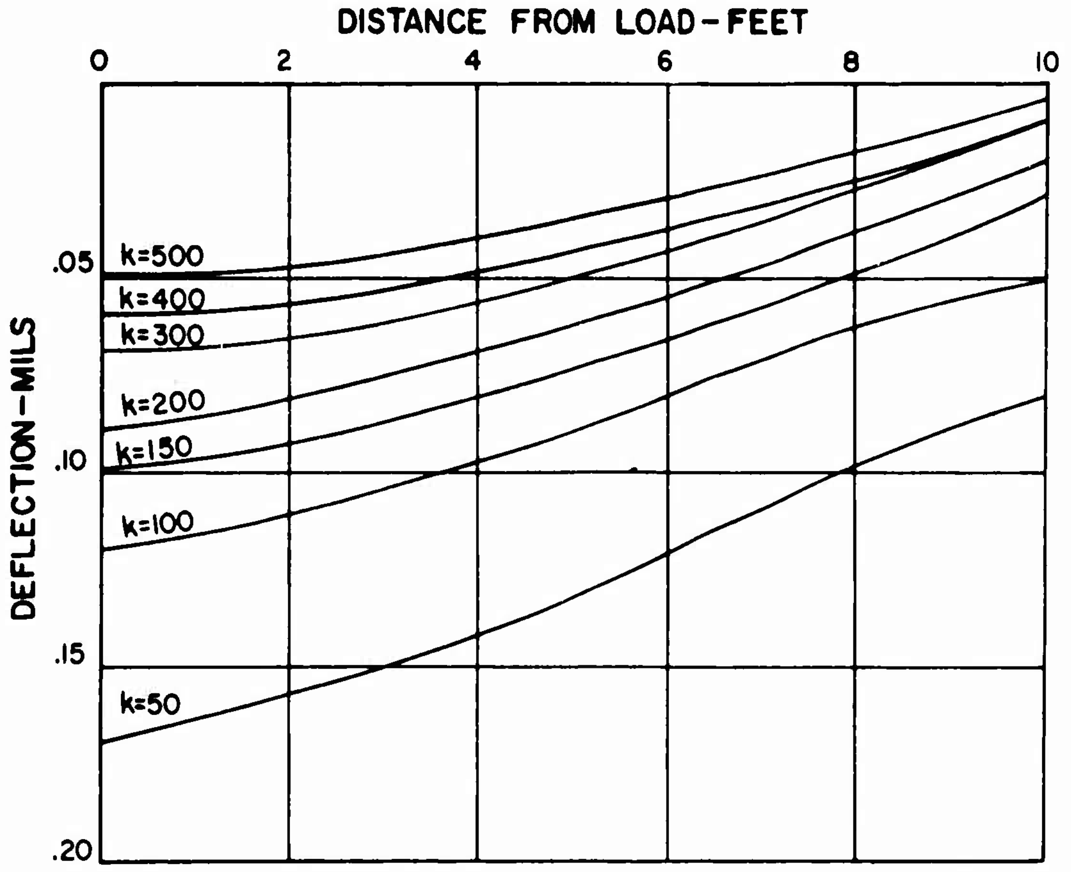


REF WESTERGEARD ANALYSIS,
HIGHWAY RESEARCH BOARD,
VOL 7, NO. 2, 1926.

NOTE: REFERENCE APPLIES TO
FIGURES 3 THROUGH 7.

THEORETICAL DEFLECTION OF CONCRETE PAVEMENT
UNDER 500 POUND LOAD TWO WHEELS 20" C TO C
250 POUNDS PER WHEEL 16-INCH PAVEMENT (SLAB INTERIOR)

FIGURE 5

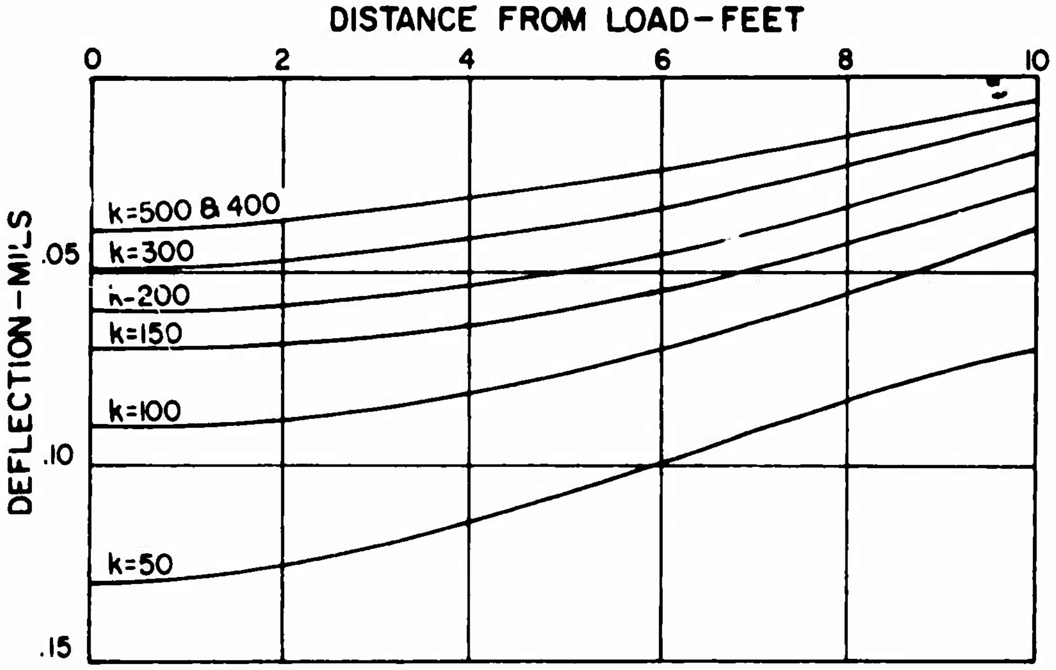


REF: WESTERGEARD ANALYSIS,
HIGHWAY RESEARCH BOARD,
VOL. 7, NO. 2, 1926.

NOTE: REFERENCE APPLIES TO
FIGURES 3 THROUGH 7.

THEORETICAL DEFLECTION OF CONCRETE PAVEMENT UNDER 500 POUND LOAD TWO WHEELS 20" C TO C 250 POUNDS PER WHEEL 20-INCH PAVEMENT (SLAB INTERIOR)

FIGURE 6

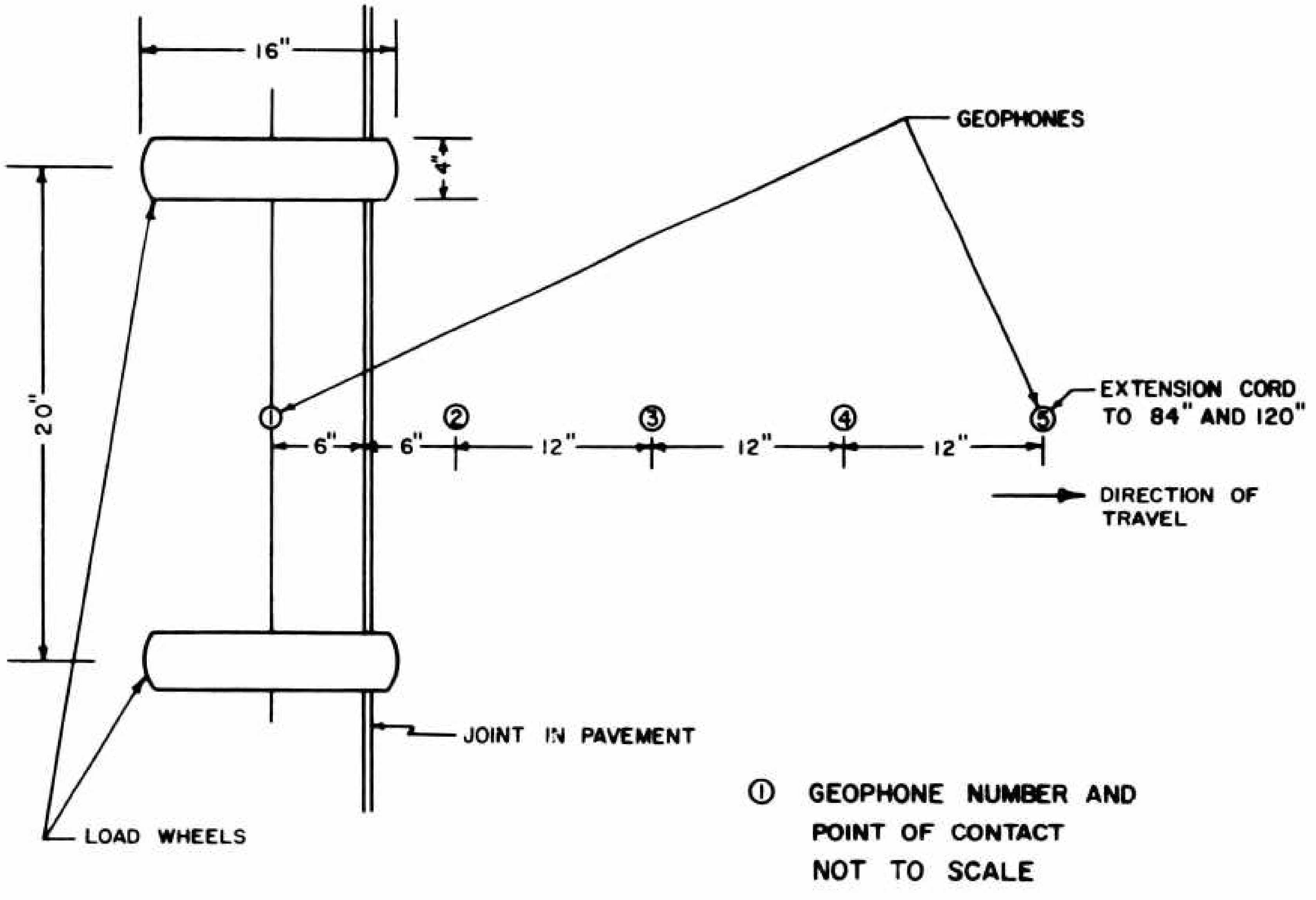


REF: WESTERGEARD ANALYSIS,
HIGHWAY RESEARCH BOARD,
VOL. 7, NO. 2, 1926.

NOTE: REFERENCE APPLIES TO
FIGURES 3 THROUGH 7.

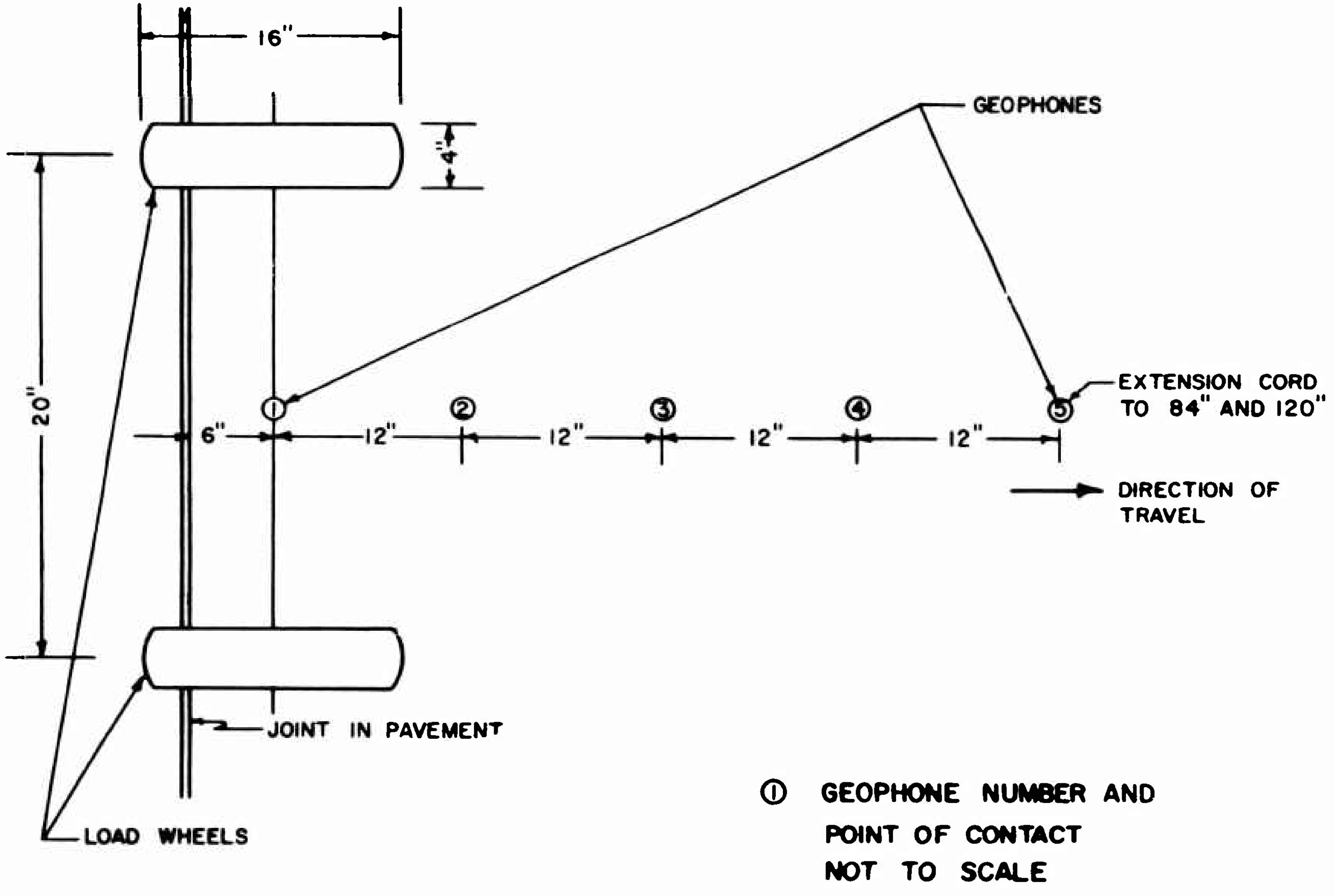
THEORETICAL DEFLECTION OF CONCRETE PAVEMENT
UNDER 500 POUND LOAD TWO WHEELS 20" C TO C
250 POUNDS PER WHEEL 24-INCH PAVEMENT (SLAB INTERIOR)

FIGURE 7



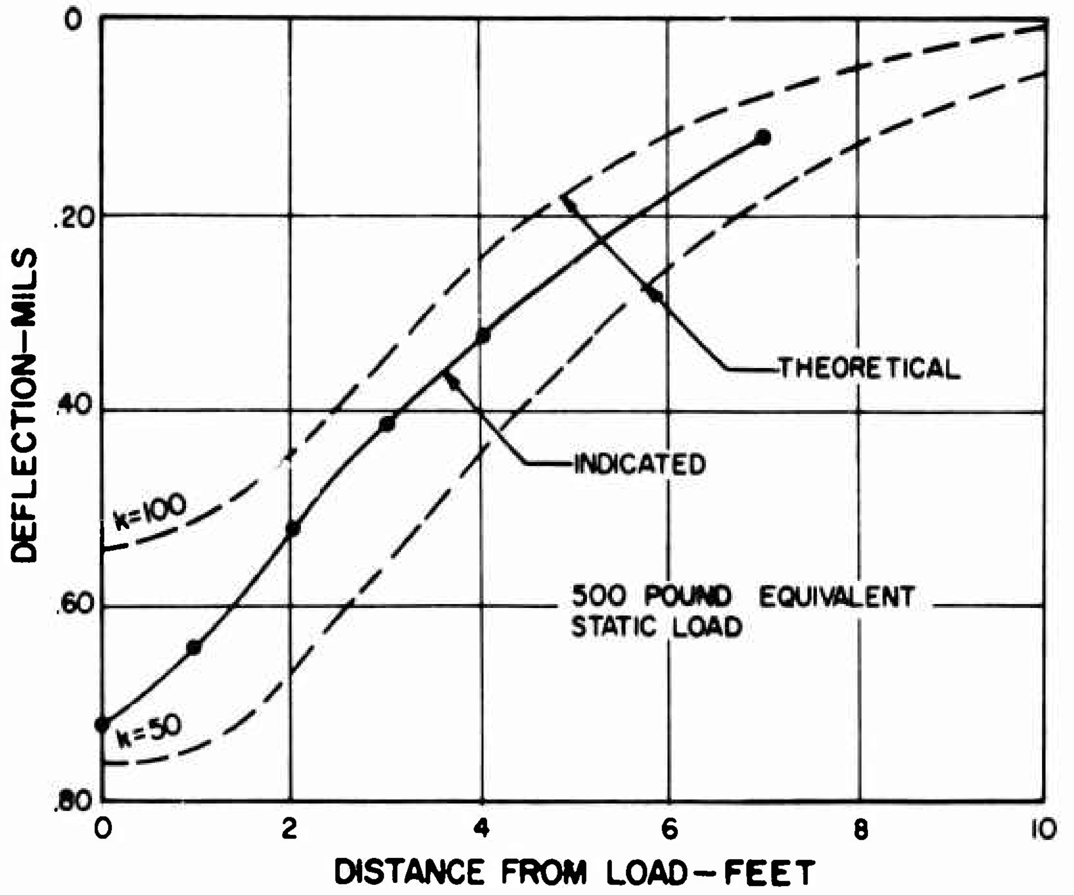
WHEELS AND GEOPHONES IN POSITION #1 AT JOINT

FIGURE 8



WHEELS AND GEOPHONES IN POSITION #2 AT JOINT

FIGURE 9

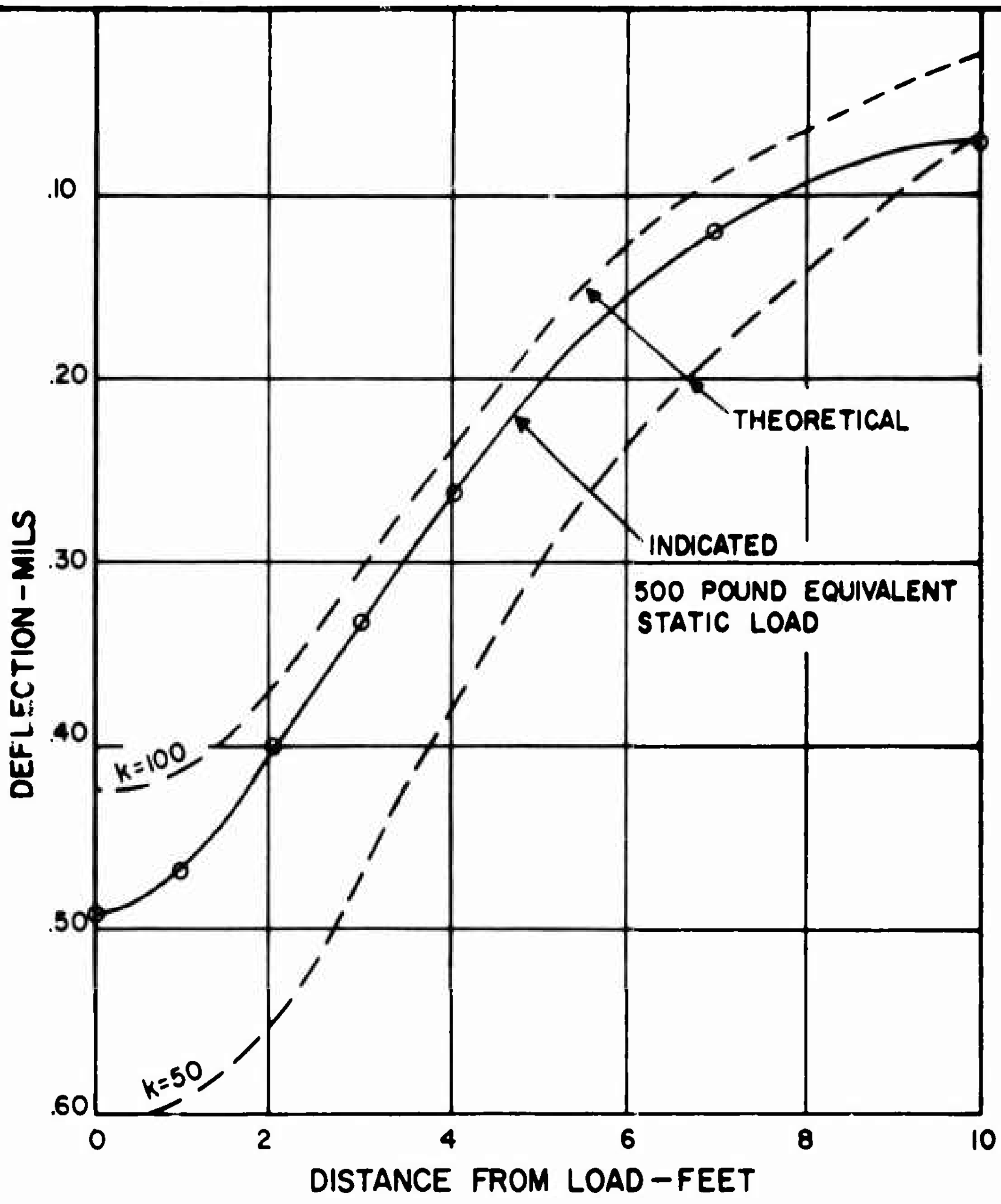


	DISTANCE FROM LOAD — FEET					
	0	1	2	3	4	7
DEFL. (MILS)	0.78	0.63	0.52	0.42	0.35	
	.77	.66	.57	.46	.35	
	.78	.72	.60	.50	.38	
	.70	.61	.43	.33	.27	0.10
	.62	.58	.49	.36	.27	.13
	.70	.64	.53	.41	.30	.12
	.68	.63	.51	.39	.30	.13
AVG.	0.72	0.64	0.52	0.41	0.32	0.12

PAVEMENT DEFLECTION TESTS
LUNKEN MUNICIPAL AIRPORT
AREA I — MID-SLAB
9"-7"-9" PCC REINF.
FAT CLAY SUBGRADE

SEPTEMBER—NOVEMBER 1966

FIGURE 10

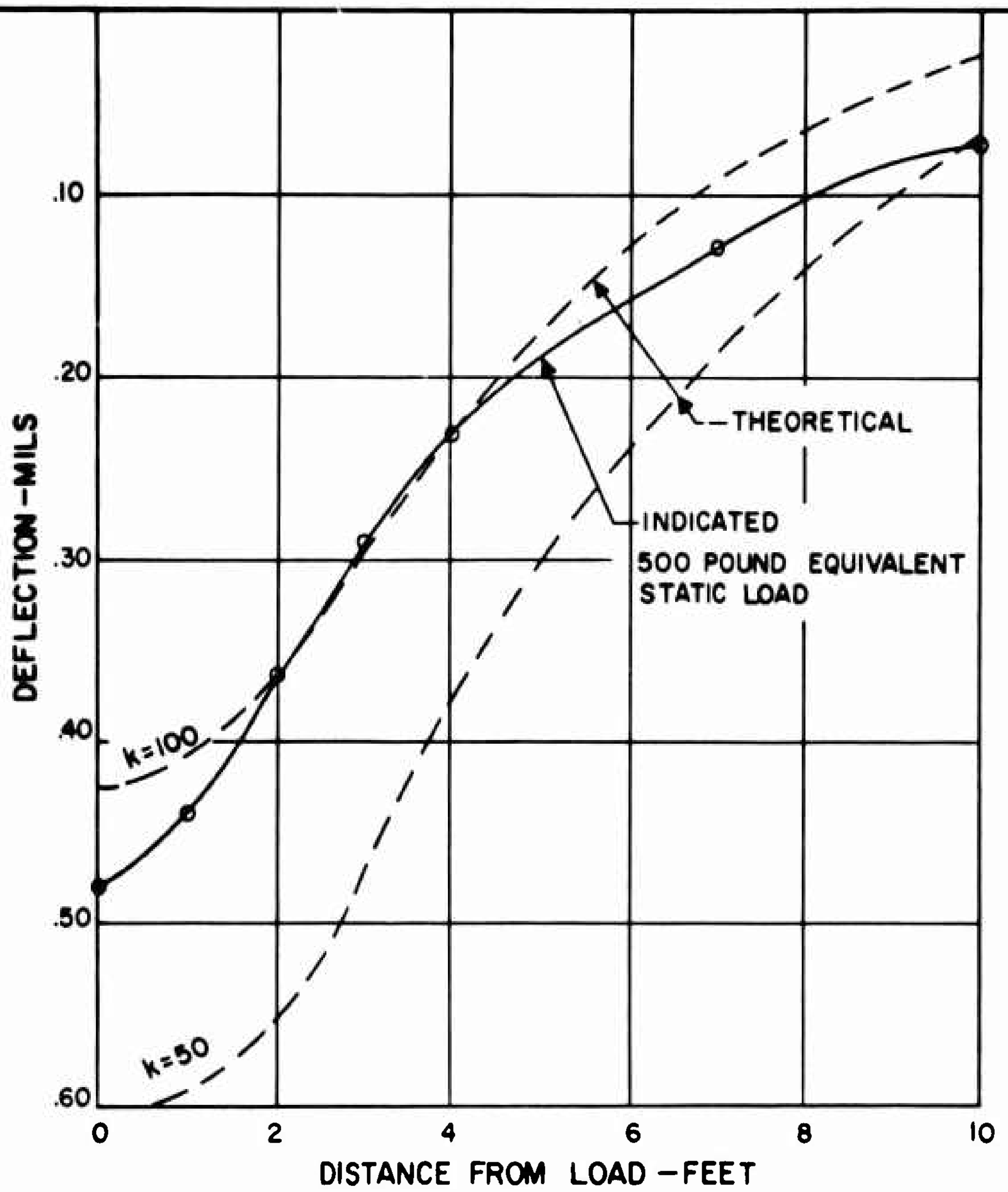


	DISTANCE FROM LOAD-FEET						
	0	1	2	3	4	7	10
DEFL.	0.54	0.52	0.43	0.34	0.26		
(MILS)	.50	.50	.44	.36	.29	0.14	0.07
	.42	.40	.34	.28	.22	.10	.06
	.50	.48	.41	.34	.28	.13	.07
	.51	.50	.42	.34	.27	.13	.07
	.45	.44	.37	.30	.24	.11	.07
AVG.	0.49	0.47	0.40	0.33	0.26	0.12	0.07

PAVEMENT DEFLECTION TESTS
LUNKEN MUNICIPAL AIRPORT
AREA 7 - MID-SLAB
8" PCC REINF.
FAT CLAY SUBGRADE

SEPTEMBER-NOVEMBER 1966

FIGURE 11

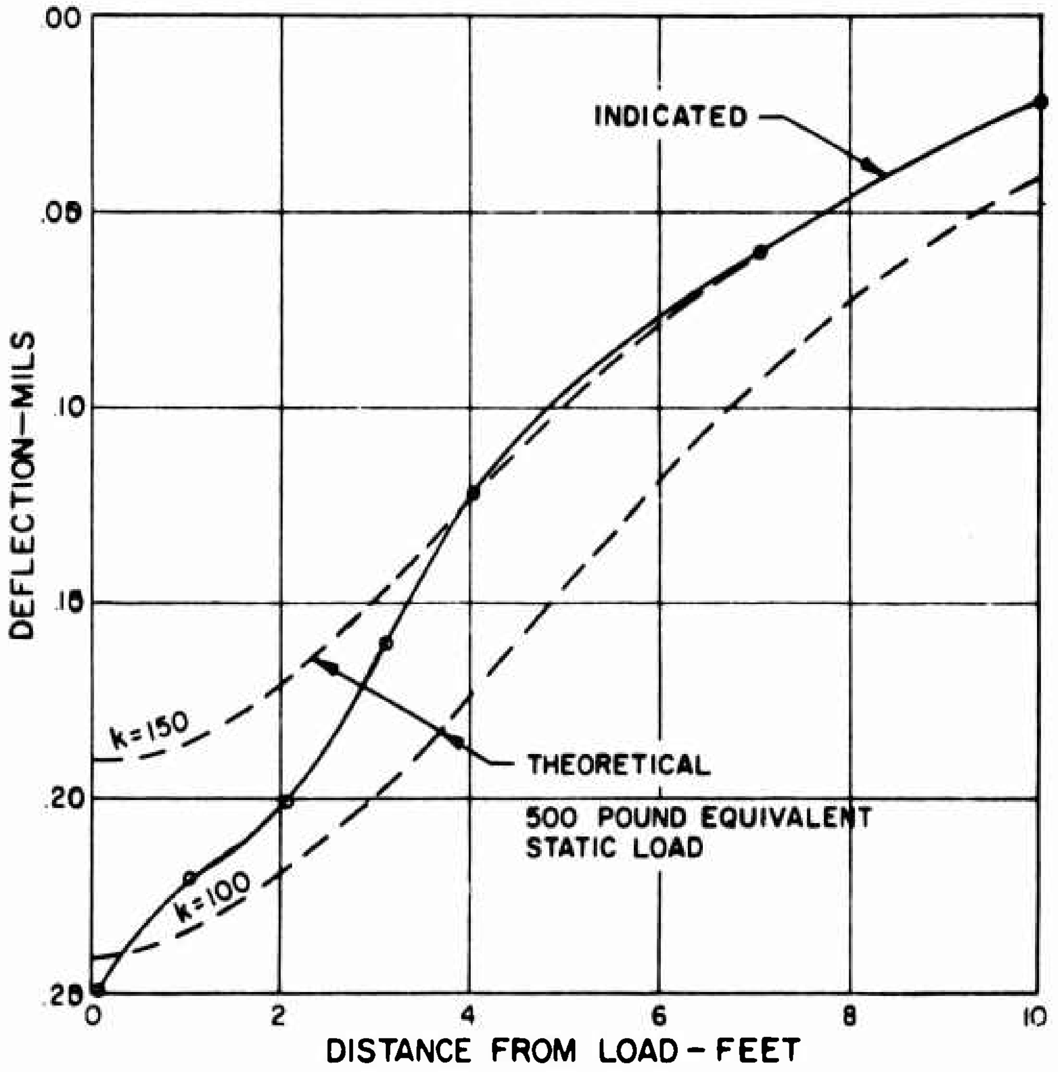


	DISTANCE FROM LOAD-FEET						
	0	1	2	3	4	7	10
DEFL.	0.53	0.49	0.41	0.34	0.26	0.13	0.07
(MILS)	.48	.42	.30	.24	.20	.11	.05
	.53	.48	.38	.30	.24	.13	.08
	.43	.40	.34	.26	.25	.17	.06
	.48	.45	.38	.30	.22	.10	.07
	.45	.42	.35	.27	.22	.12	.06
AVG.	0.48	0.44	0.36	0.29	0.23	0.13	0.07

PAVEMENT DEFLECTION TESTS
LUNKEN MUNICIPAL AIRPORT
AREA 5 – MID-SLAB
8" PCC REINF.
FAT CLAY SUBGRADE

SEPTEMBER 1966

FIGURE 12

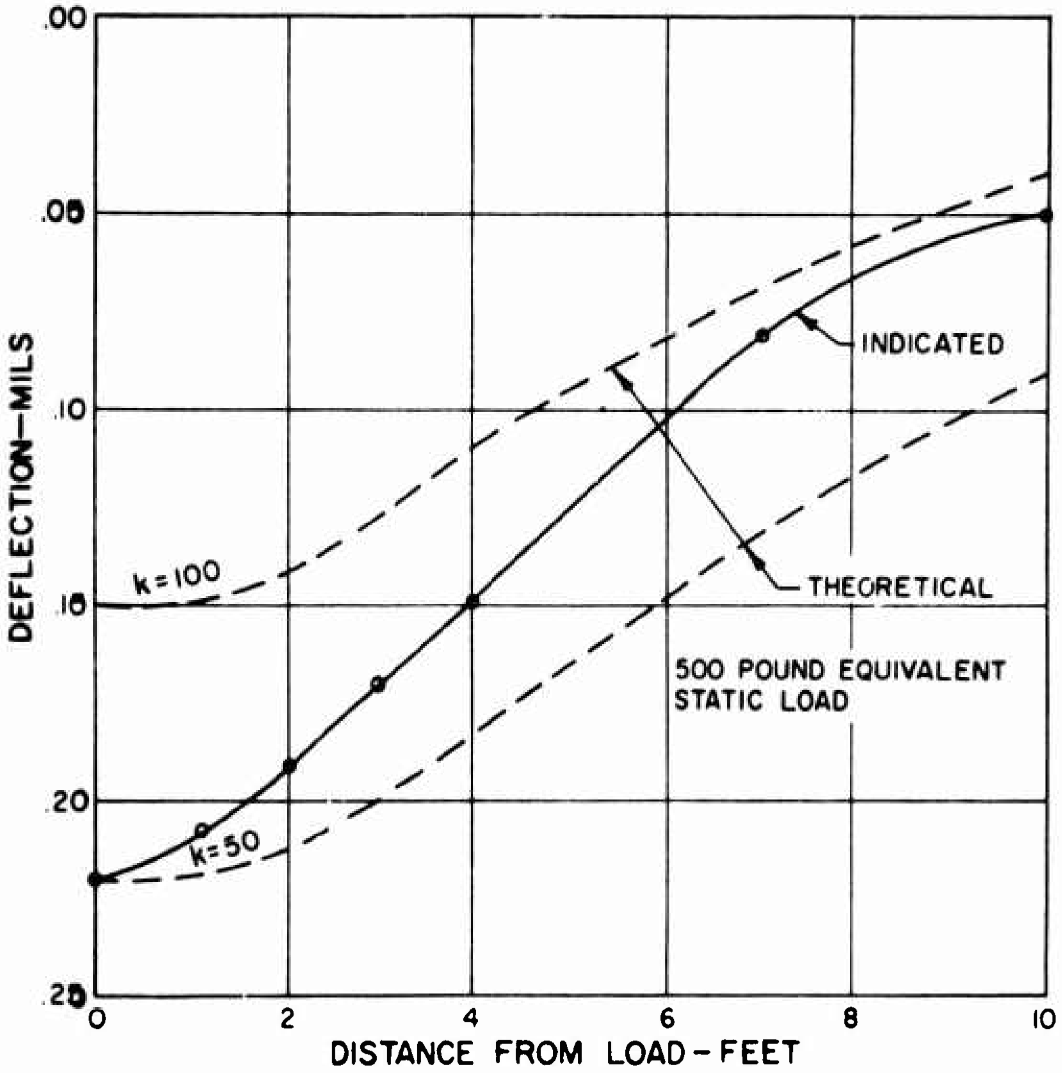


	DISTANCE FROM LOAD - FEET						
	0	1	2	3	4	7	10
DEFL.	0.20	0.18	0.16	0.13	0.10	0.05	0.02
(MILS)	.25	.20	.18	.14	.11	.06	.03
	.24	.22	.19	.15	.11	.05	.02
	.24	.22	.19	.15	.10	.05	
	.23	.21	.18	.15	.12	.03	.03
	.26	.24	.20	.17	.12	.06	.02
	.26	.24	.22	.18	.14	.08	.03
	.27	.26	.24	.21	.18	.07	
AVG.	0.25	0.22	0.20	0.16	0.12	0.06	0.02

PAVEMENT DEFLECTION TESTS
SHARONVILLE TEST TRACK
AREA 2-ITEM 60-MID-SLAB
12" PCC
LEAN CLAY SUBGRADE

SEPTEMBER-NOVEMBER 1966

FIGURE 13

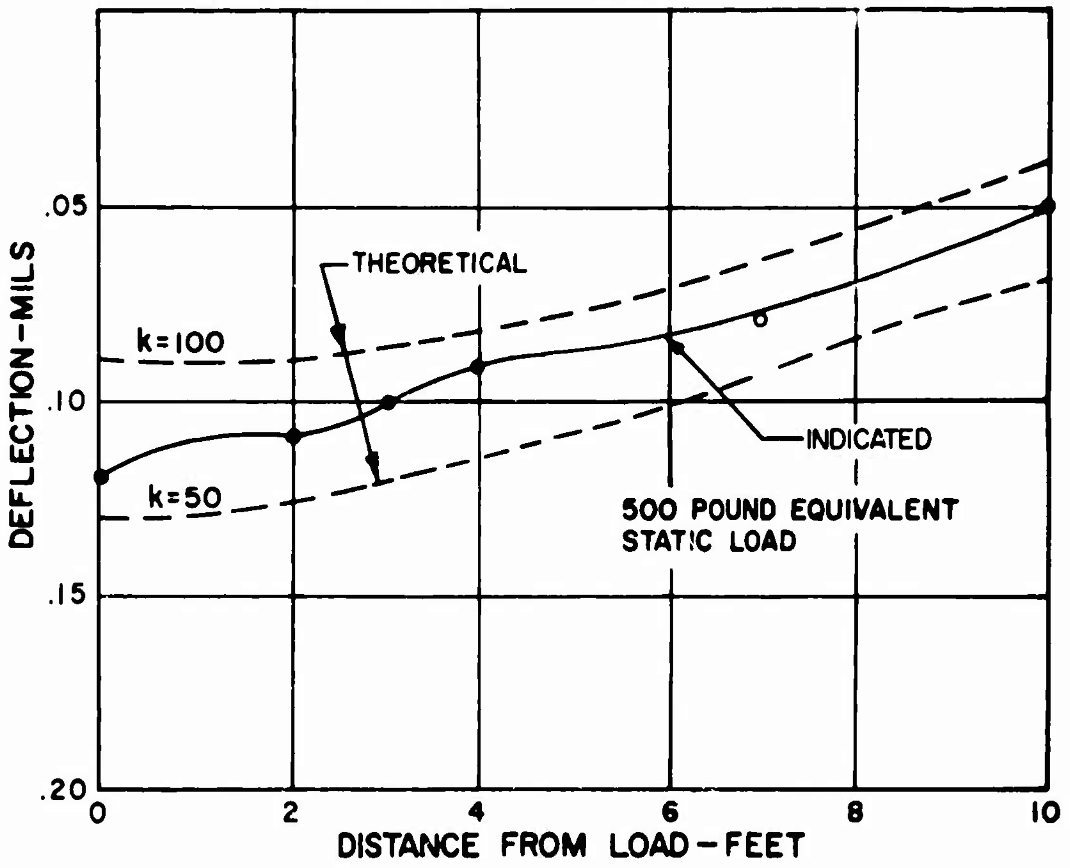


	DISTANCE FROM LOAD - FEET						
	0	1	2	3	4	7	10
DEFL.	0.21	0.21	0.19	0.17	0.15	0.08	
(MILS)	.23	.19	.18	.16	.14	.08	
	.23	.21	.20	.17	.16		
	.21	.20	.18	.16	.14	.07	0.04
	.21	.20	.18	.17	.14	.08	
	.23	.22	.20	.18	.15	.08	,03
	.22	.20	.19	.17	.14	.08	.04
	.22	.21	.20	.19	.15	.08	.04
	.22	.21	.20	.19	.15	.08	.05
AVG.	0.22	0.21	0.19	0.17	0.15	0.08	0.05

PAVEMENT DEFLECTION TESTS
SHARONVILLE TEST TRACK
AREA 7-ITEM 27-MID-SLAB
9"/8" PCC
LEAN CLAY SUBGRADE

SEPTEMBER—NOVEMBER 1966

FIGURE 14

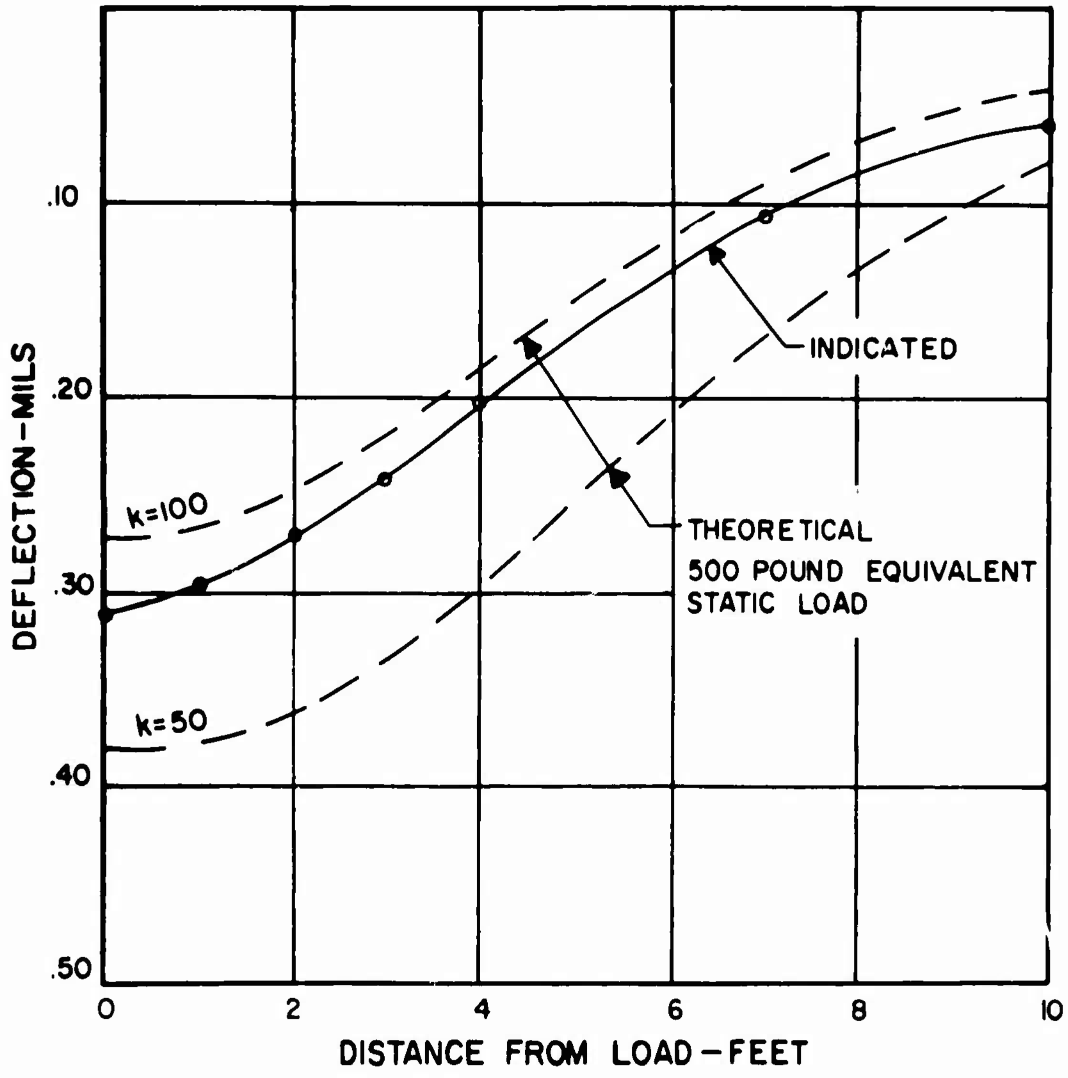


	DISTANCE FROM LOAD-FEET						
	0	1	2	3	4	7	10
DEFL.	0.12	0.12	0.11	0.10	0.10	0.08	0.05
(MILS)	.12	.12	.11	.10	.10		
	.14	.11	.11	.10	.09	.08	.05
	.12	.12	.11	.11	.10		
	.11	.11	.10	.10	.08	.08	.05
	.11	.11	.10	.10	.09	.08	.05
	.11	.11	.10	.10	.08	.08	.05
	.12	.11	.11	.10	.09	.08	.05
	.13	.12	.11	.11	.09	.08	.06
AVG.	0.12	0.11	0.11	0.10	0.09	0.08	0.05

PAVEMENT DEFLECTION TESTS
SHARONVILLE TEST TRACK
AREA 4-ITEM 73-MID-SLAB
24" PCC
LEAN CLAY SUBGRADE

SEPTEMBER-NOVEMBER 1966

FIGURE 15

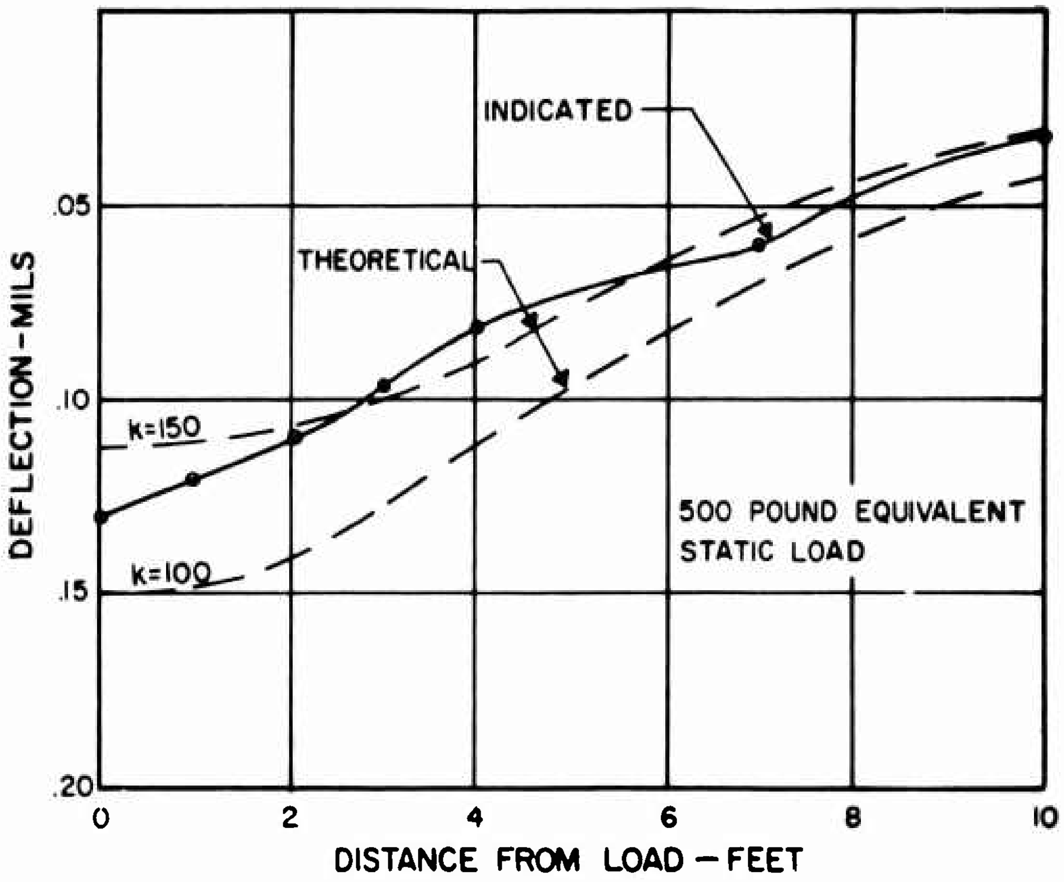


	DISTANCE FROM LOAD-FEET						
	0	1	2	3	4	7	10
DEFL. (MILS)	0.28	0.27	0.26	0.23	0.20	0.12	0.09
	.32	.31	.29	.26	.24	.15	.09
	.30	.29	.26	.24	.21	.13	.08
	.33	.31	.28	.25	.22	.12	.06
	.33	.31	.27	.24	.20	.11	.06
	.32	.29	.26	.22	.18	.07	.03
	.30	.28	.24	.21	.17	.07	.04
AVG.	0.31	0.29	0.27	0.24	0.20	0.11	0.06

PAVEMENT DEFLECTION TESTS
CLINTON COUNTY AFB
AREAS 4, 19, 22 - MID-SLAB
11" PCC

SEPTEMBER 1966

FIGURE 16

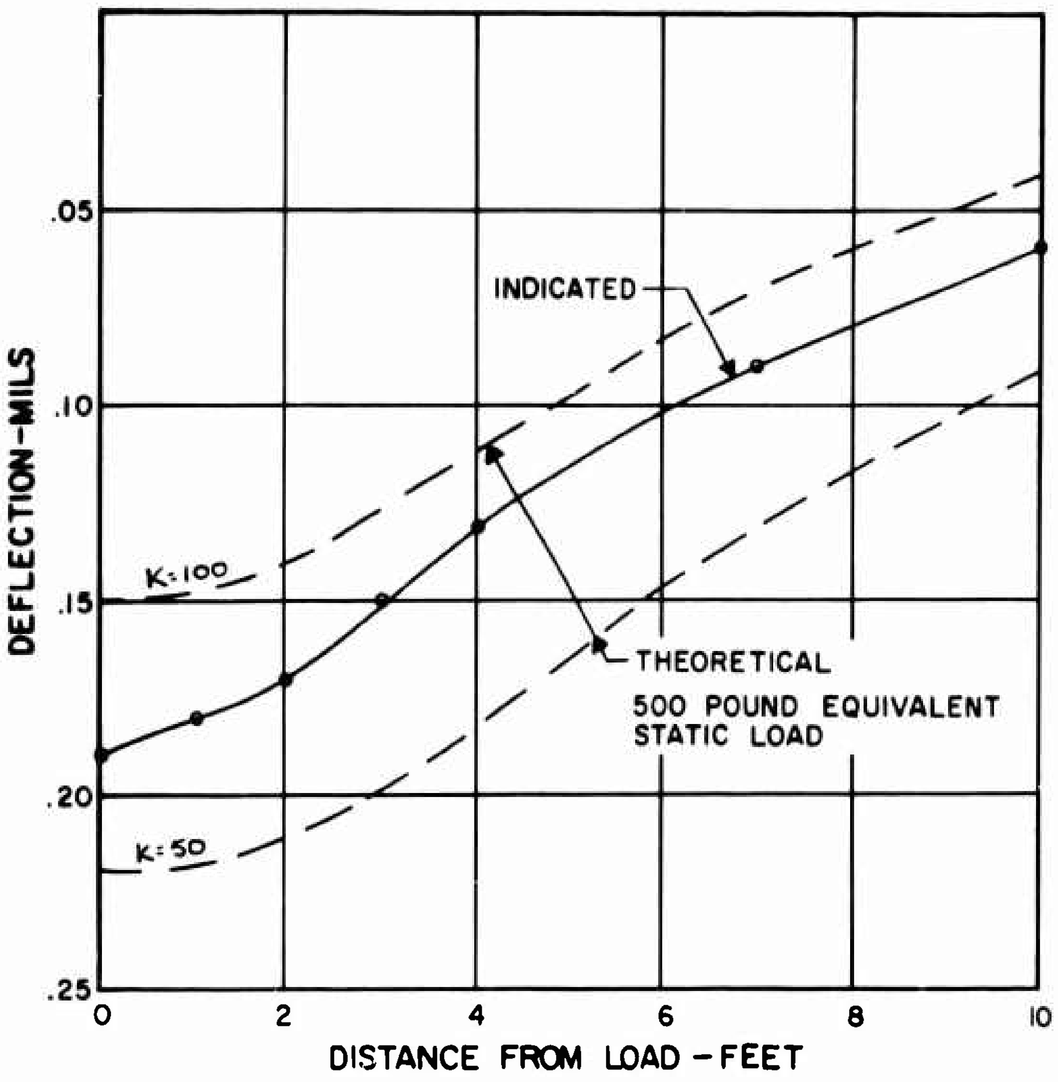


	DISTANCE FROM LOAD — FEET						
	0	1	2	3	4	7	10
DEFL.	0.14	0.13	0.11	0.10	0.08	0.06	0.03
(MILS)	.13	.12	.11	.10	.08		
	.13	.12	.11	.09	.08		
	.12	.11	.10	.09	.08	.05	.03
	.13	.12	.11	.10	.08	.06	.03
	.13	.13	.11	.10	.08	.06	.03
AVG.	0.13	0.12	0.11	0.10	0.08	0.06	0.03

PAVEMENT DEFLECTION TESTS
CLINTON COUNTY AFB
AREAS 13 & 14 - MID-SLAB
17" PCC

SEPTEMBER 1966

FIGURE 17

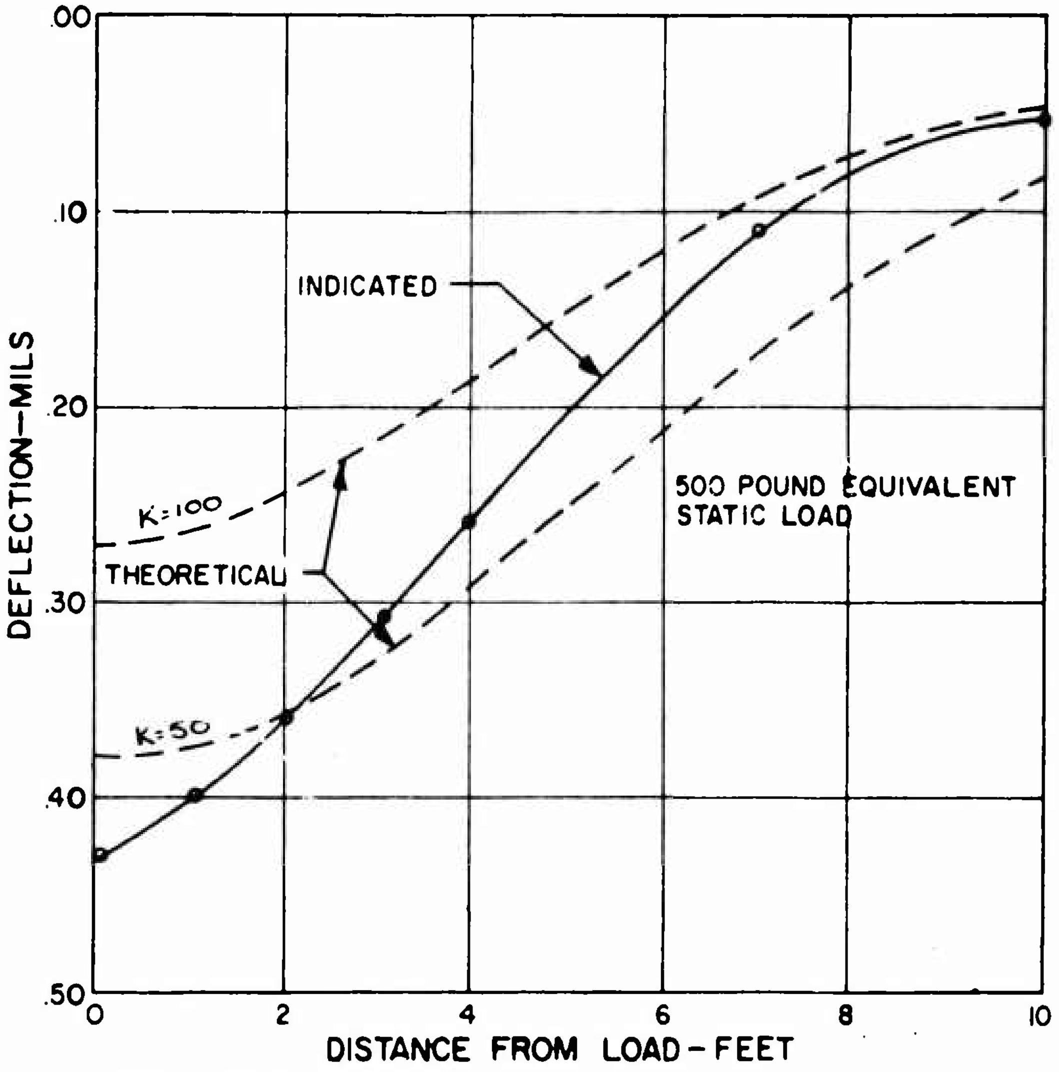


	DISTANCE FROM LOAD - FEET						
	0	1	2	3	4	7	10
DEFL.	0.19	0.18	0.17	0.15	0.13	0.09	0.06
(MILS)	.18	.18	.16	.15	.13	.08	.05
AVG.	0.19	0.18	0.17	0.15	0.13	0.09	0.06

PAVEMENT DEFLECTION TESTS
CLINTON COUNTY AFB
AREA 8 - MID-SLAB
17" PCC

SEPTEMBER 1966

FIGURE 18

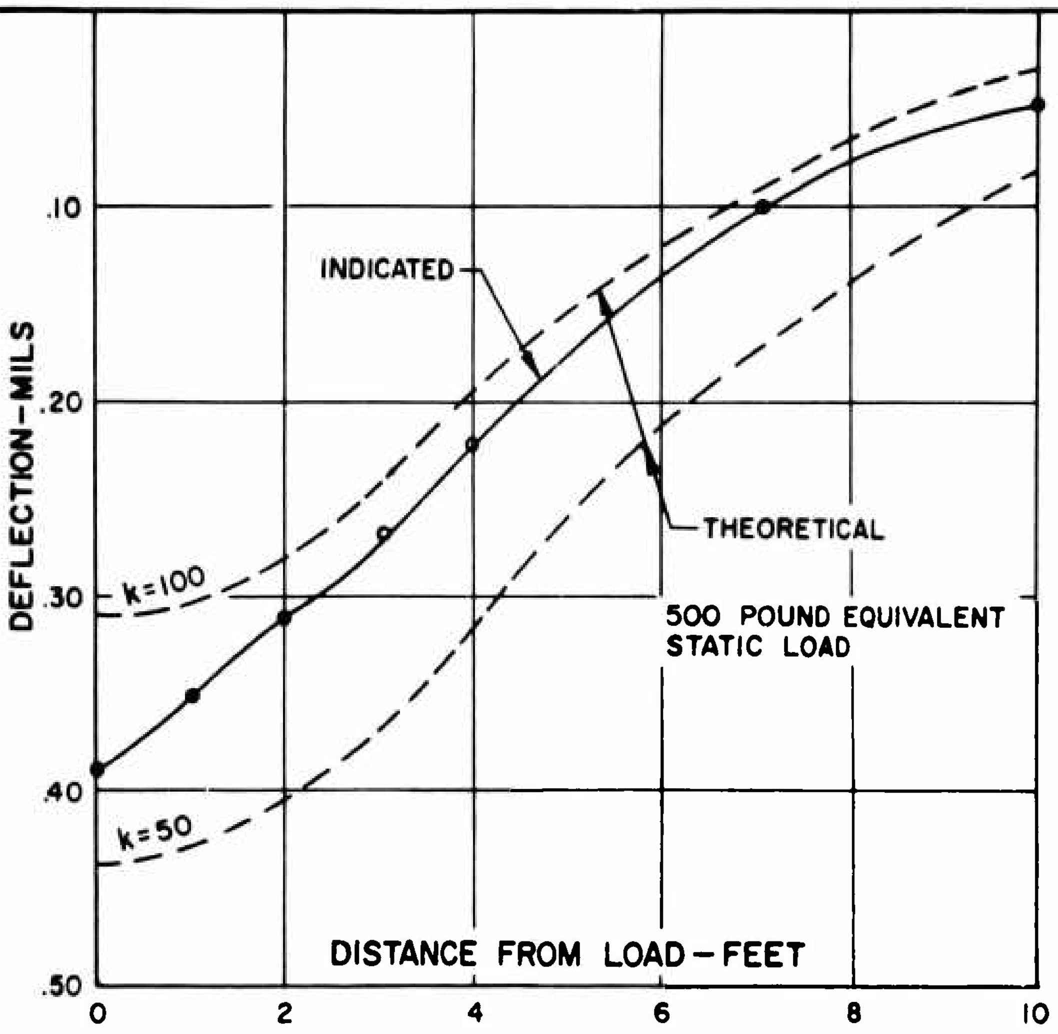


	DISTANCE FROM LOAD - FEET						
	0	1	2	3	4	7	10
DEFL.	0.43	0.39	0.34	0.29	0.24		
(MILS)	.43	.40	.36	.32	.26		
	.45	.42	.38	.33	.27		
	.48	.46	.41	.36	.30		
	.43	.41	.37	.33	.28		
	.36	.34	.30	.26	.21	0.11	0.05
	.41	.38	.33	.28	.23	.11	.04
AVG.	0.43	0.40	0.36	0.31	0.26	0.11	0.05

PAVEMENT DEFLECTION TESTS
BAKALAR AIR FORCE BASE
AREAS 30, 33 & 34
(EXCLUDING CRACKED AREAS)
11" PCC - MID-SLAB

OCTOBER 1966

FIGURE 19

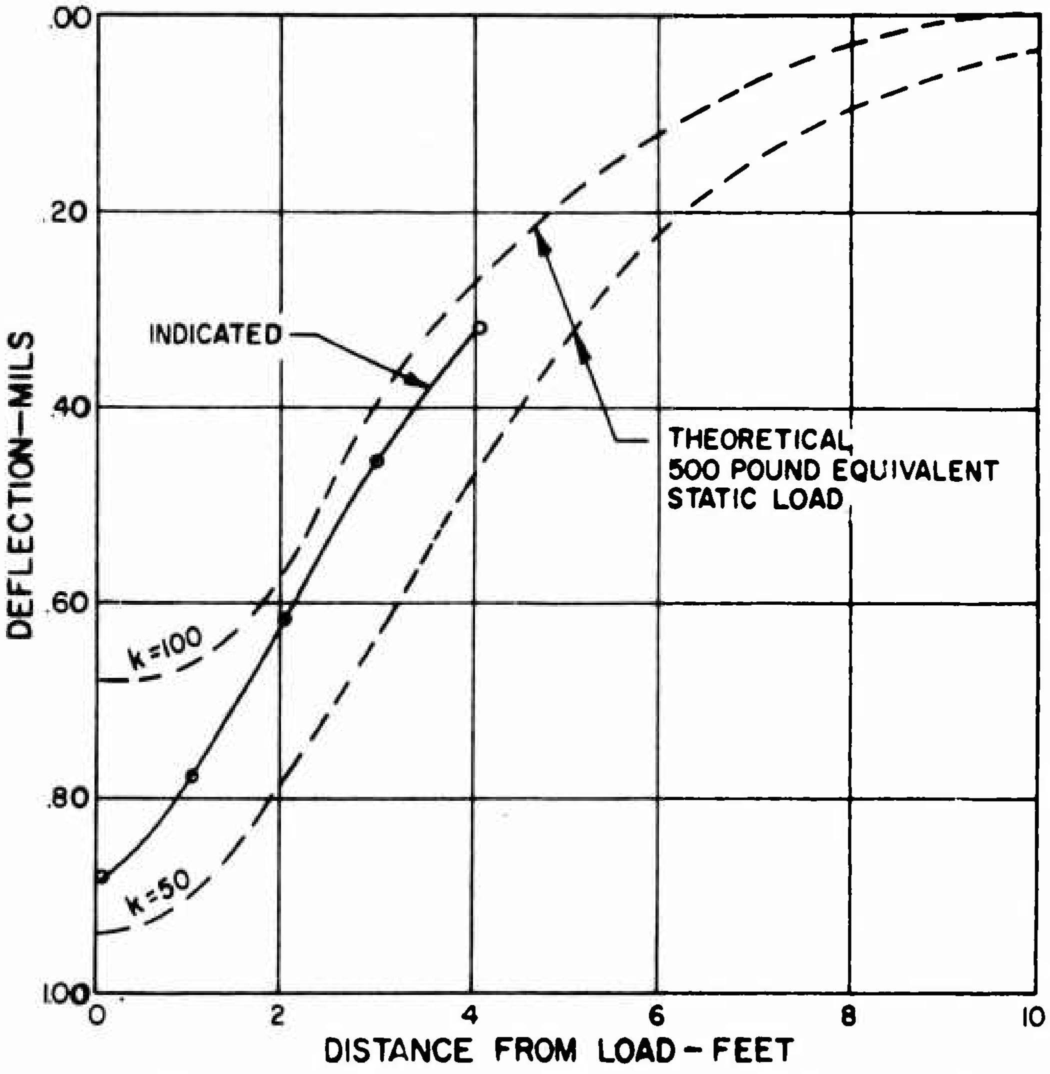


	DISTANCE FROM LOAD-FEET							
	0	1	2	3	4	7	10	15
DEFL.	0.38		0.30	0.26	0.20			
(MILS)	.42		.36	.32	.26			
	.38		.31	.26	.21			
	.37		.31	.27	.23			
	.40		.32	.27	.21			
	.38		.31	.27	.22			
	.46	0.40	.34	.29	.23			
	.41	.38	.34	.29	.24			
	.36	.33	.29	.25	.21			
	.37	.35	.32	.28	.24			
	.39	.36	.31	.26	.20			
	.38	.35	.31	.27	.22			
	.38	.35	.30	.26	.23	0.09	0.05	0.02
	.34	.31	.28	.24	.20	.10	.05	.02
AVG.	0.39	0.35	0.31	0.27	0.22	0.10	0.05	0.02

PAVEMENT DEFLECTION TESTS
BAKALAR AIR FORCE BASE
AREA 28-MID-SLAB
10" PCC REINF

OCTOBER 1966

FIGURE 20

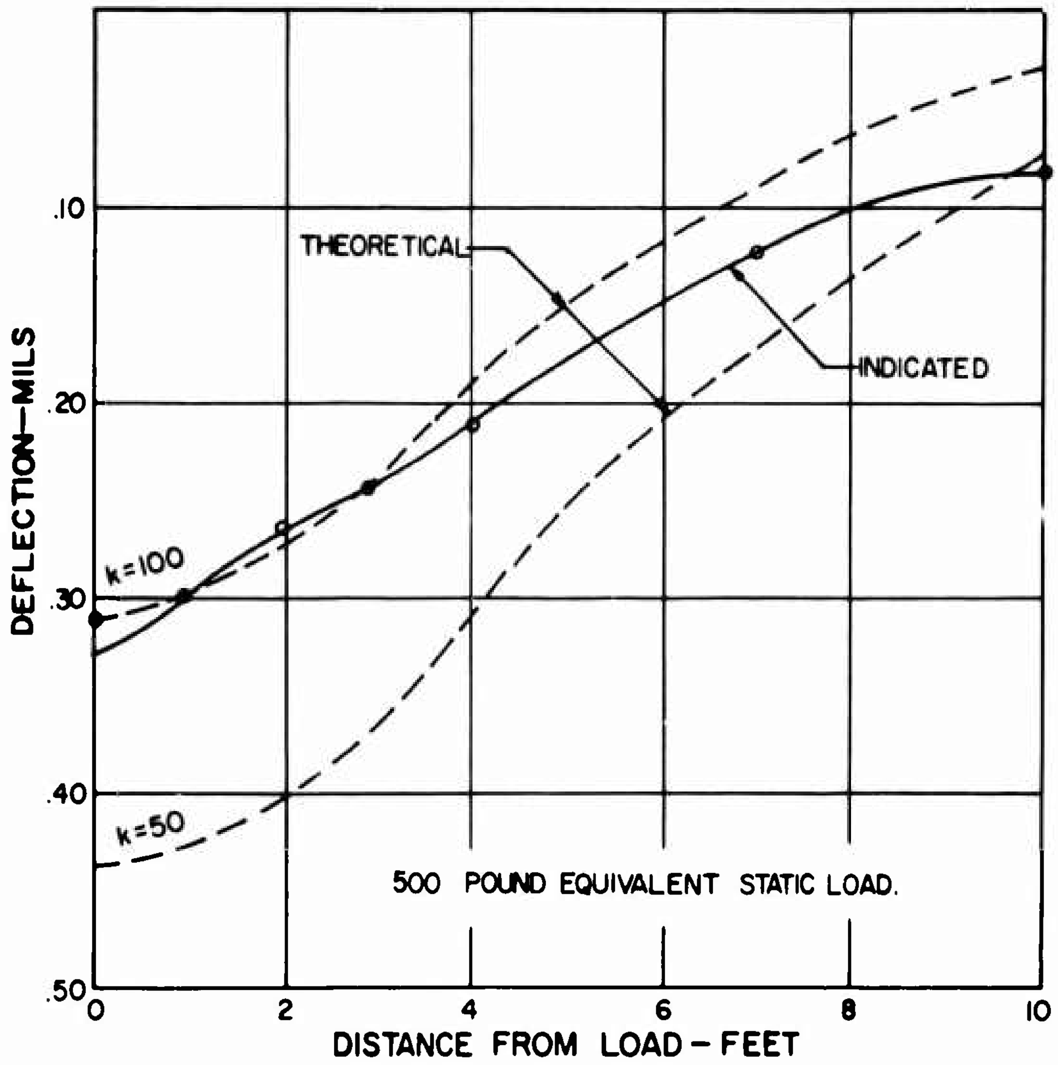


	DISTANCE FROM LOAD - FEET					
	0	1	2	3	4	
DEFL.	0.96	0.87	0.75	0.54	0.41	AREA 7
(MILS)	.81	.75	.59	.44	.32	
	.90	.81	.62	.46	.32	
	.84	.71	.54	.38	.28	AREA 15A
	.81	.70	.57	.43	.29	
	.93	.84	.65	.48	.31	AREA 26B
AVG.	0.88	0.78	0.62	0.46	0.32	

PAVEMENT DEFLECTION TESTS
BAKALAR AIR FORCE BASE
AREAS 7, 15A & 26B
6" PCC - MID-SLAB

OCTOBER 1966

FIGURE 21

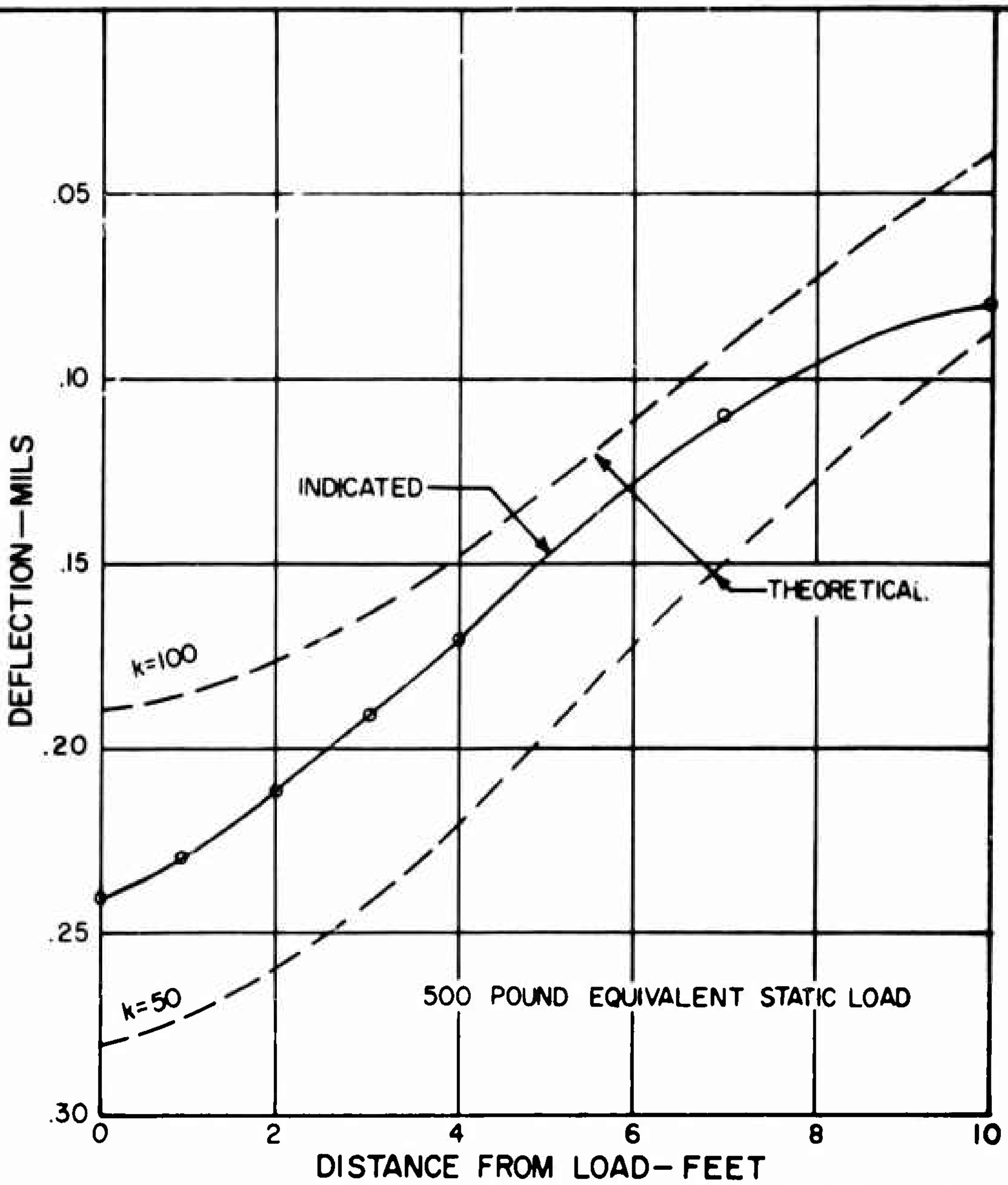


	DISTANCE FROM LOAD - FEET						
	0	1	2	3	4	7	10
DEFL.	0.36	0.32	0.29	0.26	0.22	0.13	0,08
(MILS)	36	.31	.29	.25	.21		
	.35	.31	.29	.25	.21		
	.34	.30	.27	.24	.20	.11	.07
	.34	.30	.27	.24	.20		
	.31	.29	.26	.24	.21		
	.29	.27	.24	.22	.19		
	.30	.28	.25	.23	.20		
AVG.	0.33	0.30	027	0.24	0.21	0.12	0.08

PAVEMENT DEFLECTION TESTS
WURTSMITH AIR FORCE BASE
AREAS 11 & 15
10" PCC - MID-SLAB
SAND SUBGRADE

OCTOBER 1966

FIGURE 22

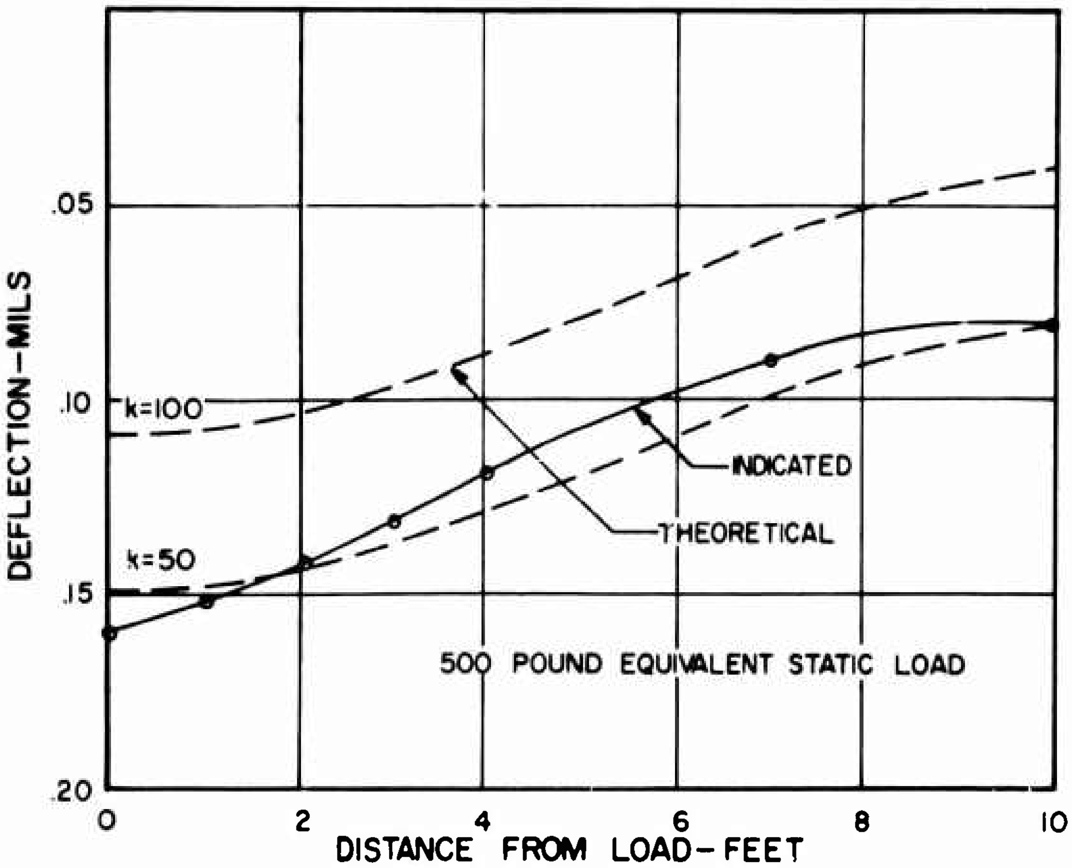


	DISTANCE FROM LOAD- FEET						
	0	1	2	3	4	7	10
DEFL. (MILS)	0.25	0.23	0.22	0.19	0.16	0.11	0.08
	.25	.23	.22	.19	.16	.11	.08
	.26	.25	.23	.20	.17	.11	.08
	.22	.22	.20	.19	.17		
	.23	.23	.22	.20	.18		
	.25	.23	.21	.20	.18		
	.23	.23	.21	.19	.17		
AVG.	0.24	0.23	0.21	0.19	0.17	0.11	0.08

PAVEMENT DEFLECTION TESTS
WURTSMITH AIR FORCE BASE
AREAS 4,5, & 16
14" PCC - MID - SLAB
SAND SUBGRADE

OCTOBER 1966

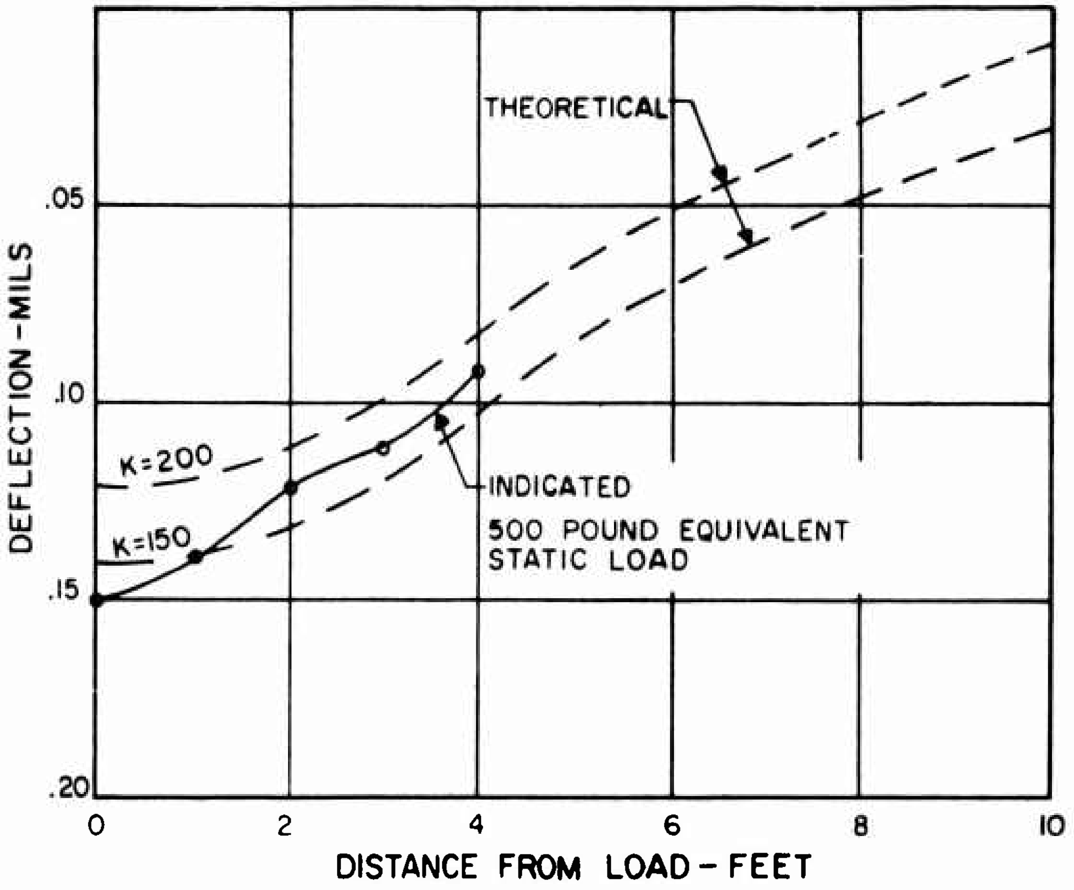
FIGURE 23



	DISTANCE FROM LOAD – FEET						
	0	1	2	3	4	7	10
DEFL (MILS)	0.17	0.15	0.15	0.13	0.12	0.09	0.08
	.16	.14	.14	.13	.11	.09	.07
	.17	.16	.15	.14	.14		
	.16	.16	.15	.14	.14		
	.16	.15	.14	.14	.13		
	.15	.15	.14	.13	.13		
	.15	.14	.13	.13	.12		
	.15	.14	.13	.13	.13		
	.14	.14	.13	.13	.13		
AVG.	0.16	0.15	0.14	0.13	0.12	0.09	0.08

PAVEMENT DEFLECTION TESTS
WURTSMITH AIR FORCE BASE
AREAS 8, 26, 31 & 40
21" PCC – MID – SLAB
SAND SUBGRADE

OCTOBER 1966
FIGURE 24

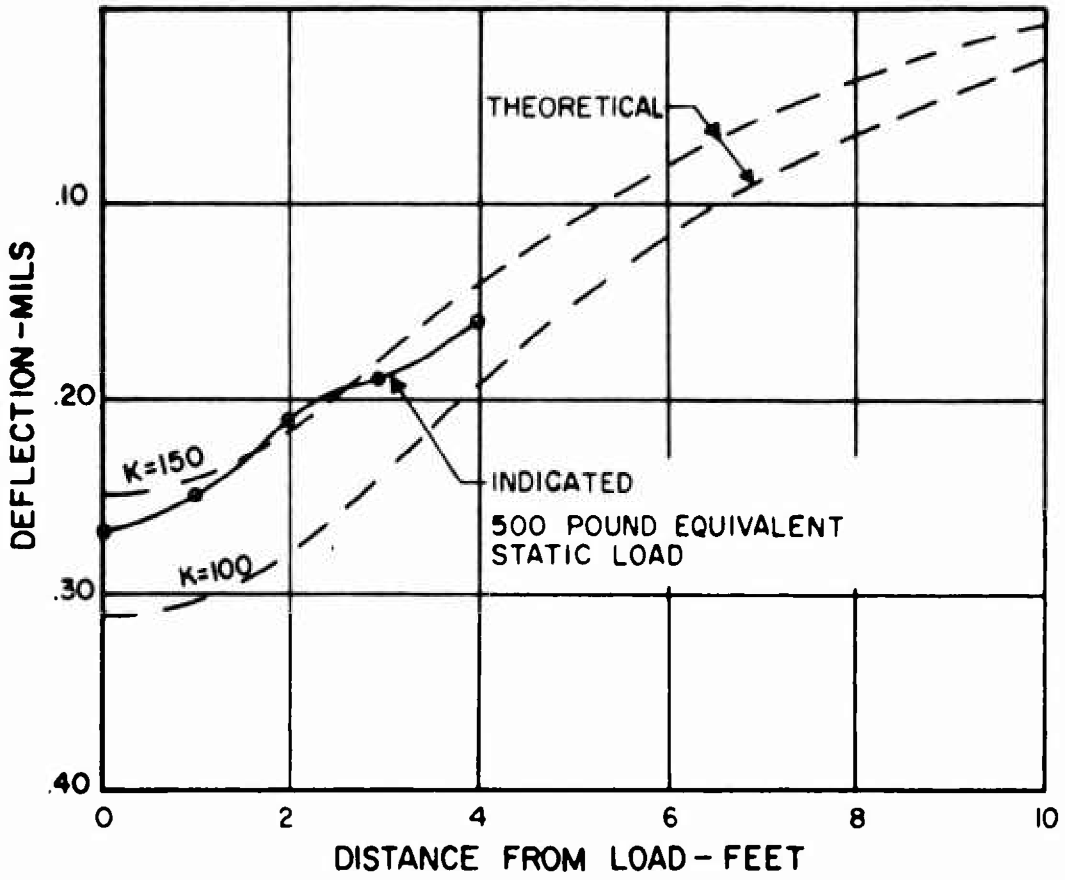


	DISTANCE FROM LOAD - FEET				
	0	1	2	3	4
DEFL.	0.15	0.14	0.13	0.11	0.09
(MILS)	.16	.15	.13	.11	.10
	.16	.14	.13	.11	.10
	.15	.14	.12	.11	.09
	.15	.14	.12	.11	.09
	.14	.13	.11	.11	.10
AVG.	0.15	0.14	0.12	0.11	0.09

PAVEMENT DEFLECTION TESTS
WRIGHT PATTERSON AFB
AREA 6 - MID-SLAB
15" PCC
GRAVELLY CLAY SUBGRADE

OCTOBER 1966

FIGURE 25

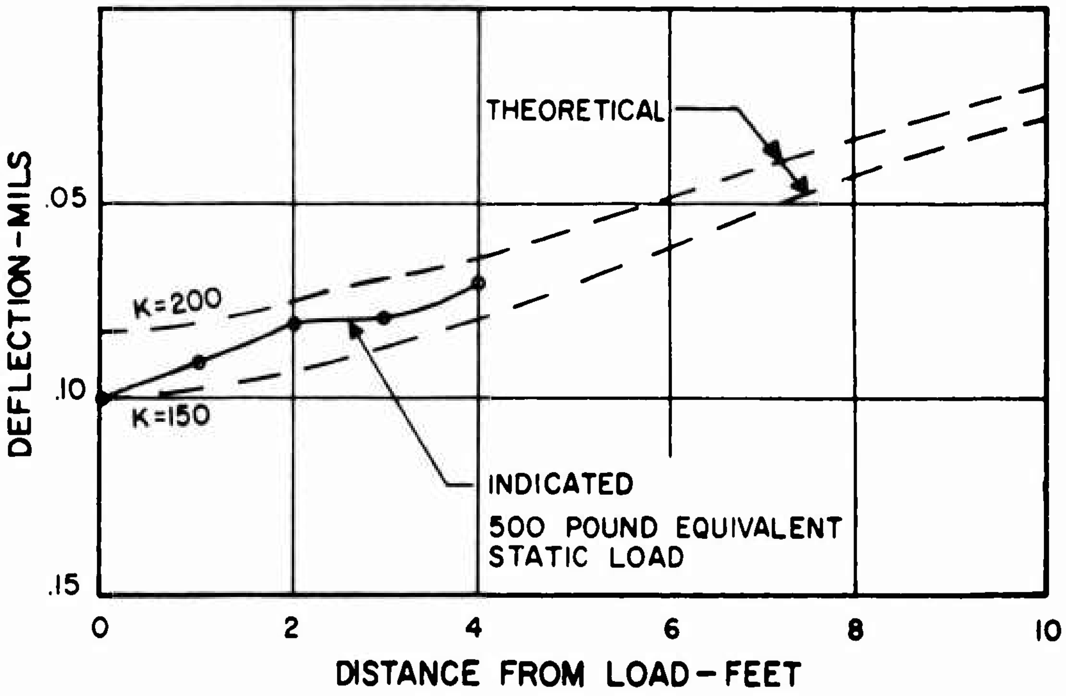


	DISTANCE FROM LOAD-FEET				
	0	1	2	3	4
DEFL. (MILS)	0.26	0.25	0.22	0.24	0.19
	.26	.23	.20	.16	.13
	.30	.28	.25	.24	.20
	.28	.26	.22	.21	.18
	.27	.25	.21	.17	.13
	.24	.22	.18	.14	.11
AVG.	0.27	0.25	0.21	0.19	0.16

PAVEMENT DEFLECTION TESTS
WRIGHT PATTERSON AFB
AREAS 23 & 24 MID-SLAB
10" PCC
SILTY SAND SUBGRADE

OCTOBER 1966

FIGURE 26

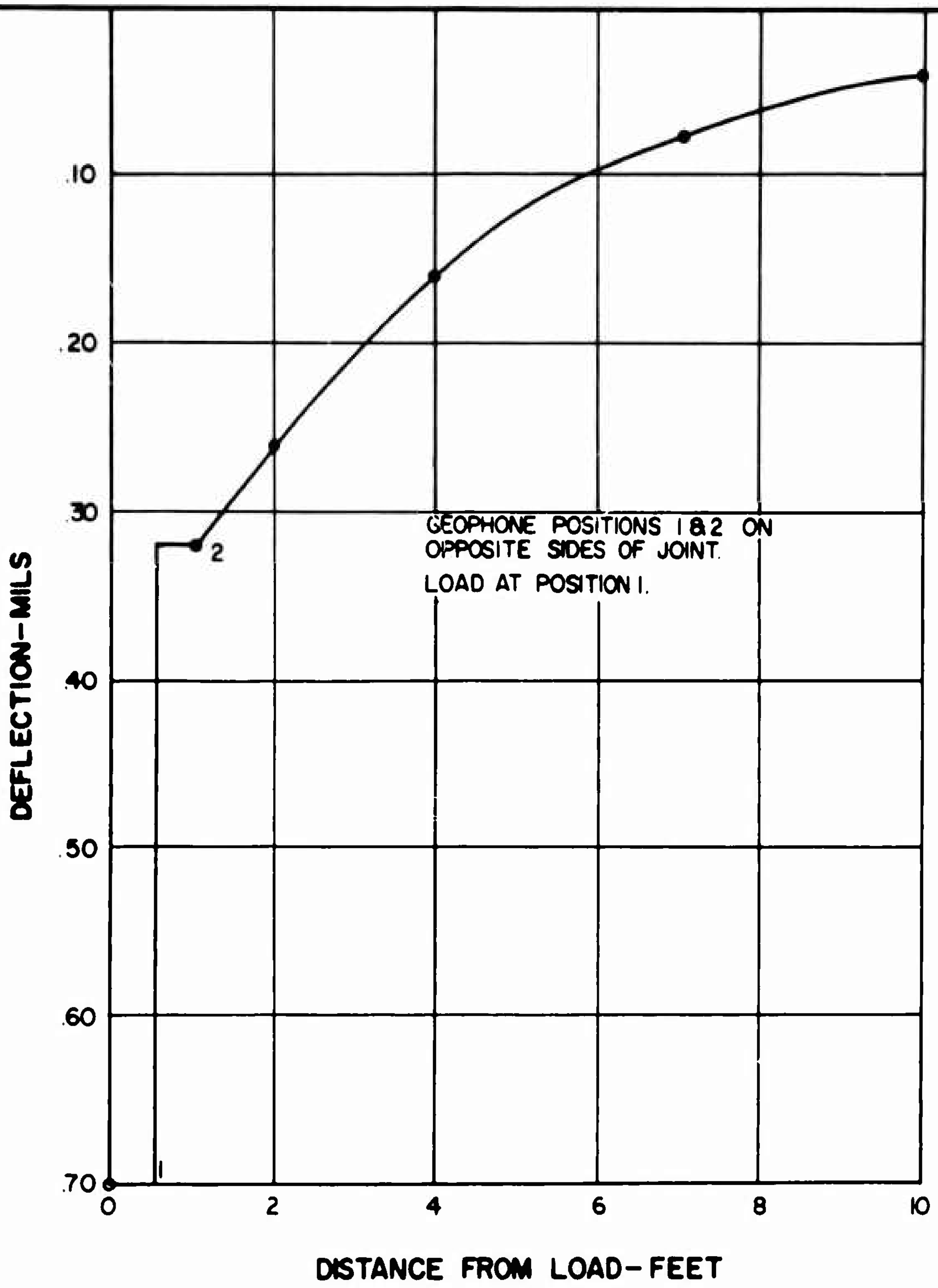


	DISTANCE FROM LOAD - FEET				
	0	1	2	3	4
DEFL.	0.10	0.09	0.09	0.07	0.07
(MILS)	.10	.09	.08	.07	.08
	.09	.08	.08	.08	.08
	.09	.08	.07	.08	.07
AVG.	0.10	0.09	0.08	0.08	0.07

PAVEMENT DEFLECTION TESTS
WRIGHT PATTERSON AFB
AREA 8 - MID-SLAB
19" PCC
GRAVELLY CLAY SUBGRADE

OCTOBER 1966

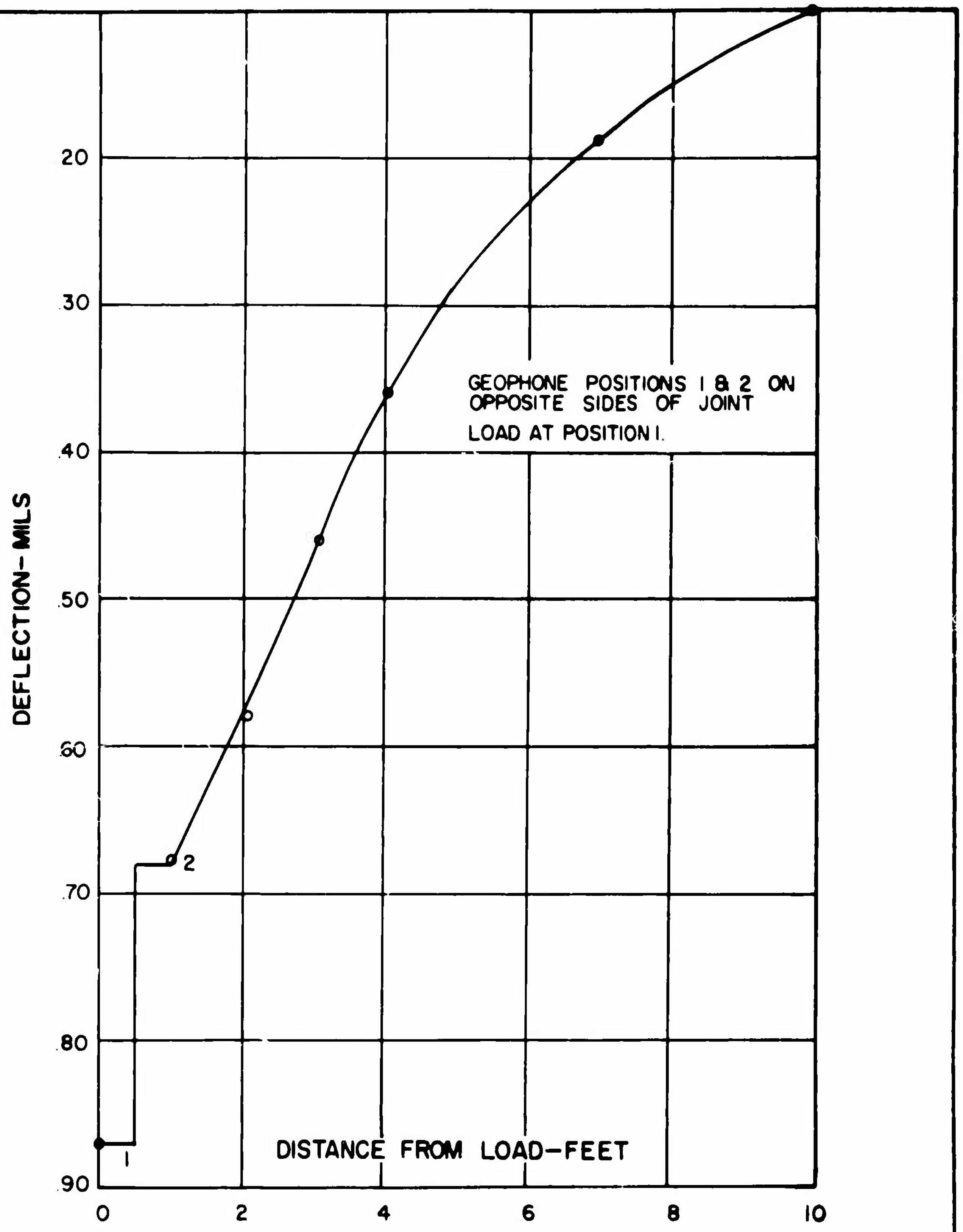
FIGURE 27



LOAD TRANSFER TESTS
SHOWING LARGE VERTICAL DISPLACEMENT
BETWEEN SLABS (STEP-UP)
CLINTON COUNTY AFB
TEST AREA 25-DUMMY JOINT
11" PCC
LEAN CLAY SUBGRADE

SEPTEMBER 1966

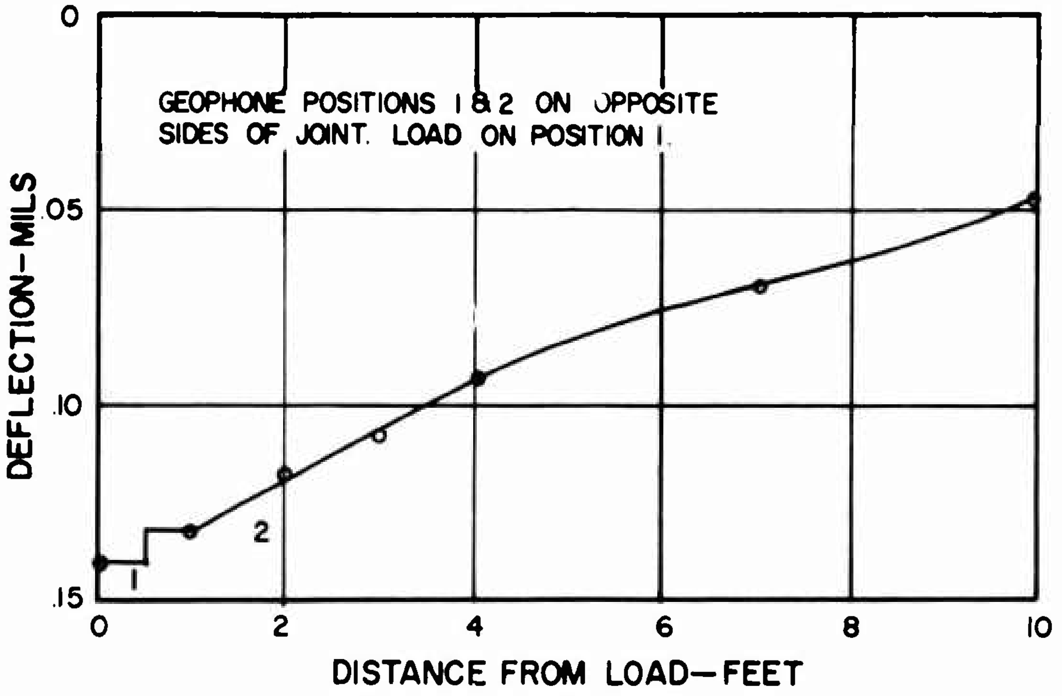
FIGURE 28



LOAD TRANSFER TEST
SHOWING MEDIUM VERTICAL DISPLACEMENT
BETWEEN SLABS (STEP UP)
WURTSMITH AFB
TEST AREA 3-DUMMY JOINT
14" PCC
SAND SUBGRADE

OCTOBER 1966

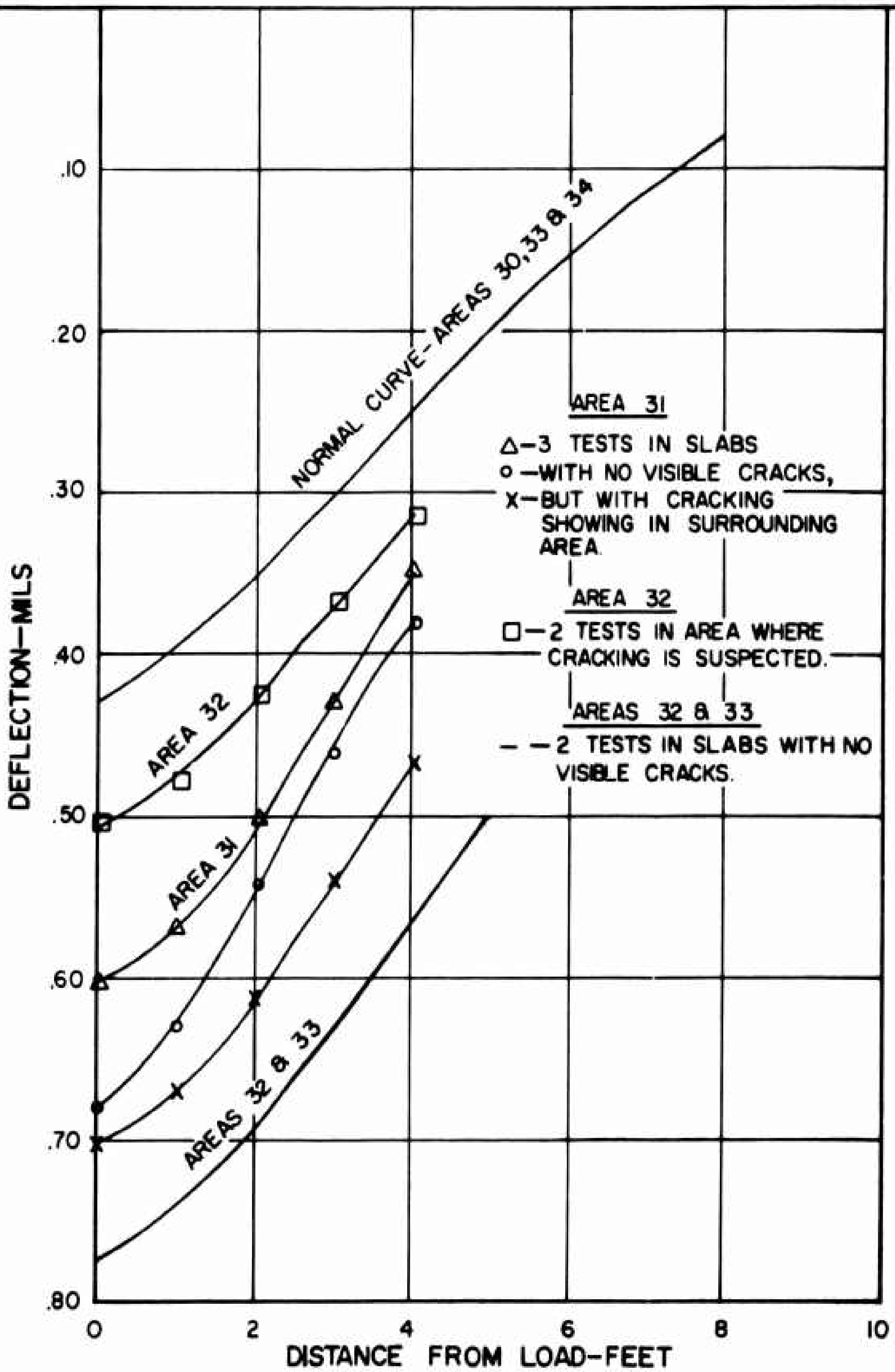
FIGURE 29



LOAD TRANSFER TEST
SHOWING SMALL VERTICAL DISPLACEMENT
BETWEEN SLABS (STEP UP)
CLINTON COUNTY AFB
TEST AREA 23 A-DUMMY JOINT
21" PCC
LEAN CLAY SUBGRADE

SEPTEMBER 1966

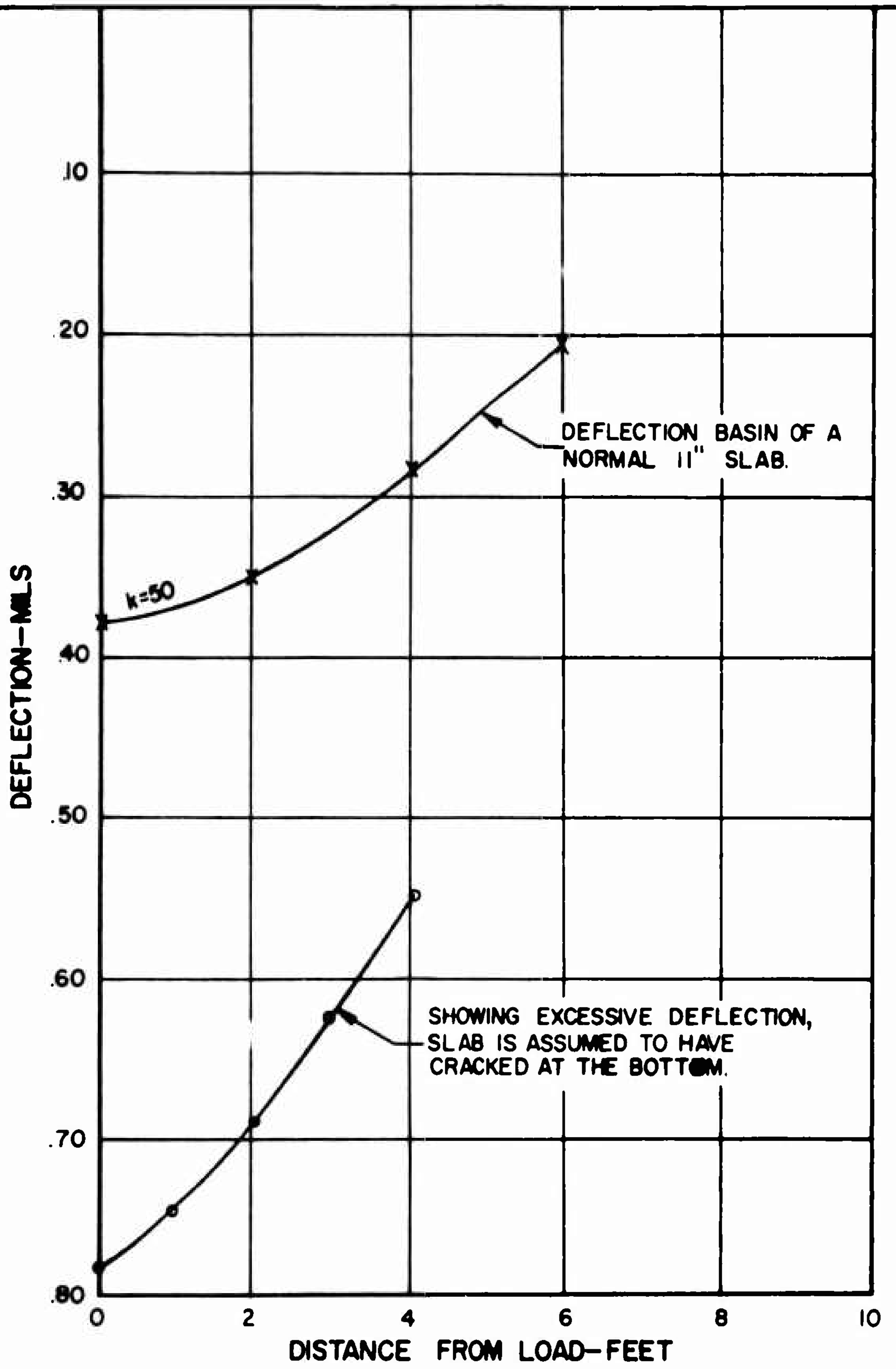
FIGURE 30



PAVEMENT DEFLECTION TESTS
DEPARTURE FROM NORMAL
BAKALAR AFB
11" PCC SLAB-INTERIOR

OCTOBER 1966

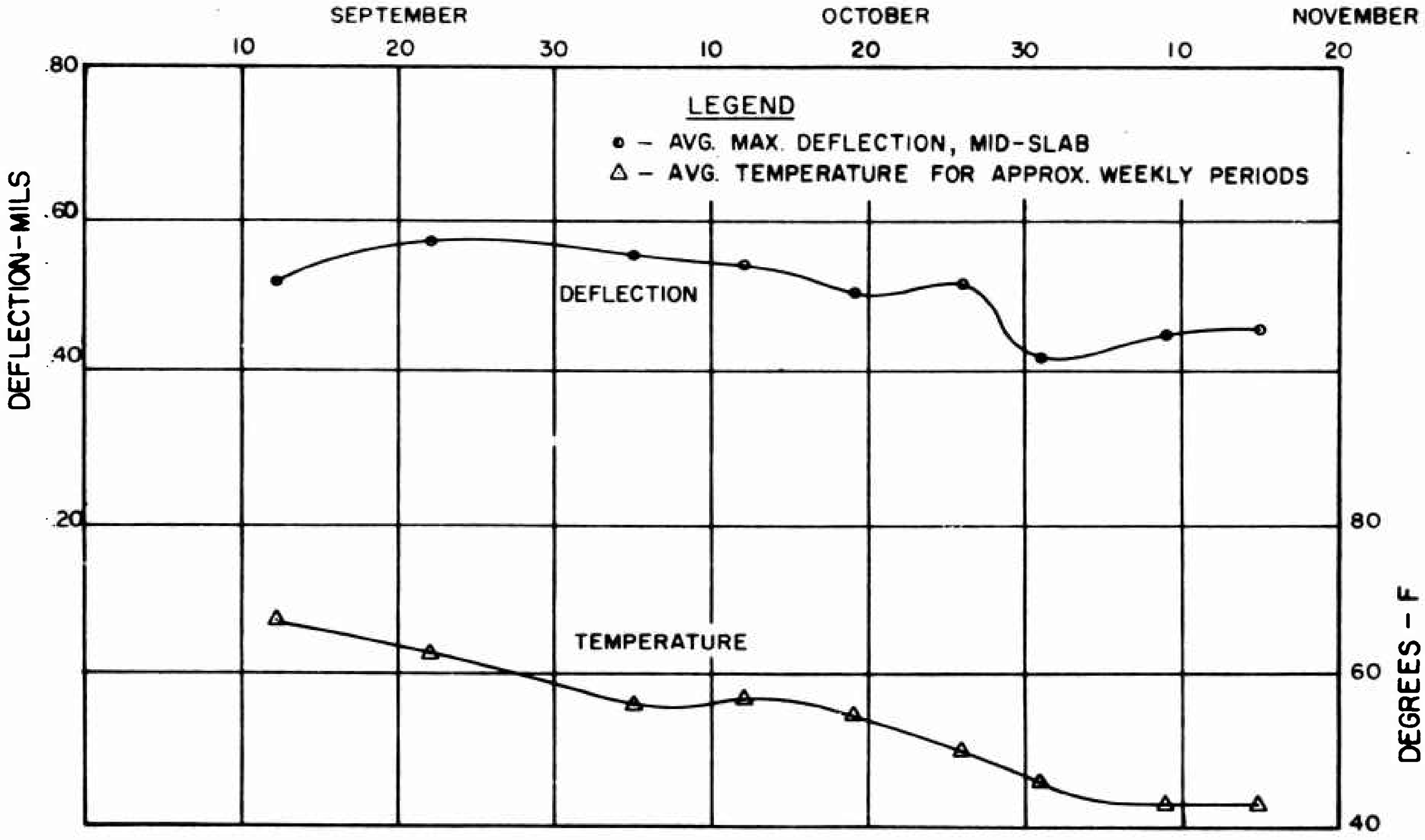
FIGURE 31



PAVEMENT DEFLECTION TESTS
DEPARTURE FROM NORMAL
BAKALAR AFB
AREA 32 A-11" PCC
OPERATIONS APRON EXTENSION

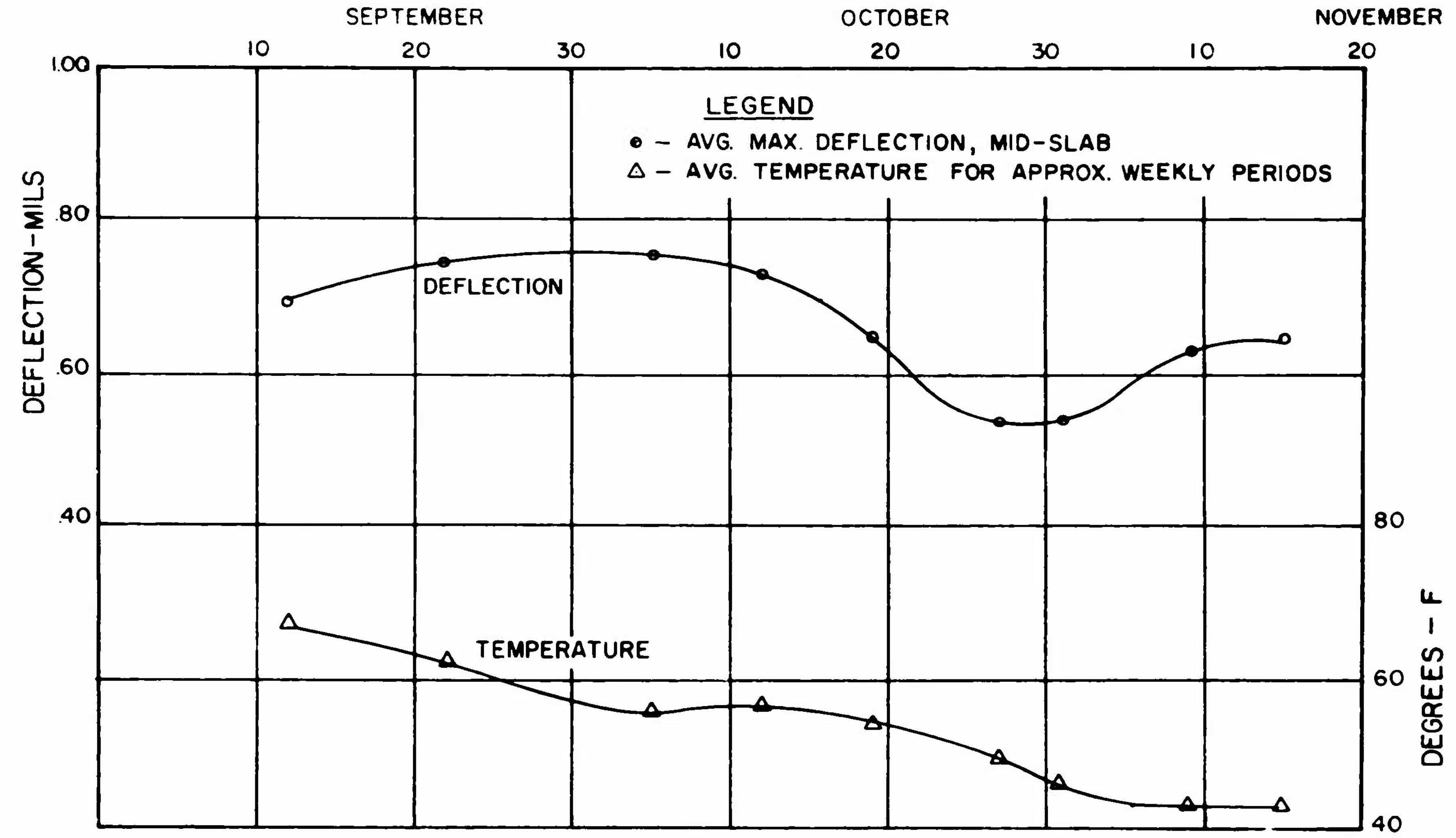
OCTOBER 1966

FIGURE 32



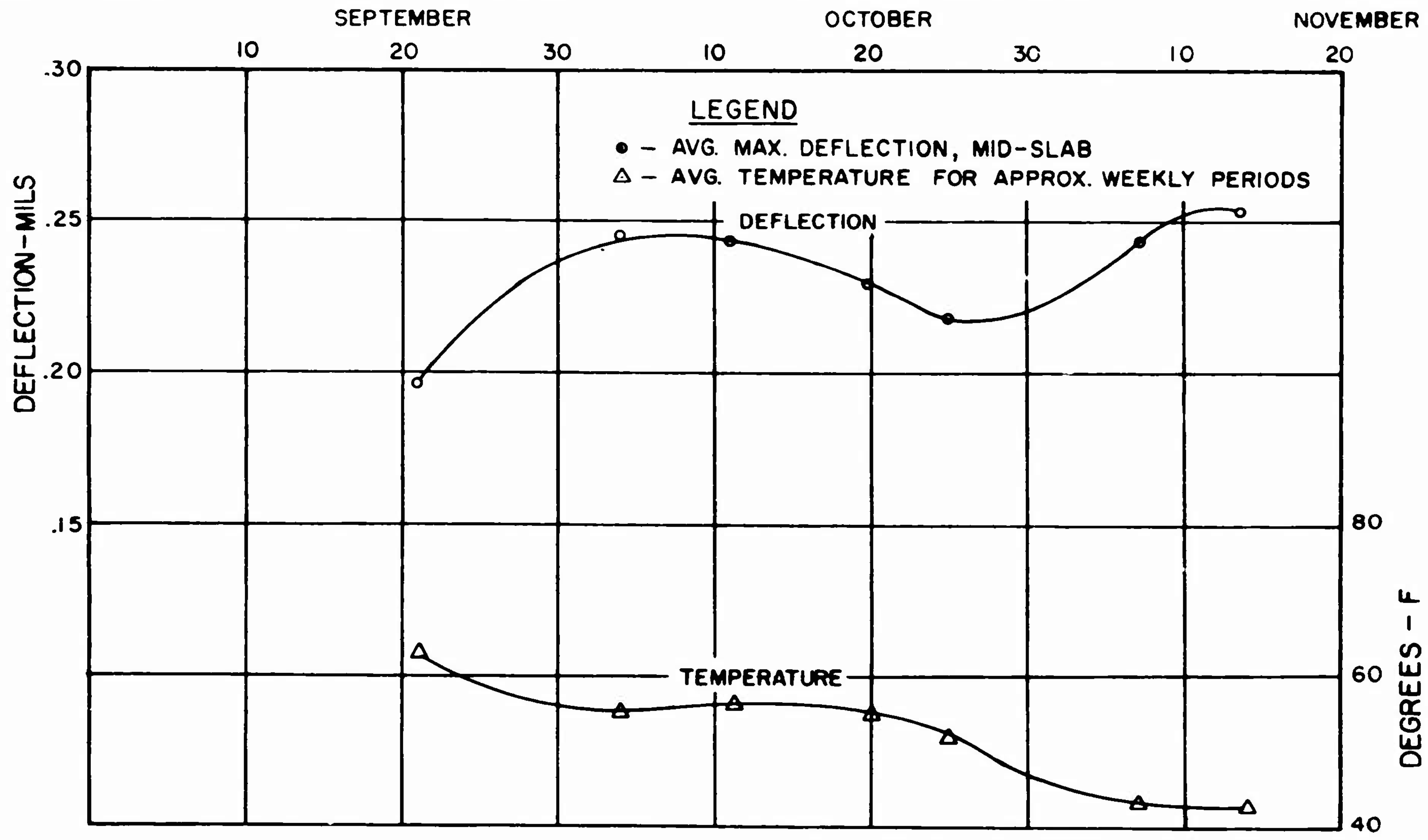
DEFLECTION – TEMPERATURE CHART
LUNKEN MUNICIPAL AIRPORT
AREAS 5, 6, 9 & 10
TAXIWAY A – 8" PCC REINFORCED

FIGURE 33



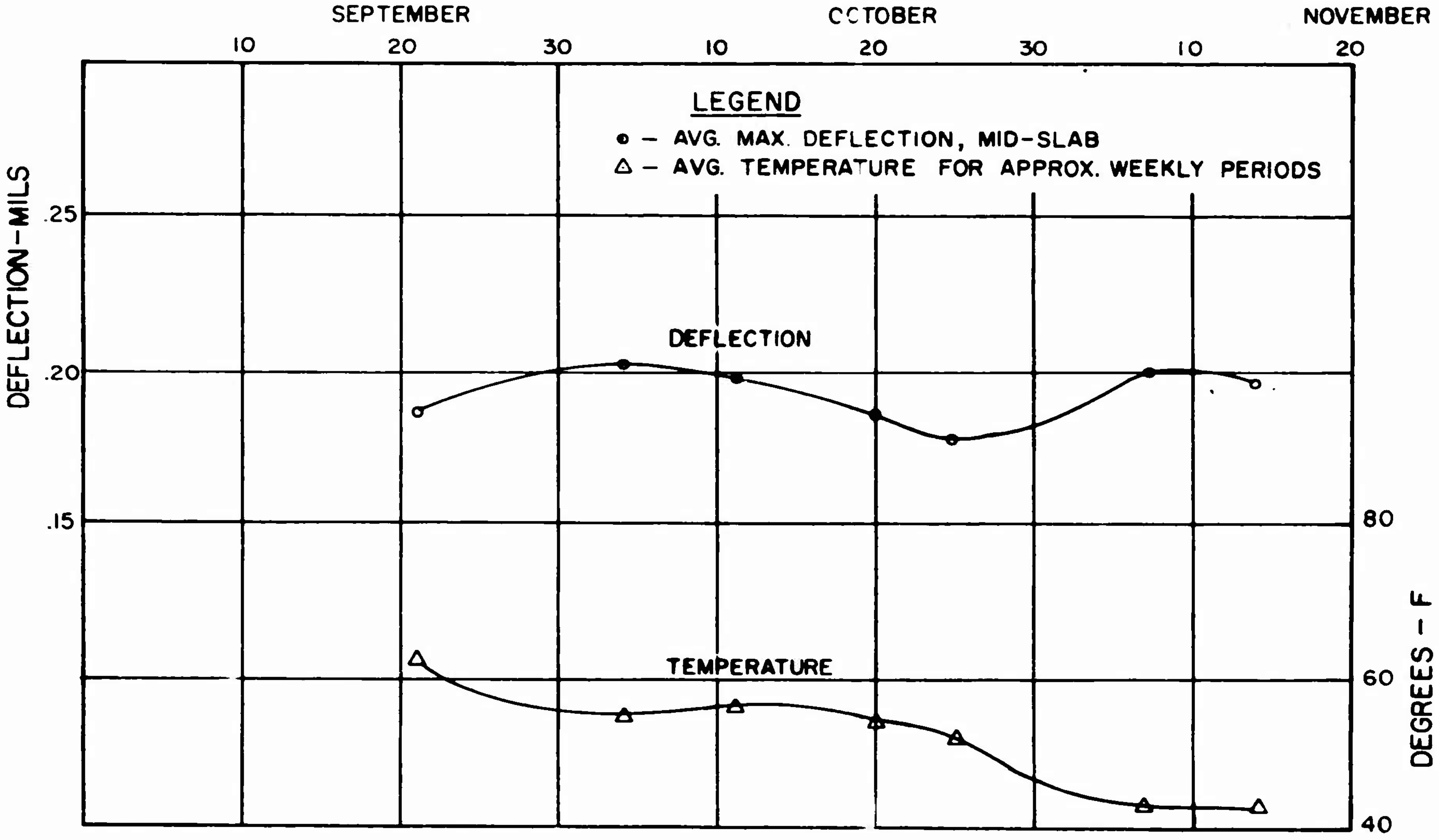
DEFLECTION—TEMPERATURE CHART
LUNKEN MUNICIPAL AIRPORT
AREAS 1, 2, 3, 4, 7, & 8
APRON - 7" PCC REINFORCED

FIGURE 34



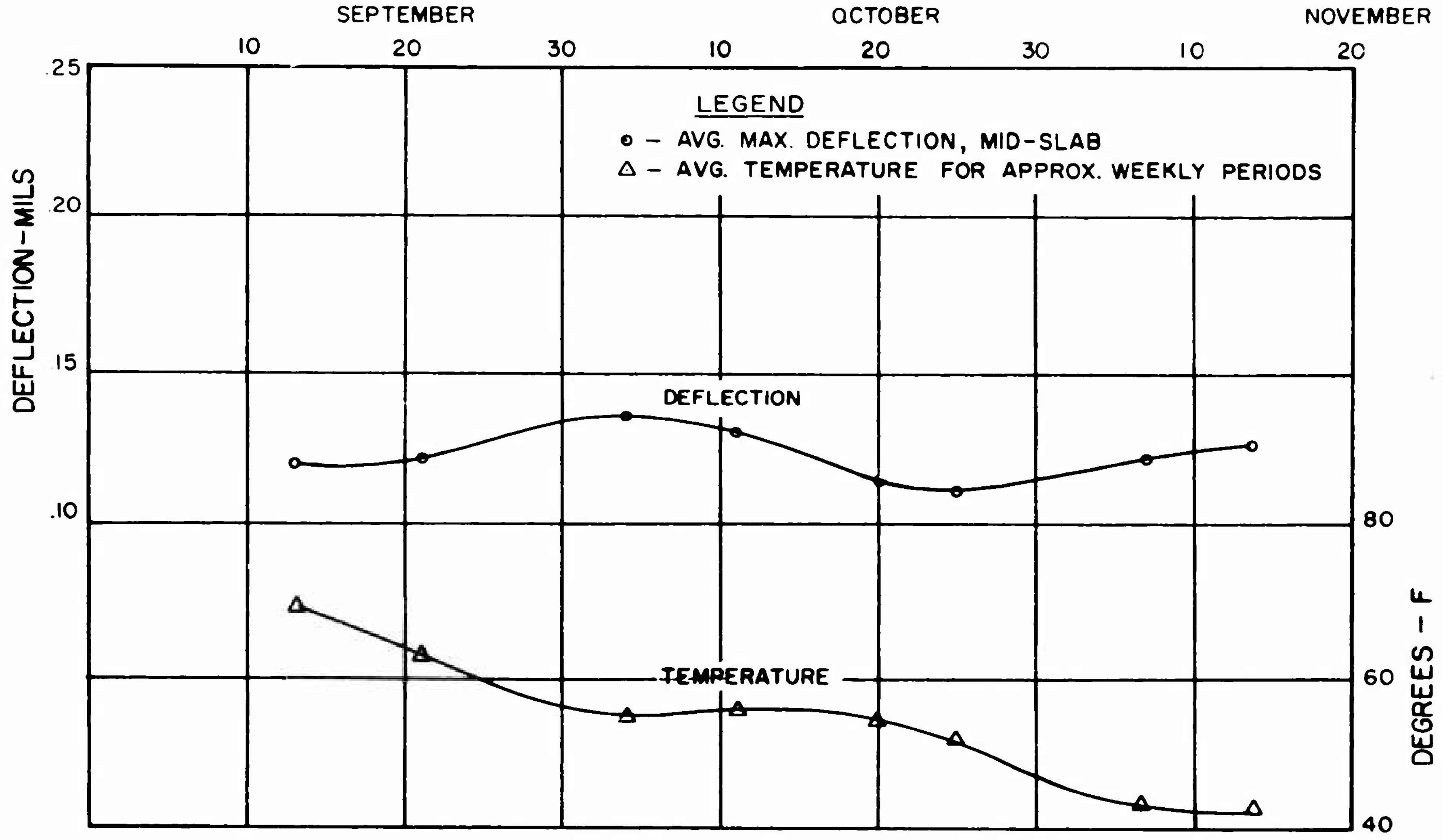
DEFLECTION–TEMPERATURE CHART
SHARONVILLE TEST TRACK
AREA 2–ITEM 60–12" PCC

FIGURE 35



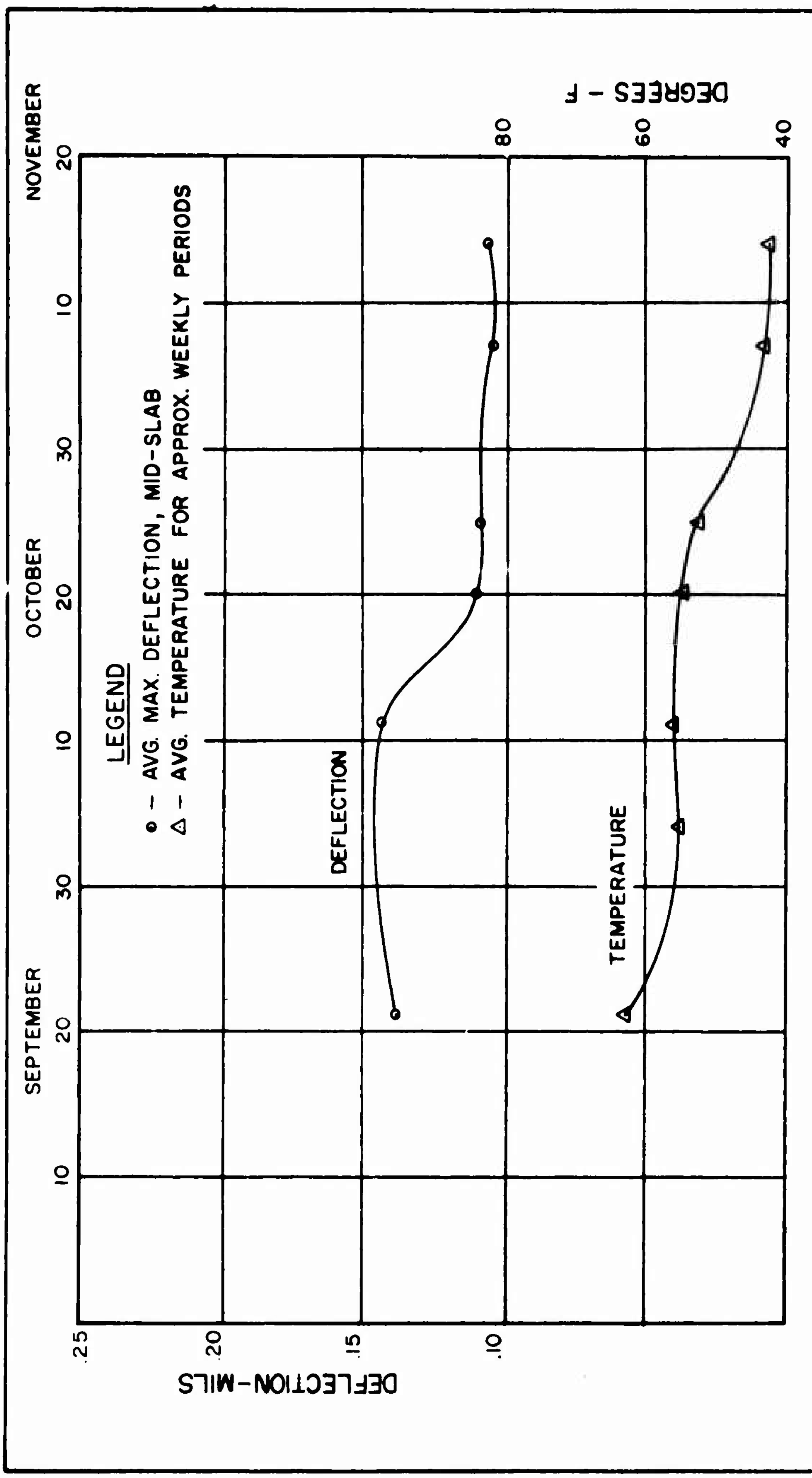
DEFLECTION–TEMPERATURE CHART
SHARONVILLE TEST TRACK
AREA I - ITEM 59 – 16" PCC

FIGURE 36



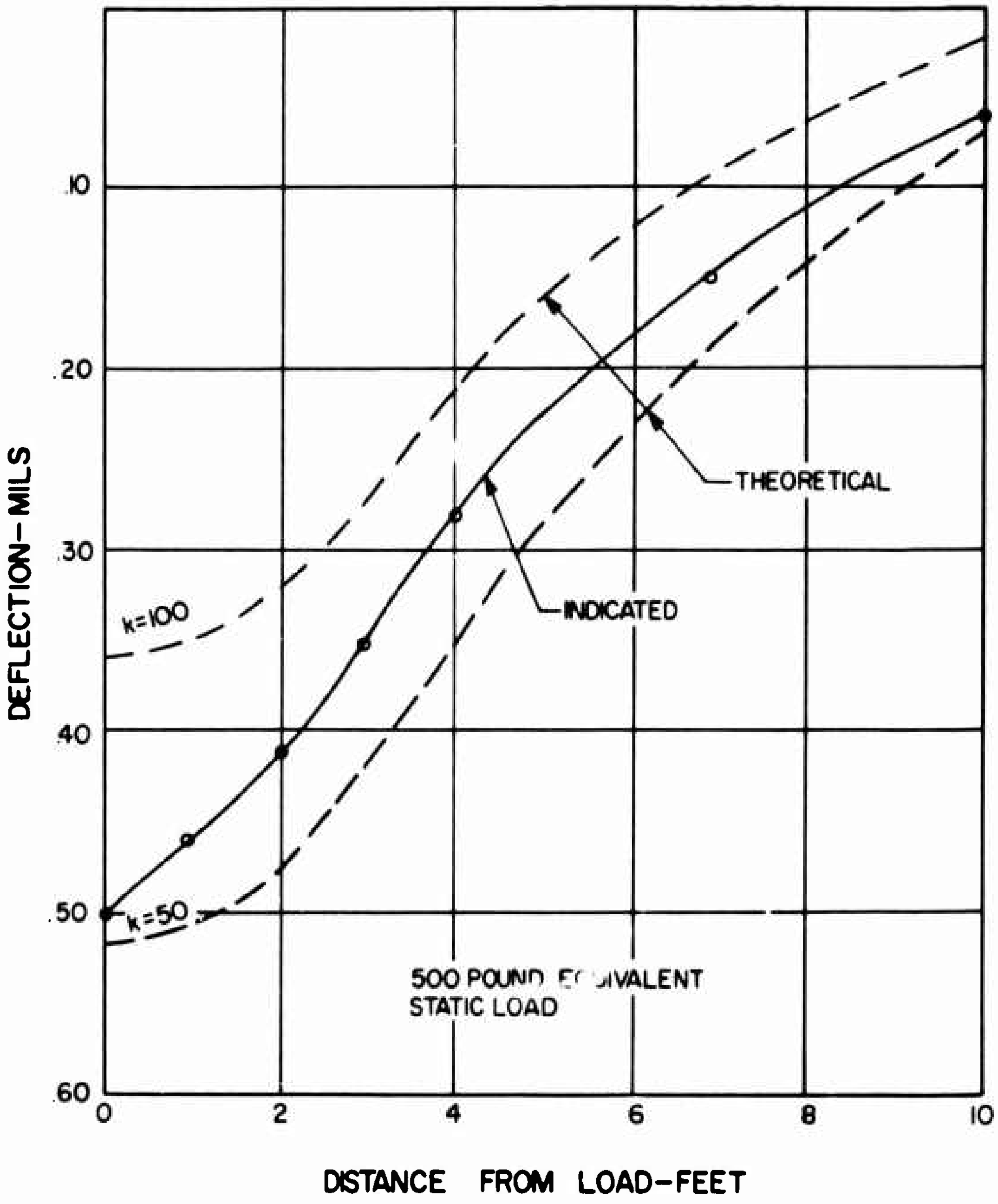
DEFLECTION – TEMPERATURE CHART
SHARONVILLE TEST TRACK
AREA 4 – ITEM 73 - 24" PCC

FIGURE 37



DEFLECTION-TEMPERATURE CHART
SHARONVILLE TEST TRACK
AREA 3 - ITEM 60 - 16"/6" PCC

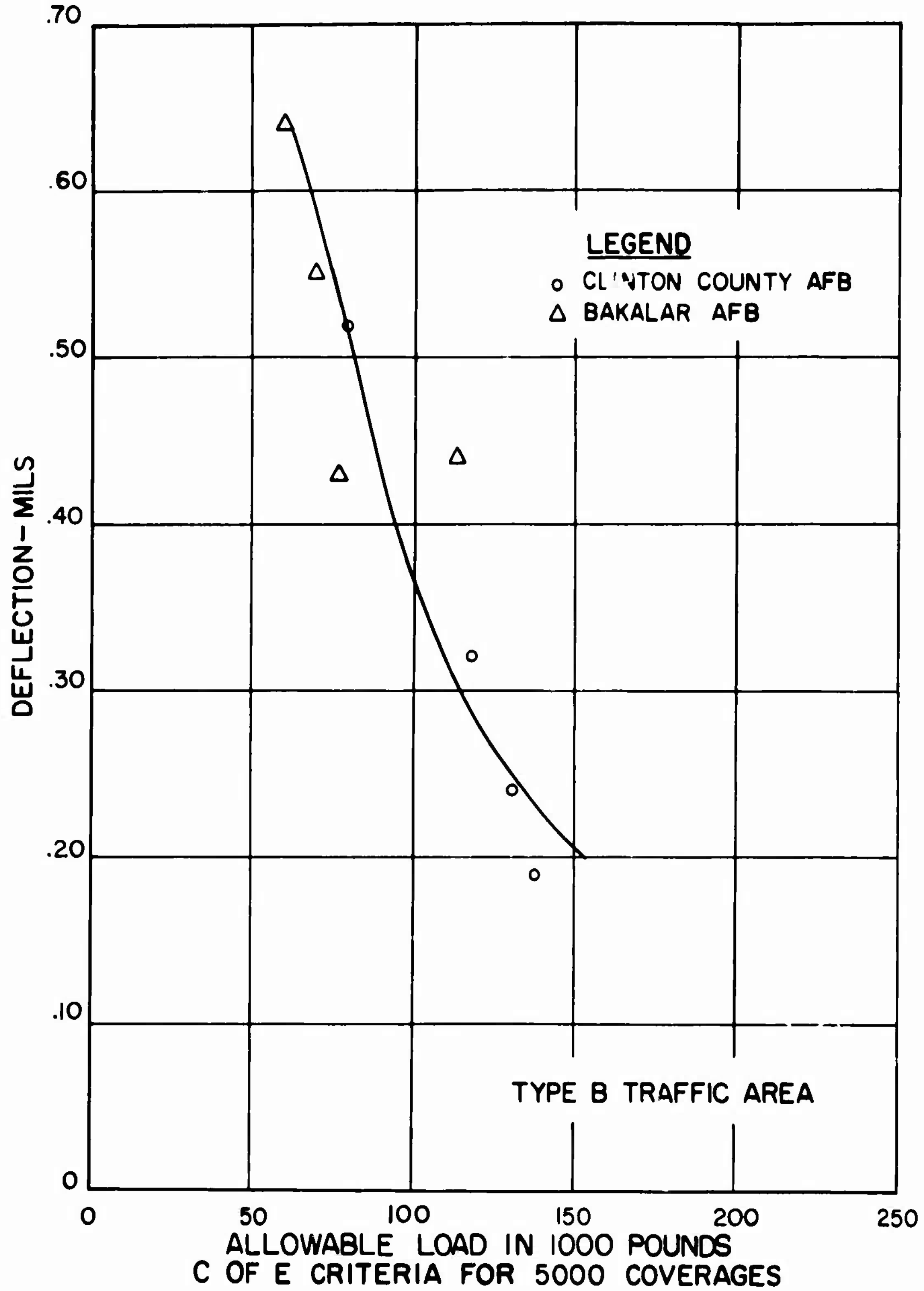
FIGURE 38



PAVEMENT DEFLECTION TESTS
SHARONVILLE TEST TRACK
TEST AREAS 9,10,11 & 12
9" PCC PRESTRESSED-MID-SLAB

OCTOBER-NOVEMBER 1966

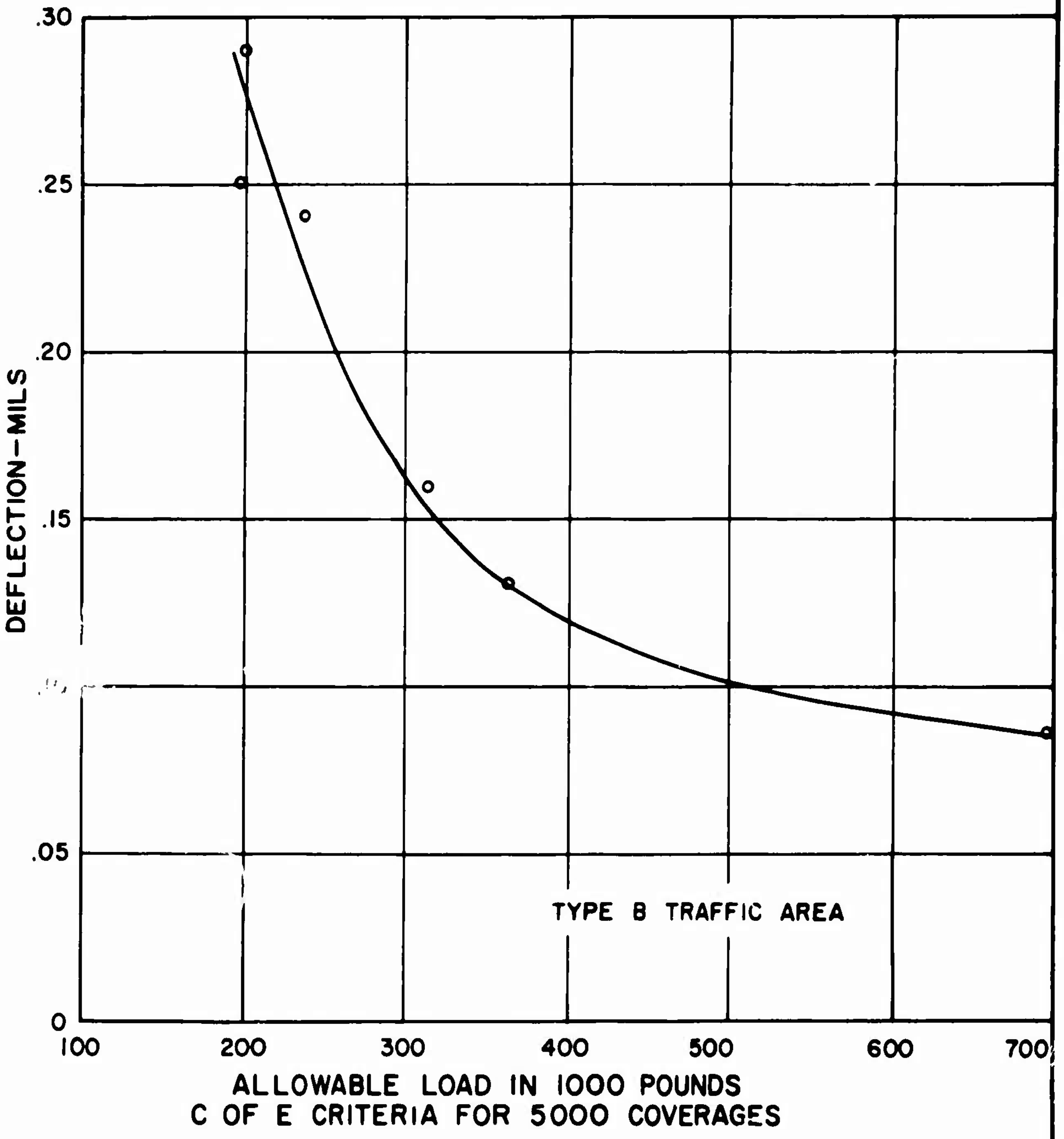
FIGURE 39



DYNAFLECT TESTS
CLINTON COUNTY AFB & BAKALAR AFB
DEFLECTION VS. ALLOWABLE LOAD
C-119 AIRCRAFT

SEPT. - OCT. 1966

FIGURE 40

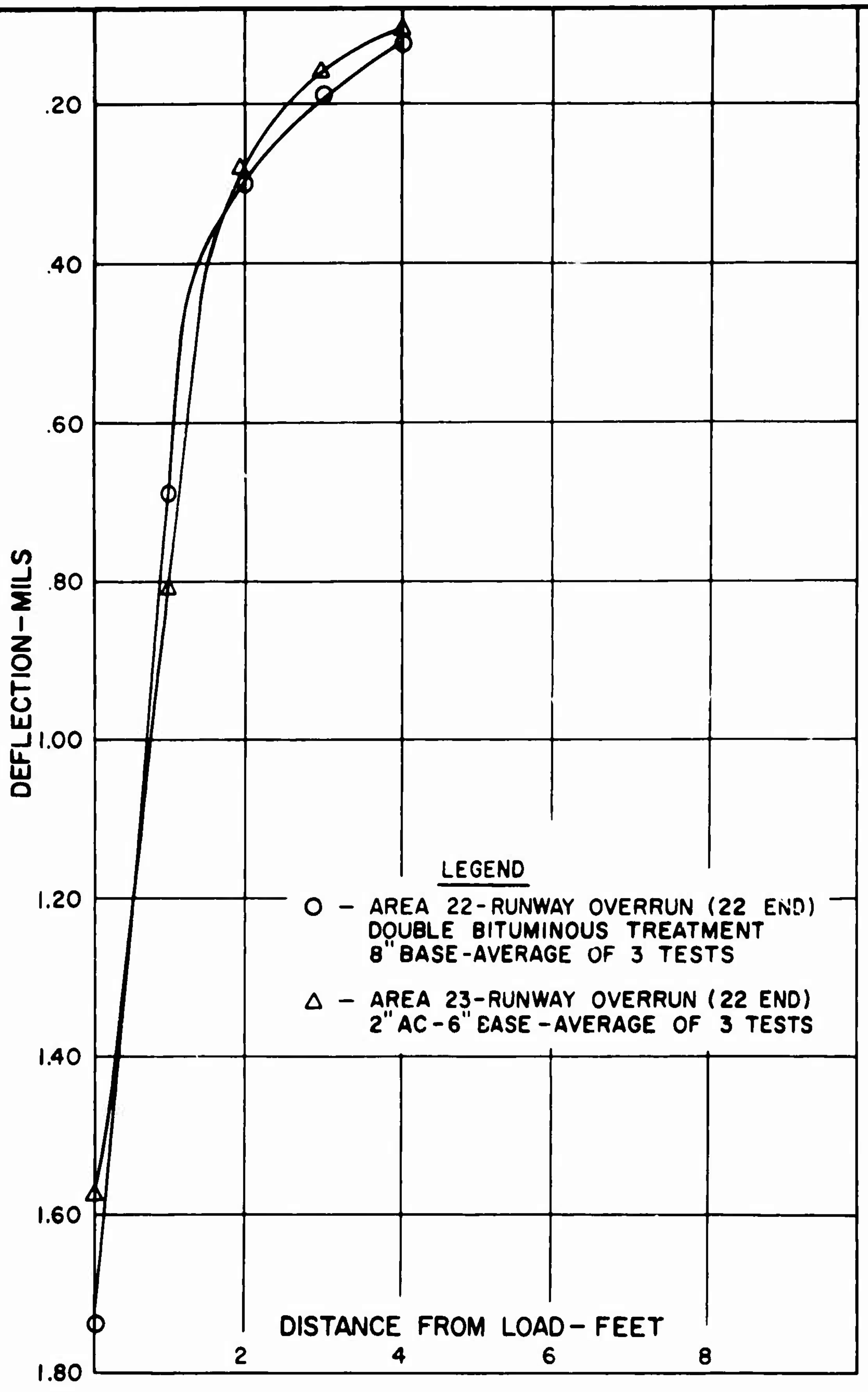


ALLOWABLE LOAD IN 1000 POUNDS
C OF E CRITERIA FOR 5000 COVERAGES

DYNAFLECT TESTS
WRIGHT PATTERSON AFB
DEFLECTION VS. ALLOWABLE LOAD
B-52 AIRCRAFT

OCTOBER 1966

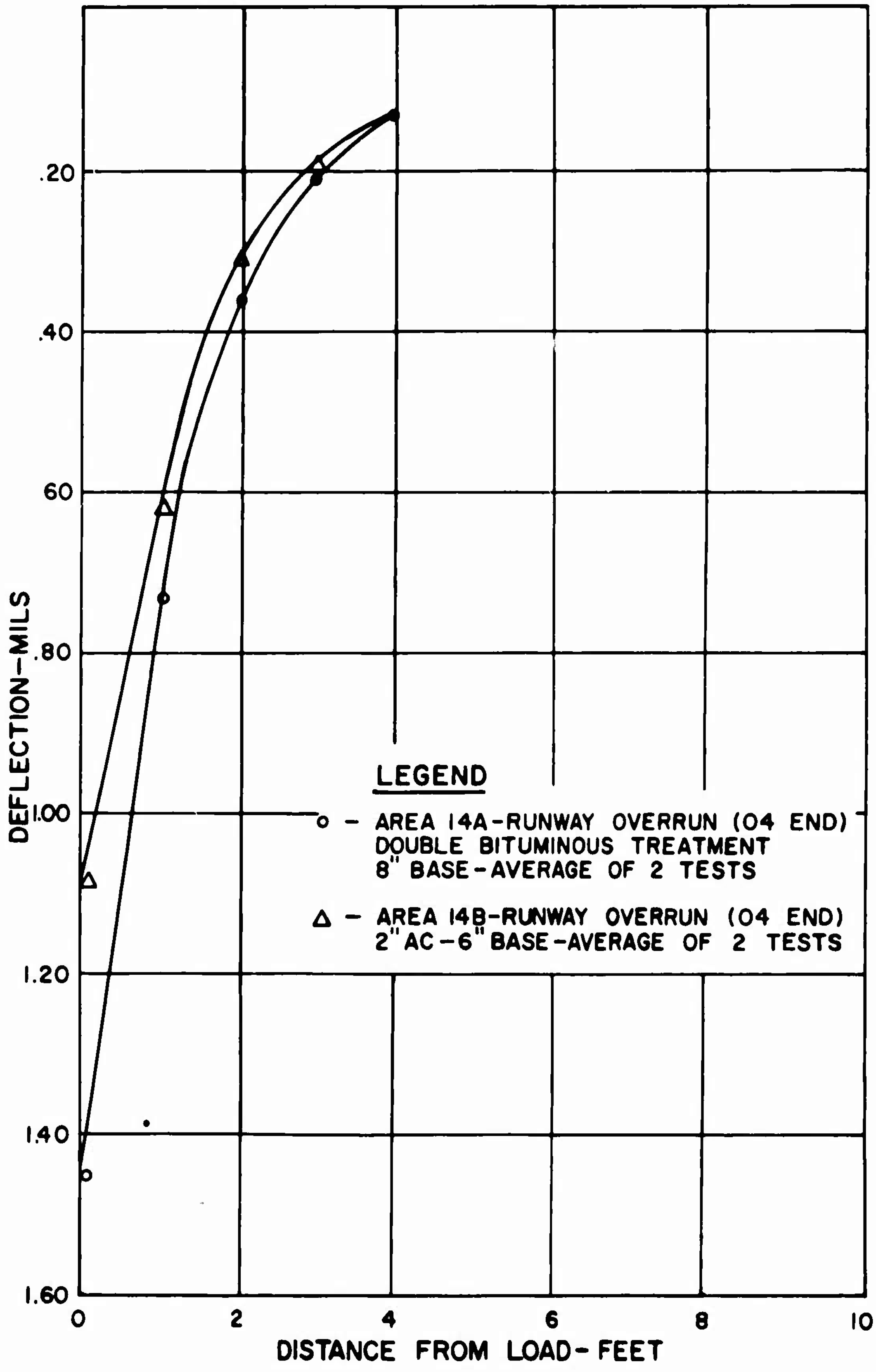
FIGURE 41



DYNAFLECT TESTS
FLEXIBLE PAVEMENT DEFLECTION TESTS
BAKALAR AIR FORCE BASE
CLAYEY SAND-SILTY SAND SUBGRADE

OCTOBER 1966

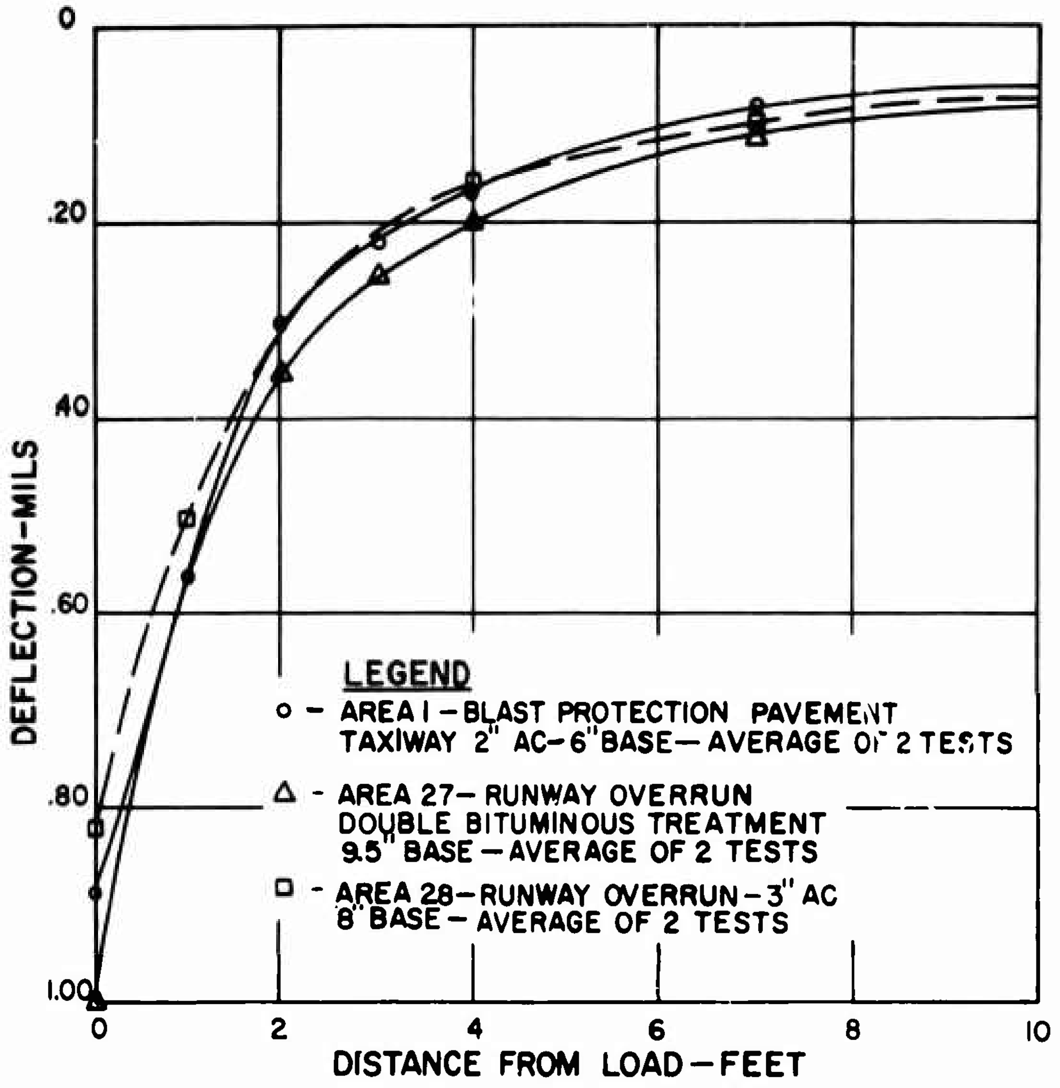
FIGURE 42



DYNAFLECT TESTS
FLEXIBLE PAVEMENT DEFLECTION TESTS
BAKALAR AIR FORCE BASE
CLAYEY SAND-SILTY SAND SUBGRADE

OCTOBER 1966

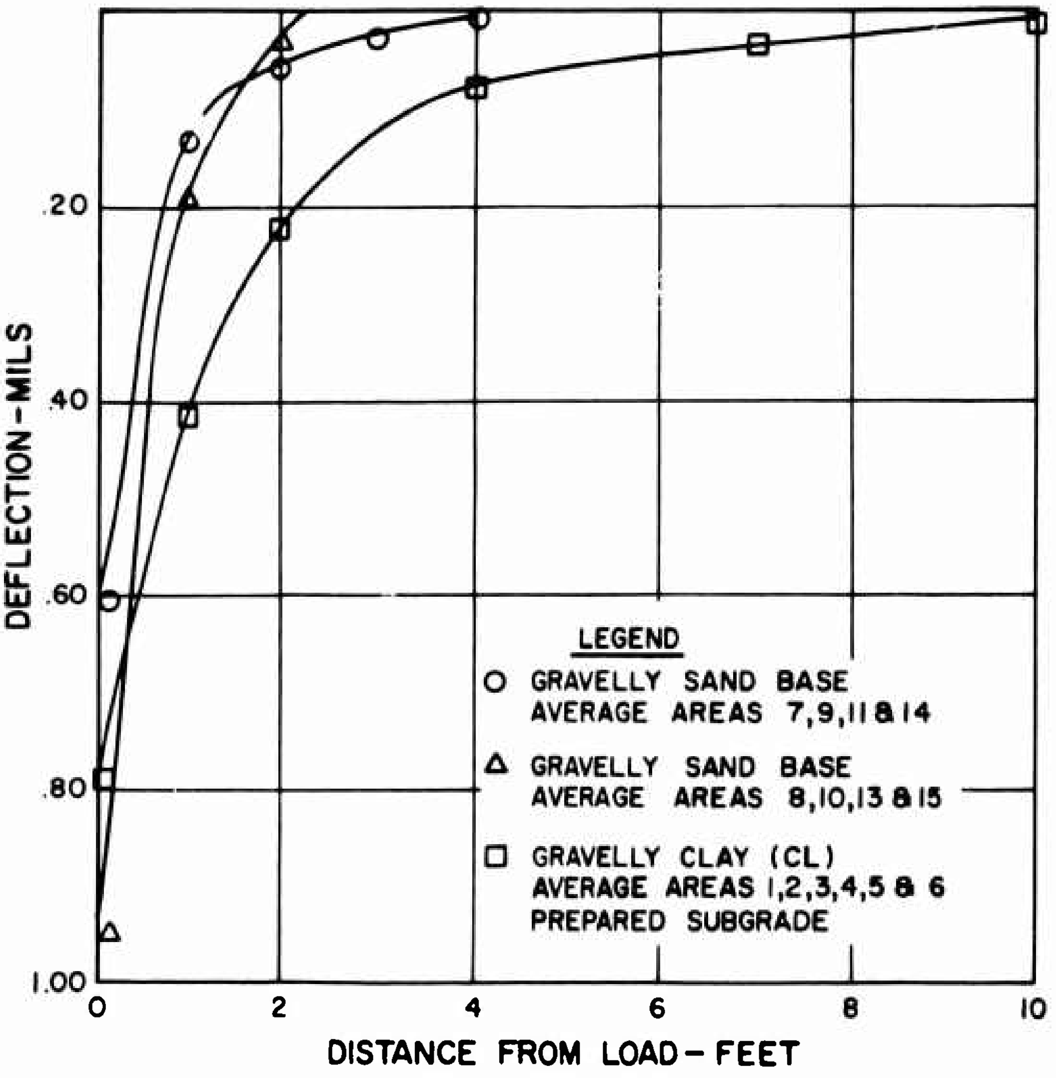
FIGURE 43



DYNAFLECT TESTS
FLEXIBLE PAVEMENT DEFLECTION TESTS
WURTSMITH AIR FORCE BASE
SAND SUBGRADE

SEPTEMBER 1966

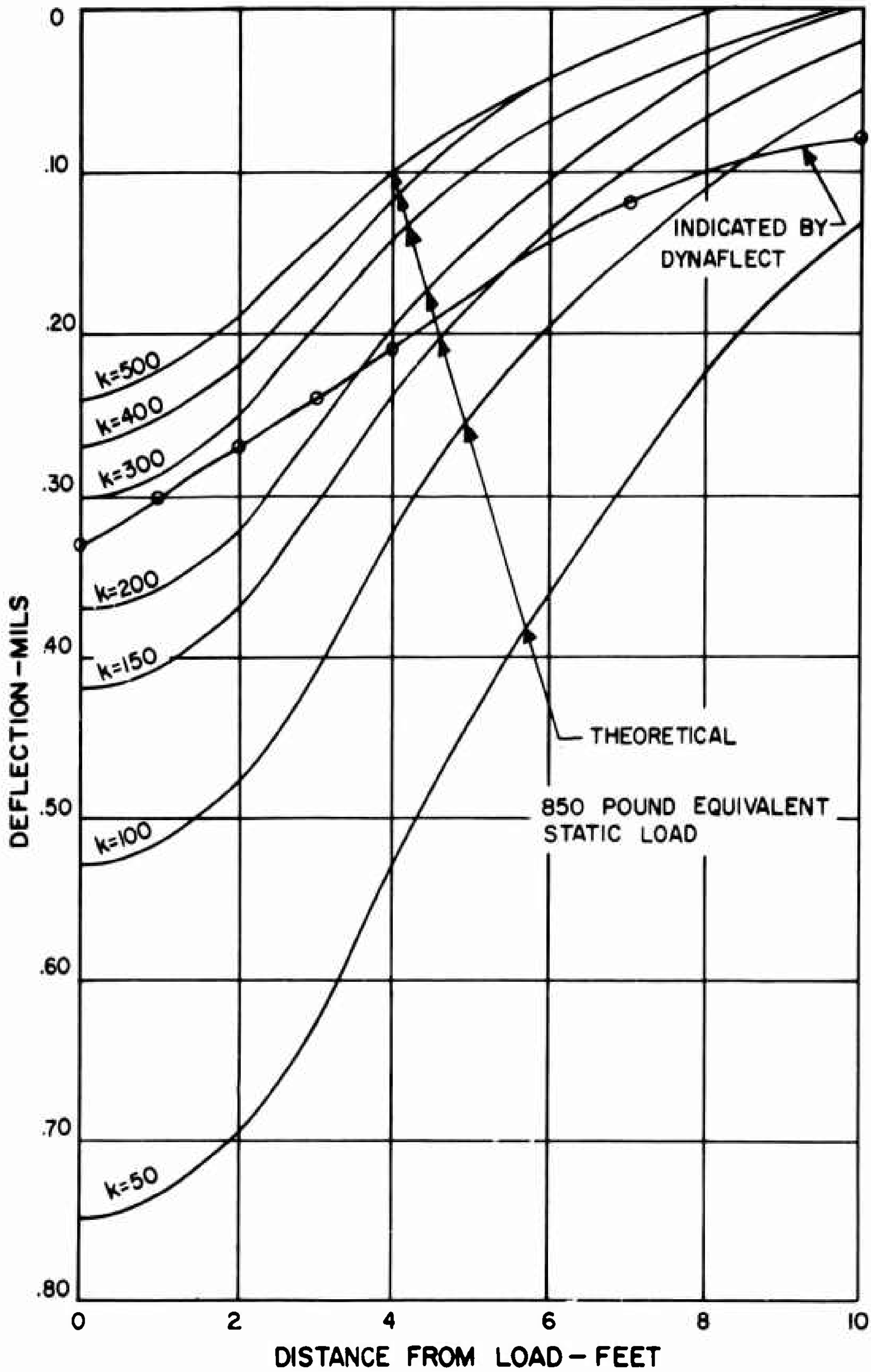
FIGURE 44



DYNAFLECT TESTS
DEFLECTION TESTS
INTERSTATE 71 SUBGRADE & BASE
COMPARISON TEST OF TWO TYPICAL
PLOTS OF BASE MATERIAL

OCTOBER 1966

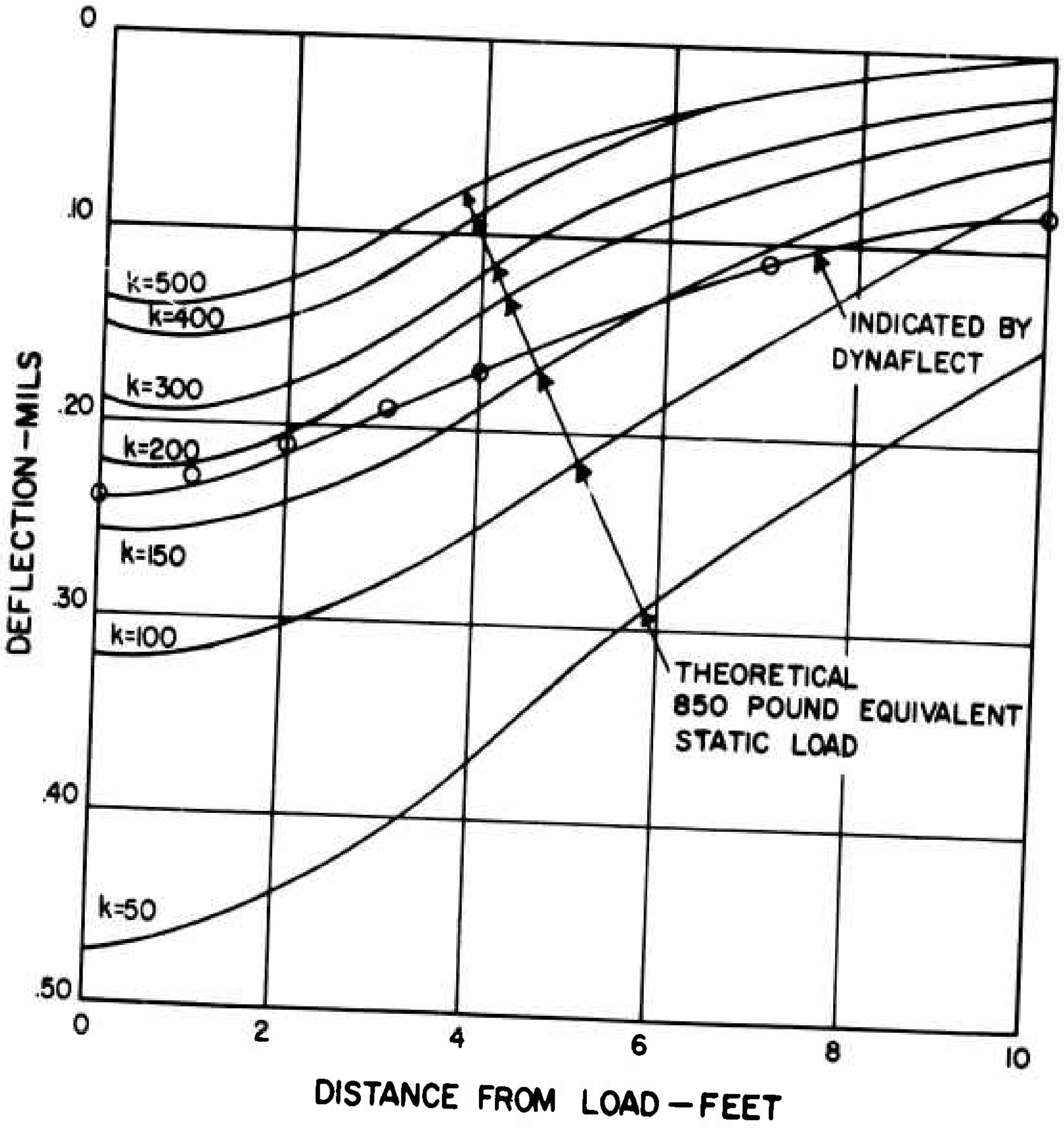
FIGURE 45



DYNAFLECT TESTS
PAVEMENT DEFLECTION TESTS
WURTSMITH AIR FORCE BASE
AREAS 11 & 15 MID-SLAB 10" PCC
SAND SUBGRADE

OCTOBER 1966

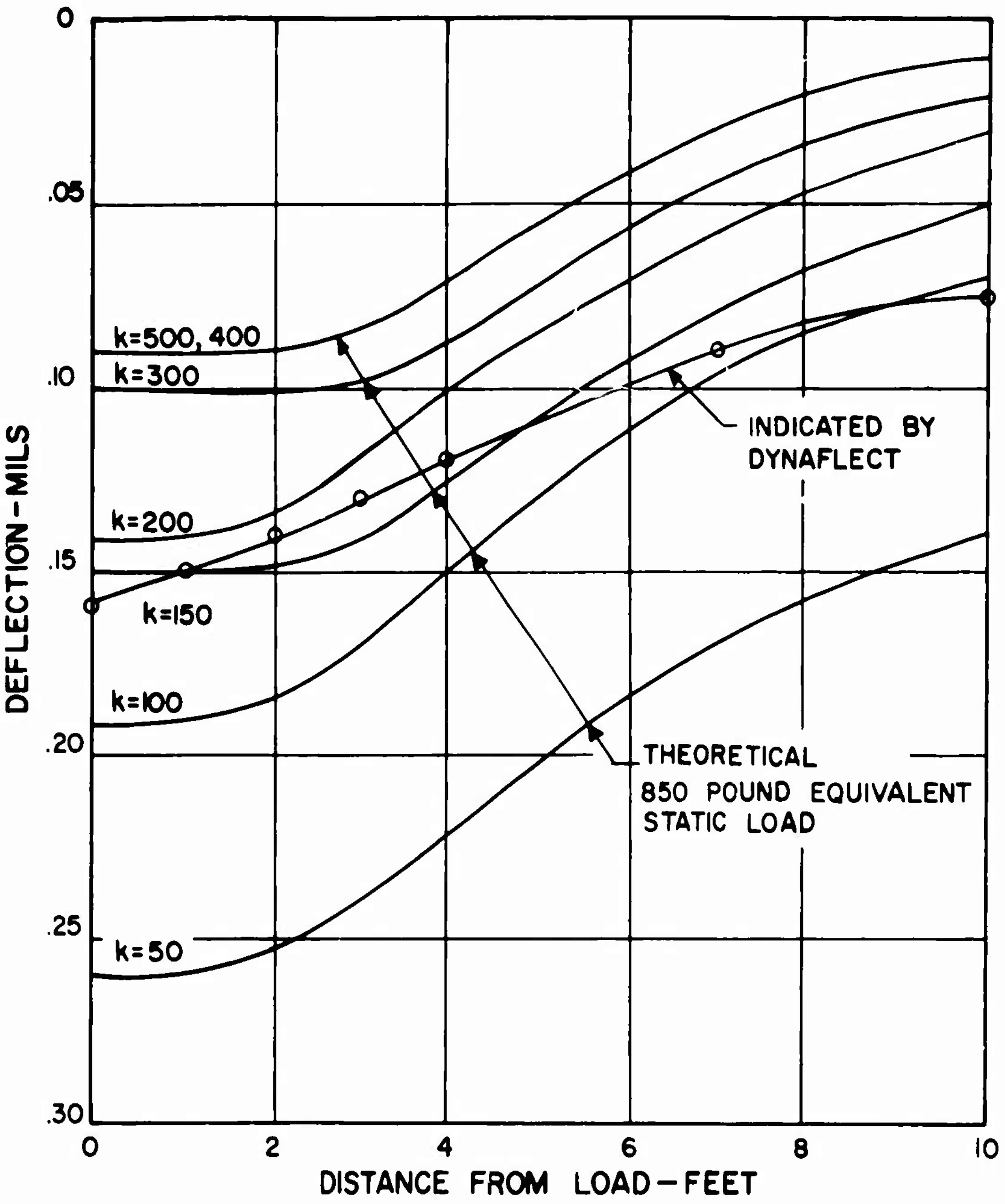
FIGURE 46



DYNAFLECT TESTS
PAVEMENT DEFLECTION TESTS
WURTSMITH AIR FORCE BASE
AREAS 4,5 & 16 MID-SLAB 14" PCC
SAND SUBGRADE

OCTOBER 1966

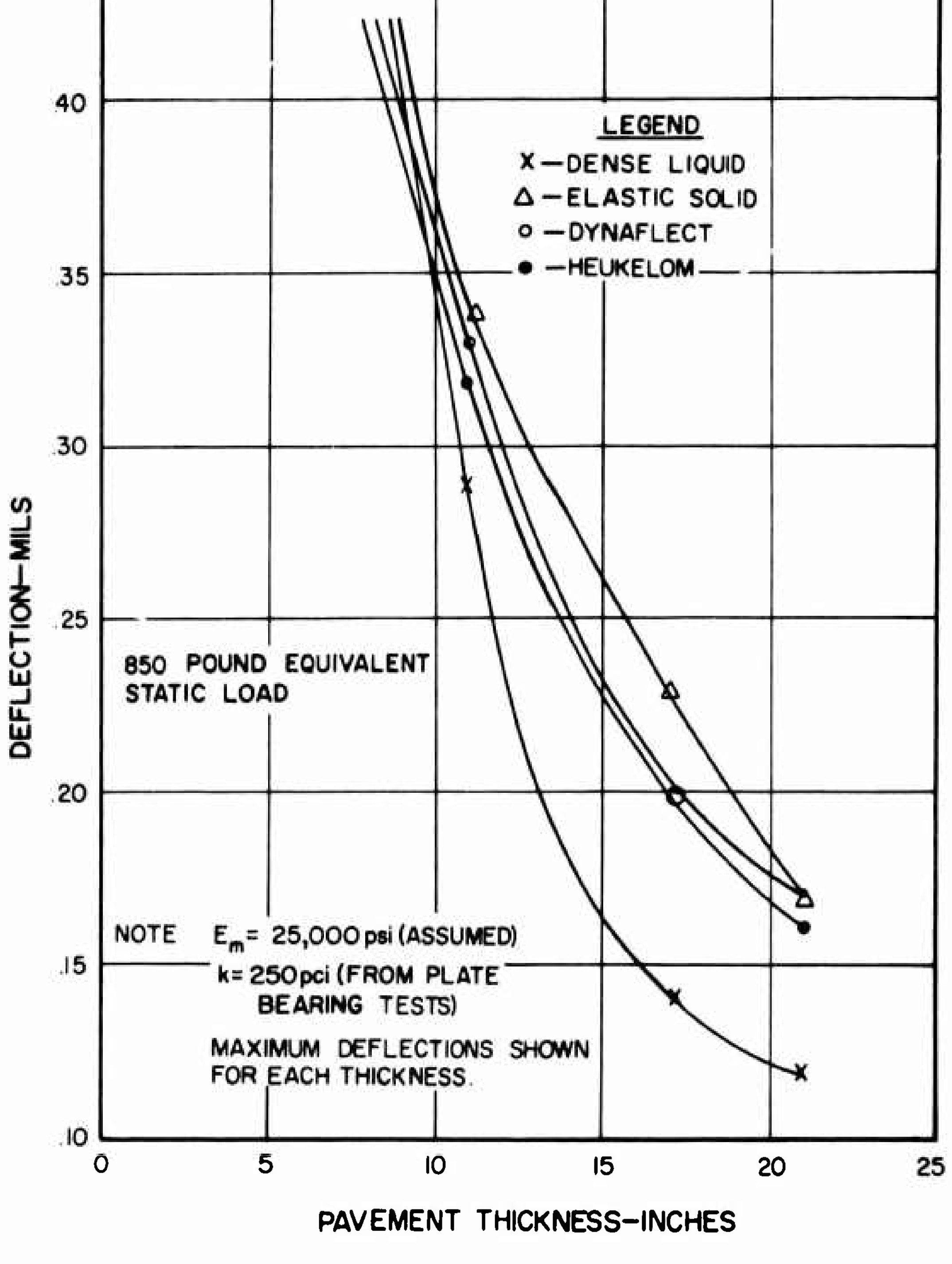
FIGURE 47



DYNAFLECT TESTS
PAVEMENT DEFLECTION TESTS
WURTSMITH AIR FORCE BASE
AREAS 8, 26, 31 & 40 - MID-SLAB 21" PCC
SAND SUBGRADE

OCTOBER 1966

FIGURE 48



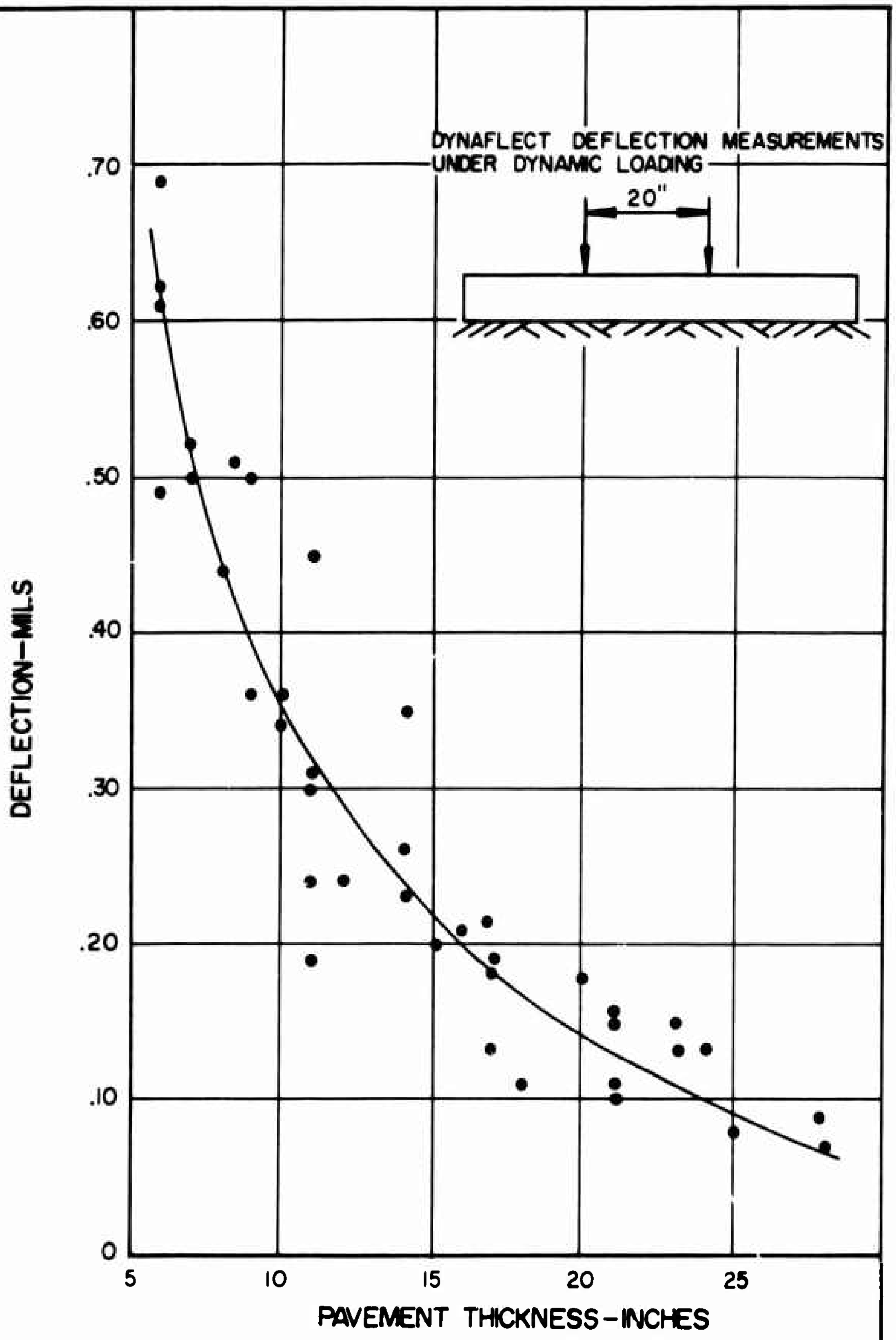
850 POUND EQUIVALENT STATIC LOAD

NOTE E_m = 25,000 psi (ASSUMED)
k = 250 pci (FROM PLATE BEARING TESTS)

MAXIMUM DEFLECTIONS SHOWN FOR EACH THICKNESS.

COMPARISON OF THEORETICAL DEFLECTIONS
WITH
ACTUAL DEFLECTIONS FOR DYNAFLECT TESTS
WURTSMITH AFB
SAND SUBGRADE

FIGURE 49



DEFLECTION
VS
PCC PAVEMENT THICKNESS

SEPTEMBER-NOVEMBER 1966

FIGURE 50

APPENDIX A

DEFLECTION MEASURING SYSTEM, CALIBRATION OF THE DYNAFLECT AND OPERATING CHARACTERISTICS

1. The movement of the pavement during the operation of the Dynaflect at a peak to peak dynamic force of 500 pounds upward and 500 pounds downward, which is added to and subtracted from the weight of the trailer (1600 pounds) at a frequency of 8 cycles per second (cps), is sensed through an array of geophones. A description of this system and the calibration of the geophones is contained in the following paragraphs.

Deflection Measuring System

2. The amplitude of the induced, cyclic vertical displacement is sensed by geophones which are lowered into contact with the surface, the first geophone being placed midway between the wheels and four additional geophones spaced at one-foot intervals along the longitudinal centerline of the trailer, as described in the text under Part II. The geophones respond to the 8 cps induced motion and produce electrical signals proportional to this motion. In these tests an extension cord was placed at the four-foot geophone position and readings were taken at intervals up to ten feet from the load in some instances. In this manner deflections throughout the region of the deflection basin were obtained.

3. The following excerpt is from Highway Research Record No. 129(3) regarding operation of the geophones:

> "Each geophone consists of a coil, spring-suspended for vertical motion, within the field of a permanent magnet. When the magnet is subjected to cyclic vertical motion, the coil tends to remain stationary. The coil acquires a cyclic velocity with respect to the magnet and a voltage proportional to the instantaneous velocity is developed within the coil. At any single frequency of excitation, the magnitude of the geophone output voltage is precisely proportional to its motion.

> The geophones are utilized, one at a time, to determine the deflection at each point in the array. The electrical output signal from each geophone is filtered and amplified to produce a reading on a meter. The narrow-band filter limits the response of the system to the fundamental frequency component of the induced motion at 8 cycles per second. Thus, the meter readings represent only the displacements induced by the force generator and are unaffected by extraneous vibrations caused by moving traffic or other sources. Deflections up to a maximum of 30 thousandths of an inch and down to a minimum of 0.01 thousandth can be measured with the present apparatus."

A view of the control panel, from which readings were obtained is shown on Plate 1A, a.

Calibration

4. Calibration of the deflection measuring system is accomplished by placing each geophone on a cam-actuated platform which provides a smooth, repetitive, 0.005-inch vertical motion at 8 cps (Plate 1A, b). Individual sensitivity controls associated with each geophone are then adjusted to obtain the corresponding reading of five milli-inches* (mils) on the deflection indicating meter. The platform and receptacles for the geophones are shown in the lower portion of the photograph (Plate 1A, b).

Operating Characteristics

5. In operating the equipment on most concrete pavement, it is necessary to take readings smaller than one-thousandth of an inch, hereinafter designated one mil*. It is therefore required to change the multiplier dial shown in the lower portion of the photograph (Plate 1A, a) to ranges of 0.1, 0.03, or 0.01 as necessary. This means that the meter readings must be multiplied by the designated factor to arrive at the deflection in mils, e.g., a meter reading of 4.6 on the 0.1 range would indicate 4.6 x 0.1 or 0.46 mil deflection. It was noted, when making tests, that small instrument errors sometimes occurred when changing ranges, particularly between 0.1 and 0.03, but these small errors were usually not enough to affect the overall results.

6. Another condition of operation that affected results was temperature change. It was noted that when a rapid temperature rise took place, as from a low of 32° F in early morning to 55° or 60° F by 1:00 PM, the calibration of the equipment was found to change slightly. This was largely overcome by keeping the geophones and the control panel box indoors under constant temperature when not in use, and protecting them

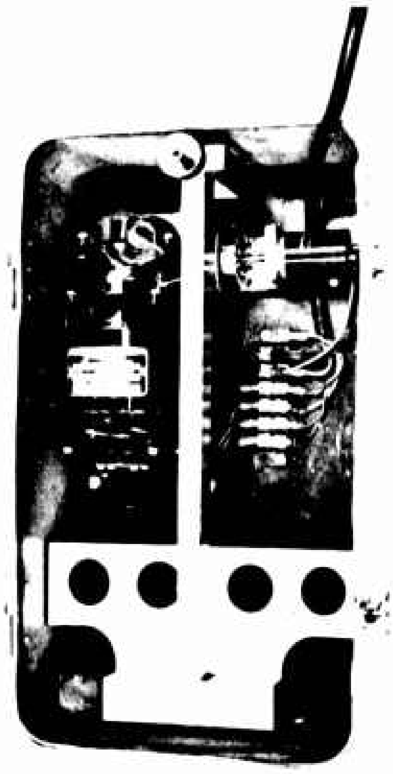
---

* 1 mil = 25.4 microns

from temperature extremes to the extent practicable when tests were performed.

7. Also of interest during operations was the repeatability of the results. It was found in all tests performed and repeated on the same day under identical climatic conditions that results were consistent with very little variation. Tests repeated from week to week or month to month under different climatic conditions are discussed in the text of this report under Discussion of Test Results, Part VI.

a. View of Dynaflect Control Panel



b. View of Dynaflect Calibration System

PLATE 1A

APPENDIX B

EQUIVALENT STATIC LOADS OBTAINED WITH THE DYNAFLECT

1. It is evident that a precise correlation of static and dynamic loading is not possible because of inherent differences in behavior patterns of the two loading systems. However, if the equivalent static load concept is looked upon as a means to obtain results with the dynamic equipment that will supplement previous data and computations based on static loadings, the idea seems valid. At first, it was thought that one equivalent loading would fulfill this purpose. All tests up to this point had been made on pavements located on similar subgrades, and 500 pounds was selected as the equivalent static load for the 1000-pound peak to peak dynamic loading of the Dynaflect on the basis of the observed results. As more experience was gained, and tests were made at Wurtsmith AFB, Michigan where the subgrade is cohesionless sand instead of the clayey materials found in Ohio and Indiana, it became apparent that one equivalent static load for all subgrades would not fulfill requirements for all locations.

2. In reviewing the test data, it was found that a weak subgrade, such as at Lunken Airport, would correlate with a lesser equivalent load than a strong subgrade. However, the differences were not considered to be great as long as the subgrade contained a degree of cohesiveness. At Wright-Patterson AFB where the subgrade contains very clayey gravel, even though the strength of the subgrade is high (k value 200-350 pci), the 500-pound equivalent static load appeared to be a reasonable one. It is estimated that the variance of an equivalent static load at Lunken Airport compared to the one at Wright-Patterson AFB might be only in the order of 400 to 500 pounds or a 100-pound difference. Nevertheless, when a cohesionless sand subgrade is considered the equivalent static load would appear to increase appreciably. At Wurtsmith AFB it is estimated that an equivalent static load would be as great as 850 pounds, and possibly more, to be consistent with the maximum deflections produced by the Dynaflect.

3. Mathematical studies were undertaken on a preliminary basis to see if reasonable equivalent static loads could be determined for variable subgrades theoretically. It was found that insufficient data exist to formulate precise computational methods at present. However, future studies with more than one frequency, including conditions for resonance, might yield data on which more precise methods might be formulated. It is also evident that equipment for obtaining the modulus of elasticity

for the subgrade soils in the vicinity of testing with the Dynaflect, is also required if variable subgrade conditions are to be studied.

4. In summary, the 500-pound equivalent static load, used in the computations for most of the deflection testing with the Dynaflect, is a preliminary figure but is considered reasonably adequate for the testing of pavements on cohesive subgrades. As further investigations proceed, it is expected that different approaches and possibly better formulated equivalent loads will be developed.

ADDENDUM

The following is quoted from Professor Gerald Pickett's comments of 21 April 1967 in regard to the theoretical aspects of the dynamic loading as discussed in Appendix B:

> "It is noted that the dynamic deflection per unit load is less than static deflection per unit load. For 1000 lbs variation in dynamic load the equivalent static load varied from 400 to 500 lbs for weak cohesive subgrades to 850 lbs for a sandy subgrade. For most cohesive subgrades the equivalent static load was about 500 lbs.
>
> These results should be expected. The system acts as a highly damped single degree of freedom inertia system would act. The three elements of such a system are mass, damping and spring. In steady state vibration the mass may act to either increase or decrease maximum deflection depending on the ratio of the driving frequency to the natural frequency. The damping decreases the maximum deflection. The damping is primarily geometric rather than frictional in that the energy goes into stress waves traveling away from the source. A strong subgrade contributes to the spring element more than a weak subgrade does without producing much change in the inertia and damping elements. As the spring becomes the dominant element, dynamic deflection approaches static deflection. A stiffer pavement increases all components and therefore may not change the relative deflections".

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11 SUPPLEMENTARY NOTES	12 SPONSORING MILITARY ACTIVITY Department of the Army

13 ABSTRACT

// ~~This~~ report presents the results obtained from portland cement concrete pavement testing with the Dynaflect, an apparatus developed ~~by the Lane Wells Company,~~ for the deflection testing of pavements under a dynamic load. Essentially the device was tested to determine if deflection measurements from dynamic loadings could be correlated with deflection measurements from static loadings, and thereby relate to allowable loadings on portland cement concrete pavement. Also of interest during the investigation was the performance of concrete pavement at joints to determine load transfer between slabs. The detection of cracking where not visible on the pavement surface, and the extent of pavement deterioration where visible cracks existed were matters for investigation.

The results of the investigation indicated that:

Correlation of deflections from dynamic and static loading appear feasible particularly for pavements on clay subgrades.

Differences in load transfer at joints could be detected.

Indications of slab integrity can be obtained.

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Unclassified
Security Classification

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Deflection						
Load Transfer						
Subgrade Modulus						
Dynamic Load						
Frequency						
Allowable Load						
Cohesion						

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