SOME RECENT FINDINGS IN FLEXIBLE PAVEMENT RESEARCH

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Extension of
AASHO Road Test Results
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ACKNOWLEDGEMENTS

1. INTRODUCTION AND SUMMARY OF RESULTS

This report is based on research of the Texas Transportation Institute done in connection with the study, "Application of the AASHO Road Test Results to Texas Conditions," sponsored by the Texas Highway Department in cooperation with the U. S. Department of Commerce, Bureau of Public Roads. The report is concerned primarily with two of the original study objectives which are quoted below:

    1. "In general, to correlate the average level of pavement performance determined from a two-year controlled traffic test (the AASHO Road Test) with performance of Texas Pavements under normal mixed traffic, and to study the effect of weather and the so-called regional effect throughout the state.

    2. "For flexible pavements in Texas, to determine approximate values (or a range of values) of coefficients for representing Texas materials to replace the layer coefficients determined at the AASHO Road Test for the materials used there, and to develop relationships between these coefficients and materials tests."

These objectives were written in 1962. At that time it was supposed that both the "regional effects" mentioned in the first objective, and the "coefficients"* referred to in the second, could be evaluated by estimating the <u>rate</u> at which surface roughness had developed in a large number of existing pavements, of known design and traffic history, scattered over the state. For reasons not strictly pertinent to this report, estimates of pavement deterioration rate appeared to be highly inaccurate, and a new approach was taken pending completion of a long-time program of observing actual rates.

The new approach, limited for the present to flexible pavements, involves the assumption that load-induced deflections of the pavement surface are an index to the potential rate of pavement deterioration. The results reported herein include: (1) the development of an empirical equation for estimating deflections from the thickness and laboratory--determined strength of the materials used in the pavement and (2) the use of the equation, together with deflections observed on 323 highway test sections, to evaluate the regional effect in Texas.

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*The AASHO Road Test coefficients were the numbers 0.44, 0.14, and 0.11 in the Thickness Index, 0.44 x Surface Thickness + 0.14 x Base Thickness + 0.11 x Subbase Thickness (see p. 40 of Ref. 1). These coefficients were assumed to be related to the strength of the Road Test flexible pavement materials, and presumal would have been different had a different set of materials been used.

With a significant regional effect evaluated, the net result of the research was an equation for deflections that contained: (1) a "Field Compression Coefficient" for each layer dependent on both laboratory strength and regional effect, and (2) a "Depth Coefficient" for each layer (including the foundation layer) dependent upon the thickness of the layer and its position in the strucutre. The equation presumably could be used in the design of flexible pavements in Texas if deflection criteria were made a part of the design procedure, and if the underlying causes of the regional effect were known.

A study of deflection criteria for use in design, and search for the physical causes of the observed regional effect, are subjects of current research.

2. TEST SECTIONS ON EXISTING HIGHWAYS

The data from existing highways utilized in this report were gathered from test sections comprising the study's Flexible Pavement Experiment. Every test section consisted of two sub-sections, each a traffic lane in width and 1200 feet long. A transition reserved for sampling operations, usually 100 feet long, separated the two sub-sections. All sections were chosen from existing highways, and none was constructed especially for this experiment.

The sections were chosen (in 1962-63) to conform, as nearly as possible, to the following experiment design involving five variables:

TABLE 1

Variable No.	Variable	No. Levels	Levels
1	Region	3	Eastern, Central, Western
2	Surfacing thickness	3	0-1", 1"-2.5", 2.5" +
3	Base strength	3	Low, Medium, High
4	Subbase strength	2	Low, High
5	Subgrade strength	3	Low, Medium, High

Surfacings less than one inch thick were surface treatments; thicker surfacings were hot-mix asphaltic concrete. Materials classified as medium strength were those approximately equal in strength (as measured by the Texas Triaxial Test[2]*) to the AASHO Road Test materials.

According to Table 1, it can be seen that the minimum number of sections require for a complete factorial experiment would be $2 \times 3^4 = 162$. Actually, more than this number were selected, and after 44 had been eliminated because of excessive irregularities discovered when the sections were drilled, a total of 323 remained in the experiment. Of this total, 188 were surfaced with asphaltic concrete ranging in thickness from approximately one to eight inches, and 135 were surface treatment sections with surfacing thickness ranging from approximately one-half to one inch. Deflection and design data from all 323 existing highway sections, together with similar data from the specially designed A&M Pavement Test Facility described briefly in the next section, form the basis for this report.

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*Superscript numbers refer to references listed in the bibliography.

3. PAVEMENT TEST FACILITY

The A&M Pavement Test Facility, located at the University's Research Annex, was constructed for the sole purpose of providing a means for evaluating nondestructive testing techniques, or more particularly, for evaluating testing equipment purporting to furnish information concerning the in situ strength of individual layers in a flexible pavement. The design of the facility is described in detail in Reference 3. For present purposes it will suffice to say that it consists of 27 12- x 40-ft. test sections, designed in accordance with the principles of statistical experiment design. The variables treated are indicated in tabular form in Table 2, the materials used in Table 3 and the experiment design employed in Table 4.

The facility was constructed in 1965, by maintenance forces of District 17 of the Texas Highway Department under the supervision of Texas Transportation Institute, and was financed by the Texas Highway Department, the Bureau of Public Roads and the Highway Research Board. The last named agency paid a portion of the facility's construction cost from funds available in NCHRP Project 1-6, "Standard Measurements for Satellite Road Test Program-- Measurements Team." Figures 1 and 2 show the facility in plan and cross-section, Figure 3 depicts construction scenes, and Figure 4 is a photograph of the completed facility.

TABLE 2

List of Variables

Variable	Levels		
	Low (-1)	Medium (0)	High (+1)
Surface Thickness	1"	3"	5"
Base Thickness	4"	8"	12"
Subbase Thickness	4"	8"	12"
Base Material Type	4	5	6
Subbase Material Type	4	5	6
Subgrade Material Type	1	2	3

TABLE 3

Materials Used in Embankment, Base and Subbase

Material* Type	Description	Where Used	AASHO Class.	Unified Soil Class.	Texas Triaxial Class.	Compressive Strenght ** psi
1	Plastic Clay	Embankment	A-7-6(20)	CH	5.0	22
2	Sandy Clay	Embankment	A-2-6(1)	SC	4.0	40
3	Sandy Gravel	Embankment	A-1-6	SW	3.6	43
4	Cr. Limestone	Base & Subb	A-1-a	GW-GM	1.7	165
5	Cr. Limestone + 2% Lime	Base & Subb	A-1-a	GW-GM		430
6	Cr. Limestone + 4% Cement	Base & Subb	A-1-a	GW-GM		2270

*The six materials are numbered in the assumed order of increasing strength.

**By Texas triaxial procedure, at a lateral pressure of 5 psi.

NOTE: The foundation material (Material Type 0) and the asphaltic concrete surfacing material (Material Type 7) were not variables in the experiment.

TABLE 4

Experiment Design

Sec. No.	Actual Design						Theoretical Design					
	Layer Thick, (In.)			Matl. Type*			Thick Level			Strength Level		
	Sur.	Base	Subb.	Base	Subb.	Subg.	Sur.	Base	Subb.	Base	Subb.	Subg.
1	5	4	4	6	4	1	+1	-1	-1	+1	-1	+1
2	1	12	4	6	4	1	-1	+1	-1	+1	-1	+1
3	1	4	12	6	4	1	-1	-1	+1	+1	-1	+1
4	5	12	12	6	4	1	+1	+1	+1	+1	-1	+1
5	5	4	4	4	6	1	+1	-1	-1	-1	+1	+1
6	1	12	4	4	6	1	-1	+1	-1	-1	+1	+1
7	1	4	12	4	6	1	-1	-1	+1	-1	+1	+1
8	5	12	12	4	6	1	+1	+1	+1	-1	+1	+1
9	5	4	4	4	4	3	+1	-1	-1	-1	-1	+1
10	1	12	4	4	4	3	-1	+1	-1	-1	-1	+1
11	1	4	12	4	4	3	-1	-1	+1	-1	-1	+1
12	5	12	12	4	4	3	+1	+1	+1	-1	-1	+1
13	5	4	4	6	6	3	+1	-1	-1	+1	+1	+1
14	1	12	4	6	6	3	-1	+1	-1	+1	+1	+1
15	1	4	12	6	6	3	-1	-1	+1	+1	+1	+1
16	5	12	12	6	6	3	+1	+1	+1	+1	+1	+1
17	3	8	8	5	5	2	0	0	0	0	0	0
18	1	8	8	5	5	2	-1	0	0	0	0	0
19	5	8	8	5	5	2	+1	0	0	0	0	0
20	3	4	8	5	5	2	0	-1	0	0	0	0
21	3	12	8	5	5	2	0	+1	0	0	0	0
**22	3	8	4	5	5	2	0	0	-1	0	0	0
**23	3	8	12	5	5	2	0	0	+1	0	0	0
24	3	8	8	4	5	2	0	0	0	-1	0	0
25	3	8	8	6	5	2	0	0	0	+1	0	0
26	3	8	8	5	4	2	0	0	0	0	-1	0
27	3	8	8	5	6	2	0	0	0	0	+1	0
28	3	8	8	5	5	1	0	0	0	0	0	-1
29	3	8	8	5	5	3	0	0	0	0	0	+1

*See Table 3 for description of materials.

MAIN FACILITY

TURNAROUND AREA

460'

76'

10' | 40' | 10'

A

SHOULDER LINE

ACCESS RAMP

50'

SEC. NO. 2	3	6	7	5	1	4	8	28
10	11	14	15	13	16	12	9	29
18	20	19	21	17	24	26	27	25

34
33
32
31
30

5'

12'

2'

SHOULDER LINE

A
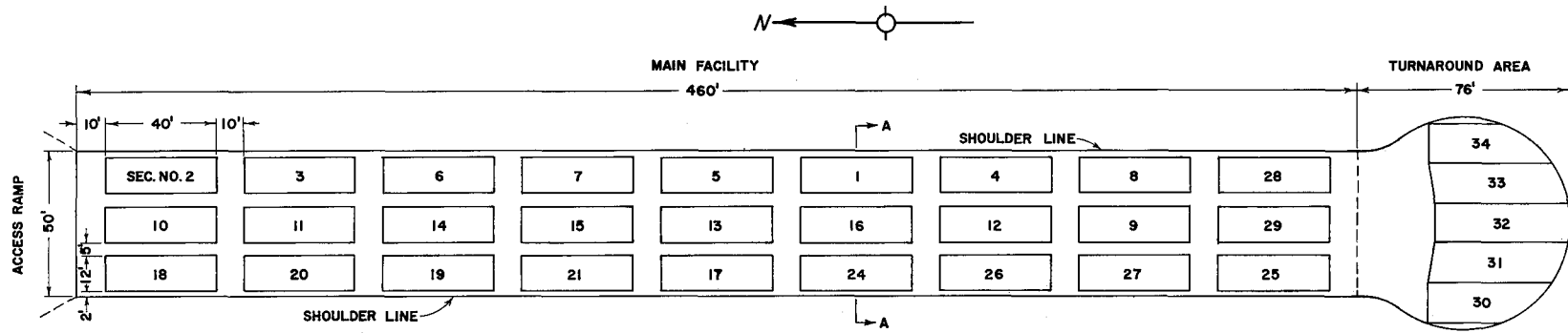
Figure 1:   Plan view of pavement test facility

50'

H.M.A.C

LIMESTONE

LIMESTONE + CEMENT

LIMESTONE

LIMESTONE + LIME

53"

LIMESTONE + CEMENT

PLASTIC CLAY

SANDY GRAVEL

SANDY CLAY

ASPHALTIC
MEMBRANE
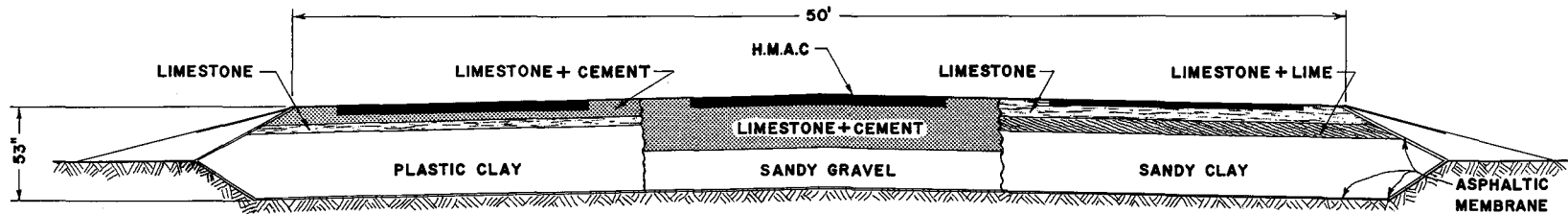
Figure 2:   Cross-section of pavement test facility (Section
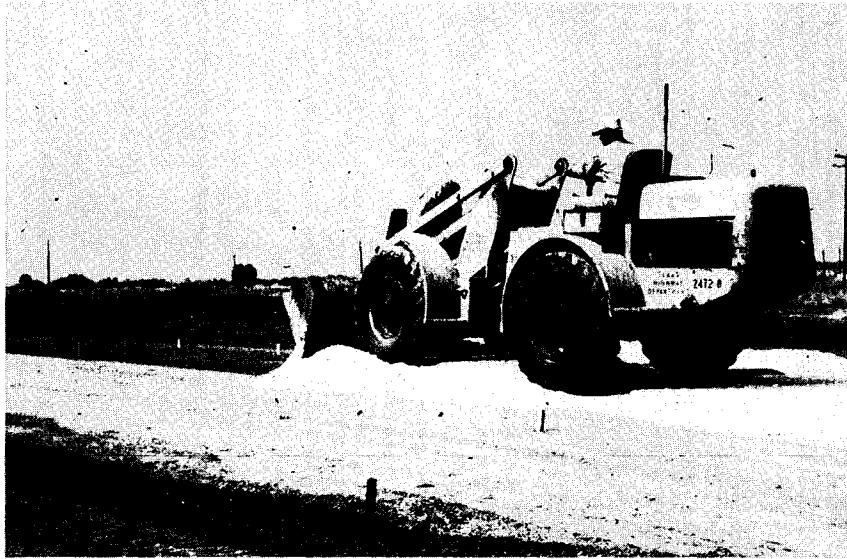A-A of Figure 1)

Figure 3: Test facility construction. Spreading crushed
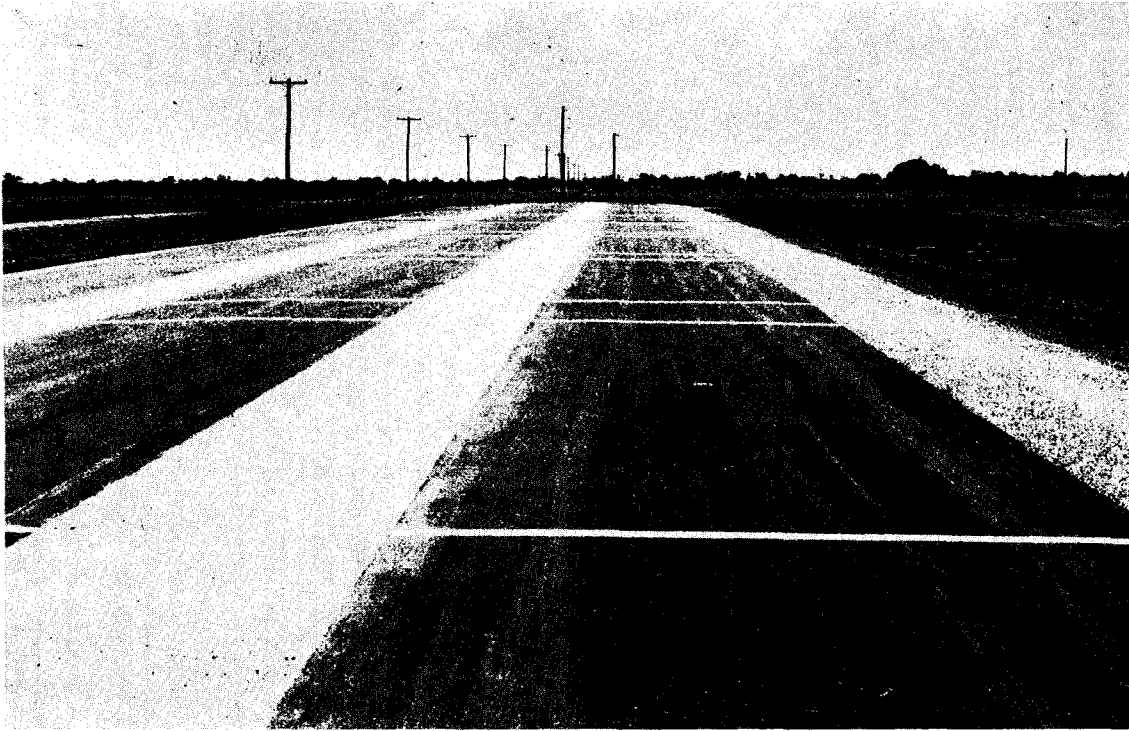limestone (upper) and mixing water and lime with
Rex Chain-Belt Pulvimixer (lower)

Figure 4: View of completed facility

4. DEFLECTION EQUIPMENT (DYNAFLECT)

In March, 1966, deflections were measured on the test facility by means of the Dynaflect (1966 Model), a one man operated device that induces and measures the deflection of the roadway surface (Figure 5). It is mounted on a small 1600-lb. two-wheel trailer that is towed behind a passenger vehicle. Deflections are measured with the vehicle and trailer stationary. Counter-rotating eccentric masses provide total live load of 1000-lbs. (500-lbs. up, 500-lbs. down) which is applied at 8 cps to the pavement through two steel wheels spaced 20 inches apart. Deflections are sensed by means of geophones normally arranged on the pavement surface as shown in Figure 6. The output of the geophones is read on a meter located in the towing vehicle.

The trailer may be moved short distances at slow speed on the load wheels. For travel between distant sections the steel load wheels are lifted and the trailer rides on pneumetic tired wheels at highway speeds. Lowering and lifting the load wheels, lowering and lifting the geophones, as well as starting and stopping the force generator, are controlled from the driver's seat of the passenger car.

The Dynaflect is produced commercially in Houston, Texas, by the Lane-Wells Company.
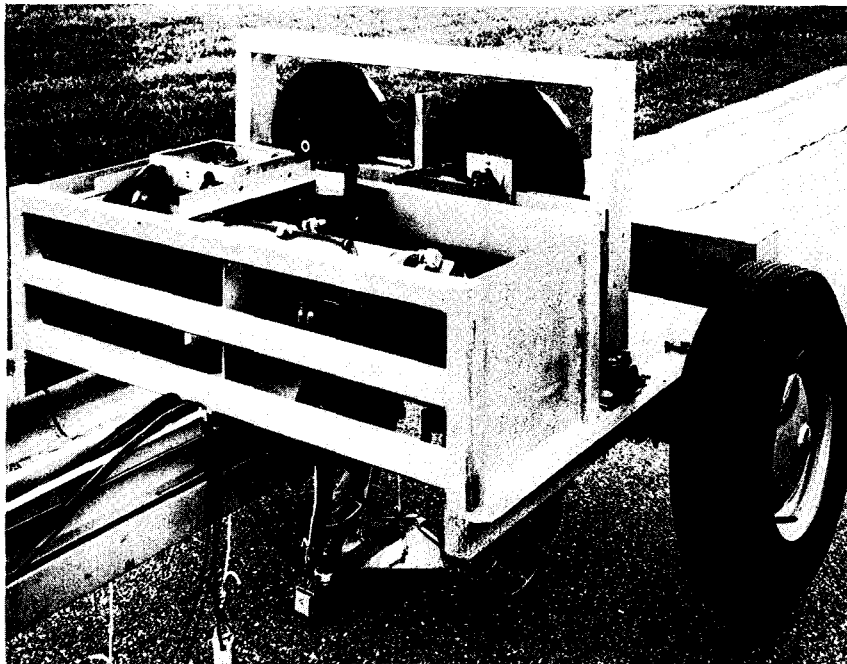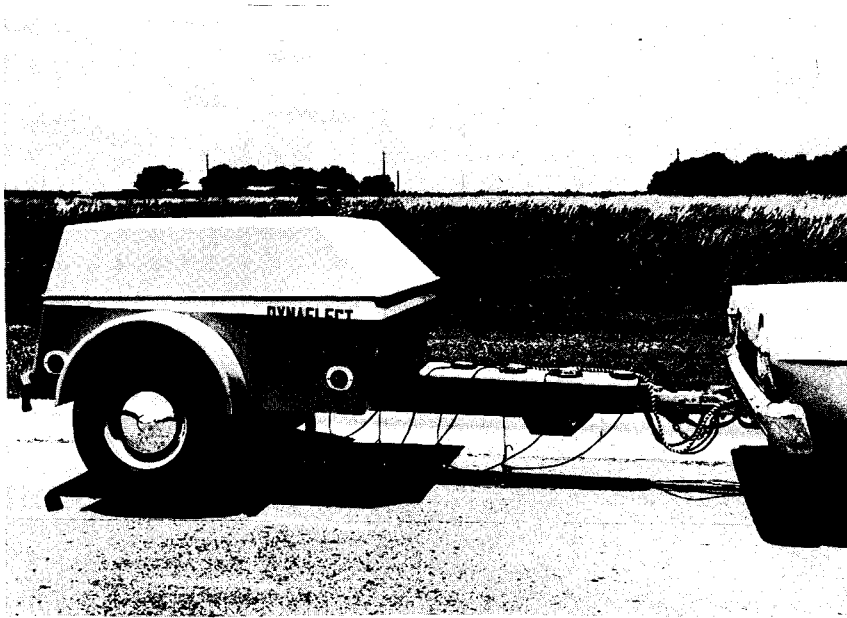
Figure 5: DYNAFLECT -- 1966 MODEL.
In the lower photograph the
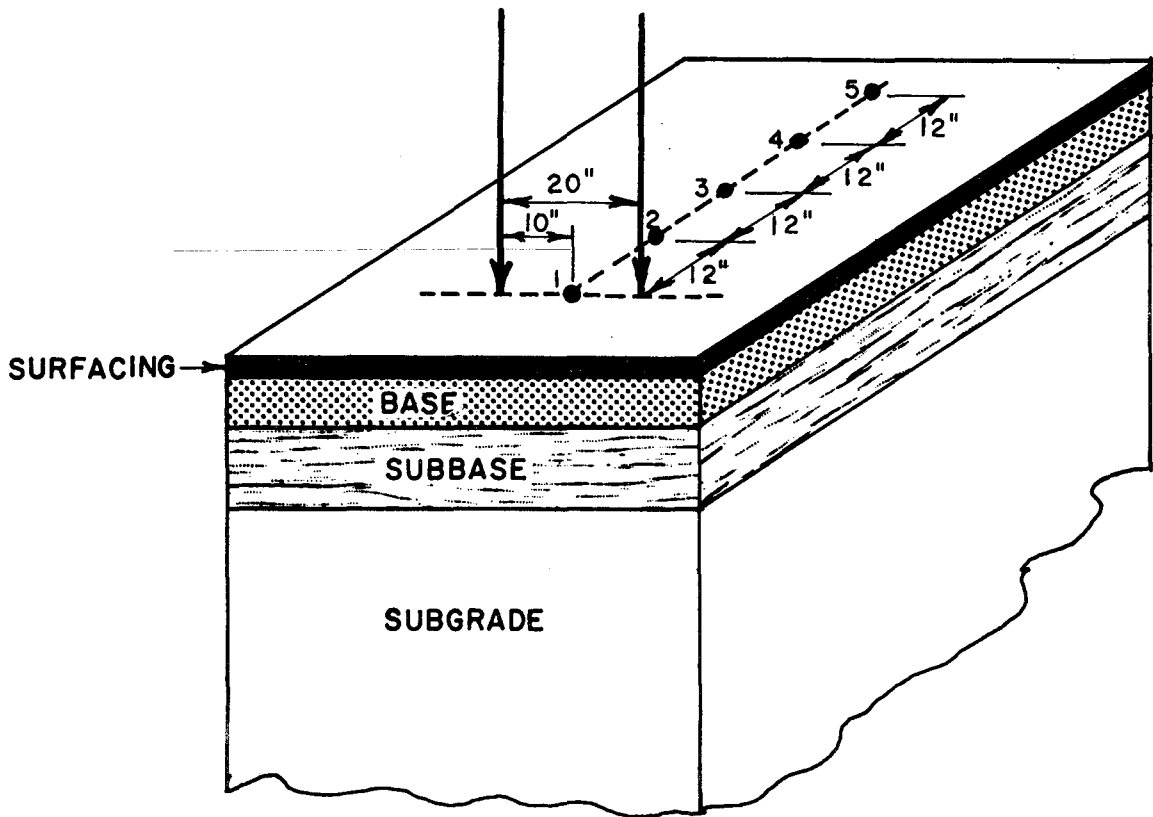trailer body has been removed.

Figure 6: POSITIONS OF DYNAFLECT SENSORS AND
LOAD WHEELS. The vertical arrows
represent the load wheels and the
points numbered 1 through 5 represent
the positions where sensors 1 through
5 pick up the motion of the pavement
surface.

5. DEFLECTION EQUATION DERIVED FROM TEST FACILITY DATA

The March, 1966, Dynaflect data taken on the A&M Pavement Test Facility were analyzed and the following empirical equation for deflections resulted for a system of n layers (including a foundation layer of infinite depth)[3]:

$$W = F_1 X_1 + F_2 X_2 + \ldots + F_1 X_1 + \ldots + F_n X_n \tag{1}$$

where W is the surface deflection (in thousandths of an inch) registered by one of the five geophones;

F_i = the "Field Compression Coefficient" of the material used in the ith layer (counting downward from the surfacing layer, for which $i = 1$);

X_i = the "Depth Coefficient" for the ith layer, given by the equation;

$$X_i = \frac{1}{(.75r + D_1 + D_2 + \ldots + D_{i-1})^{3/2}} - \frac{1}{(.75r + D_1 + D_2 + \ldots + D_i)^{3/2}}, \tag{2}$$

where $D_1, D_2 \ldots$, are the thicknesses (in inches) of Layer 1, 2, ...; and r = the horizontal distance (in inches) from either of the two points of load application to the geophone registering the deflection, W.

There were eight materials (including the foundation material) involved in the test facility. A value of F for each material was found by least-squares analysis of the deflection data. These, together with other data (including the prediction error associated with Equation 1) are given in Table 5. The materials in the table are listed in descending order of F, (or increasing order of in situ strength).

The laboratory determined ultimate compressive strengths of the six materials used in the embankment, base, and subbase are listed in Column 4 of Table 5. The values shown were obtained from 6-in. dia. by 8-in. high laboratory compacted cylinders of the materials, prepared and tested in accordance with standard Texas Highway Department procedures.[2] The cylinders were tested in a triaxial device at the standard rate of axial strain of approximately 0.0175 in./in. per minute and at an arbitrarily selected constant lateral pressure of 5 psi. Hereafter, the strength obtained as described above will be referred to as the laboratory strength of the material, and will be represented by the symbol, S.

TABLE 5

FIELD AND LABORATORY STRENGTH DATA

(1) Material	(2) Where Used	(3) Field Compression Coeff., F	(4) Lab. Comp. Strength, S (psi)	(5) Field Pulse Velocity, V (fps)
Plastic Clay (undisturbed)	Foundation	145.3	--	--
Plastic Clay (Compacted)	Embankment	95.05	22	2412
Sandy Clay	Embankment	63.46	40	2576
Gravel (Pit Run)	Embankment	35.44	43	3721
Cr. Limestone	Base and Subbase	3.997	165	5222
Cr. Limestone + 2% Lime	Base and Subbase	2.619	430	5448
Asphaltic Concrete	Surfacing	0.5305	--	--
Cr. Limestone + 4% Cement	Base and Subbase	0.2102	2270	7309

Root-mean-square residual in W: .0886 milli-inches
Mean value of W: .4500 milli-inches
RMSR as percent of mean : 19.7%

From Columns 3 and 4 of Table 5, it can be seen that as the Field Compression Coefficient, F, decreases, the laboratory strength, S, consistently increases. And, when the logarithm of F is plotted against the logarithm of S, as indicated in Figure 7, it is clear that an approximate relationship, represented by the straight line shown in the figure, exists between the two variables.

The equation of the line in Figure 7, obtained by regression analysis, is given below and provides a means for estimating the value of F from the laboratory Strength, S.

$$\log F = 3.7911 - 1.3357 \log S,$$

or, in anti-log form, and with the addition of the position subscript,

$$F_i = \frac{10^{3.7911}}{S_i{}^{1.3357}} \tag{3}$$

The correlation coefficient between $\log F$ and $\log S$ was 0.99.

Evidence that the coefficients, F, are related to at least one of the in situ properties of the materials is furnished by the data given in Column 5 of Table 5. Each figure in this column is the average of a number of field measurements of the velocity (in feet per second) with which compressional waves traveled horizontally through the material indicated.* Such velocities, according the elasticity theory, are related to the stiffness of the materials, the stiffer materials having the greater velocities. The relation between the velocity, V, and the logarithm of the field compression coefficient, F, is indicated in Figure 8. The equation of the straight line, found by regression analysis, is given below:

$$\log F = 3.3368 - 5.3766 \, V \times 10^{-4} \tag{4}$$

The correlation coefficient between $\log F$ and V was 0.99.

The high correlation coefficients associated with Equation 3 and 4 (.99 in both cases) served to convince these writers that:

(1)   The Field Compression Coefficients determined from the deflection data taken on the A&M Pavement Test Facility had physical significance.

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* The measuring system employed involved the use of ceramic piezoelectirc crystals as pulse generator and receiver, and was designed especially for this use. Some further details are given in Appendix A of Reference 3 and in Reference 7.
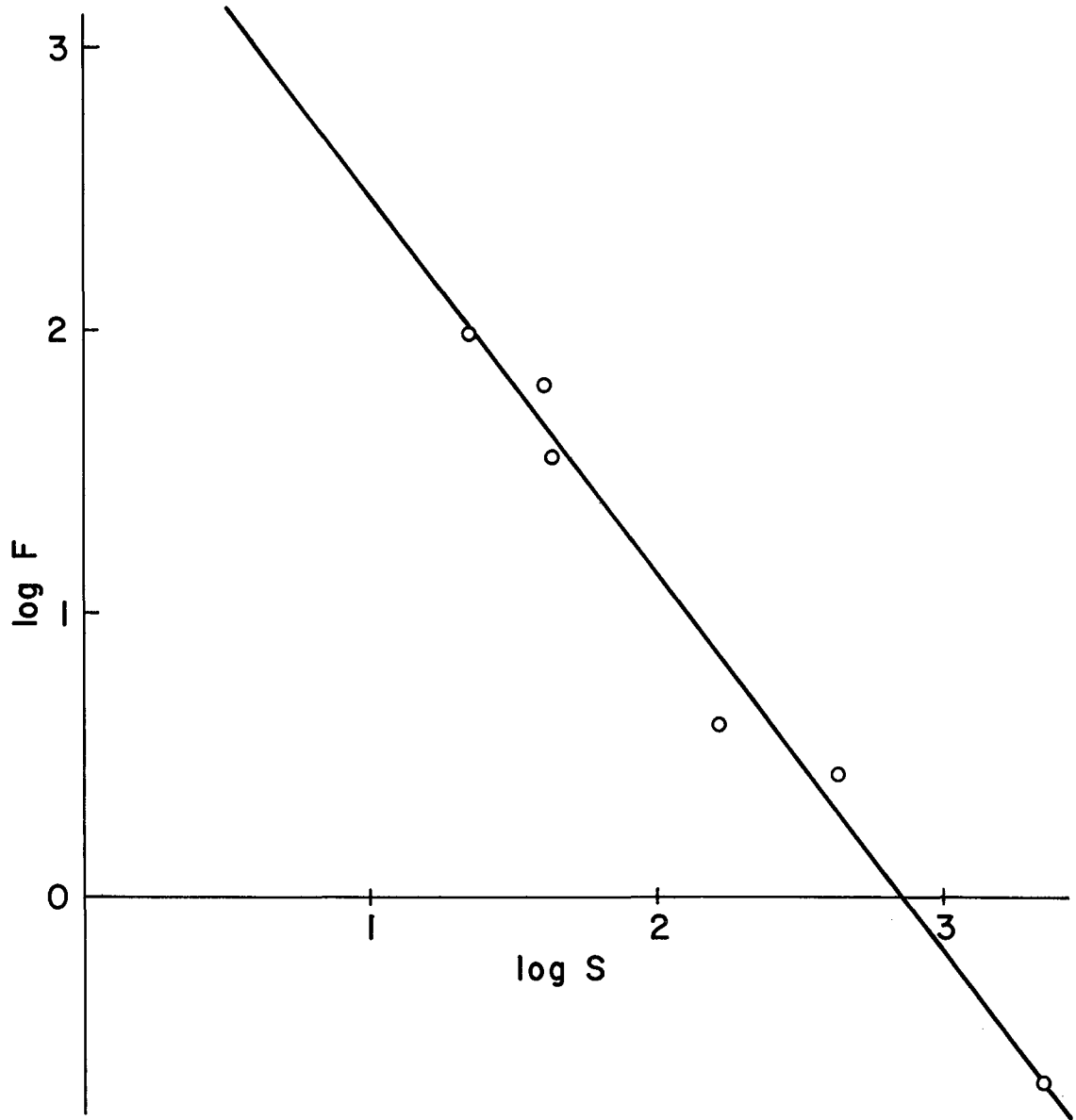
Figure 7:   RELATIONSHIP OF FIELD
            COMPRESSION COEFFICIENT
            TO LABORATORY STRENGTH.
            Data from Table 5.
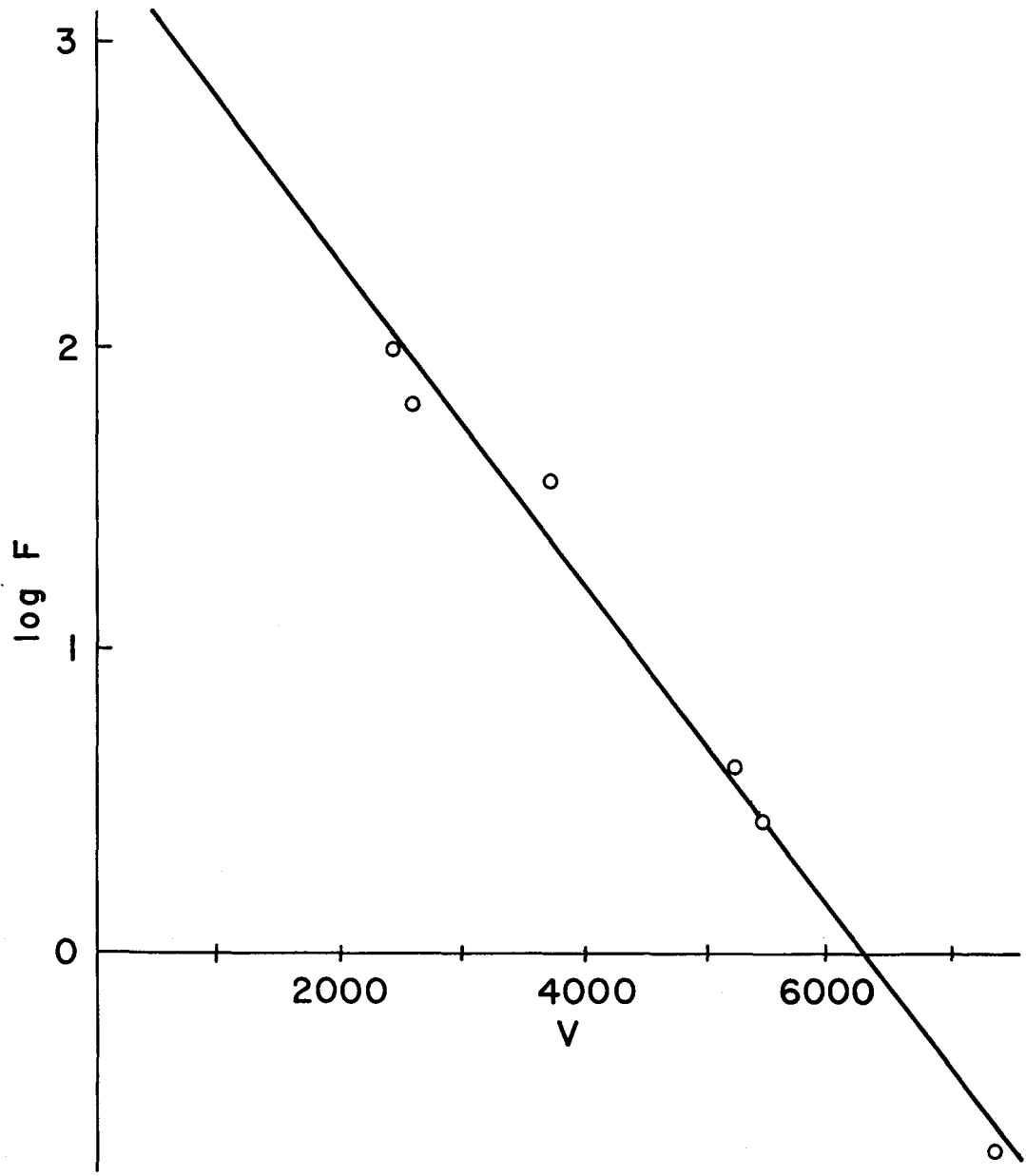
Figure 8: RELATIONSHIP OF FIELD
COMPRESSION COEFFICIENT TO
PULSE VELOCITY. Data from
Table 5.

(2)   Any discrepancy between surface deflections observed on highway sections, and deflection predicted by Equations 1 and 2 from laboratory strength and layer thickness data, probably represented the regional effect sought in the first objective quoted at the beginning of this report.

6. THE REGIONAL EFFECT IN TEXAS AND ENGINEERING IMPLICATIONS

As mentioned previously, one objective of the research was to determine the so-called "regional effect," where a region can be defined as one or more geographical areas within which all pavements of similar design exhibit similar long-time behavior under similar traffic. We stipulate that the surface deflection of a flexible pavement is an index to its potential long-time behavior under traffic, and narrow the definition of a region to that of one or more areas within which all pavements of similar design deflect the same amount under a specified wheel load. That such region exist within a given area we term a _regional hypothesis_ that can be tested by measuring design parameters and deflections on existing highways in the area.

This section of the report is devoted to describing the use of the deflection equation (Equation 1) and other data to delineate regional boundaries in Texas. Also, in this section evidence will be presented to prove the regional hypothesis stated above; however, the reasons for the existence of the regions are the subject of current research and will not be discussed in this report.

For use in the study of regional effects the equations given in Section 5 were altered as indicated in the following paragraphs.

We begin by writing equations, based on Equation 1, 2, and 3 in Section 5, for the static deflection caused by application of a 9000-lb. wheel load (18-kip single axle load) to a section in the $r\underline{th}$ region. The equations apply to a four-layer system but may be extended to any number of layers.

$$W_r = 22.4 \, (F_{r1} X_1 + F_{r2} X_2 + F_{r3} X_3 + F_{r4} X_4) \quad , \qquad (5)$$

where $W_r =$ the deflection (in units of 0.001 in.) of a section in the rth region caused by the application of a 9000-lb. wheel load.

The factor 22.4 in Equation 4 is a constant that converts Dynaflect deflections sensed by Geophone No. 1 (see Figure 6) to estimates of the static deflection caused by a 9000-lb. wheel load.* F_{ri} is the _field compression coefficient_ for the material i^{th} layer. Expressions defining the depth coefficients in terms of the layer thicknesses of a section, were taken from Equation 2 and are given below:

$$X_1 = \frac{1}{(7.5)^{3/2}} - \frac{1}{(7.5 + D_1)^{3/2}}$$

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*See Appendix A.

$$X_2 = \frac{1}{(7.5 + D_1)^{3/2}} - \frac{1}{(7.5 + D_1 + D_2)^{3/2}}$$

$$(6)$$

$$X_3 = \frac{1}{(7.5 + D_1 + D_2)^{3/2}} - \frac{1}{(7.5 + D_1 + D_2 + D_3)^{3/2}}$$

$$X_4 = \frac{1}{(7.5 + D_1 + D_2 + D_3)^{3/2}} \qquad .$$

The expression for F_{ri}, in terms of the laboratory strength, S_i, (Equation 6, below) was obtained from Equation 3 by multiplying the right hand side of that equation by a _regional_ _factor_, C_r, that has the value of unity at the A&M Pavement Test Facility. Thus

$$F_{ri} = C_r \frac{10^{3.7911}}{S_i^{1.3357}} \qquad .$$

$$(7)$$

We chose the number, 0, as the " regional number" of the A&M Pavement Test Facility. Thus, $C_O = 1.0$, and W_O is the estimate of the deflection of a section in the A&M facility caused by a 9000-lb. wheel load.

We have called C_r a regional factor because it modifies the relationship between the _in_ _situ_ compressibility of a material and its _laboratory_ _strength_ (as can be seen from Equation 7) and because the "regional effect" (that is, the effect of the local environment) must, if it exists, manifest itself as a change in the _in_ _situ_ strength of the materials in the pavement structure.

By comparing Equations 5 and 7 it can be shown that the former can be reduced to the following form:

$$W_r = C_r W_O \qquad .$$

Here, W_O is an estimate of the deflection that would be observed at the A&M Pavement Test Facility on a section having a given set of design parameters $(D_1, D_2, D_3, S_1, S_2, S_3, S_4)$, while W_r is an estimate of the deflection that would be observed on that section if it were located in the rth region. It follows that an estimate, $\hat{C}_r$, is given by

$$\hat{C}_r = W_r / W_O$$

$$(8)$$

if we interpret W_r as an _observed_ deflection in the rth region and W_O as the deflection predicted from Equation 5 for $r = 0$ $(C_O = 1)$.

The data available for testing the regional hypothesis, the procedures followed and the rationale of the method are outlined in the sections numbered 1 through 6 that follow.

(1) The following design data (except the compressive strength, S_1, of the surfacing material) were available for each of 323 flexible sections on Texas Highways.

TABLE 6

DESIGN PARAMETERS FOR ONE TEST SECTION

Layer No., i	Description	Thickness (In.)	Compressive Strength (psi)
1	Surfacing	D_1	S_1
2	Base	D_2	S_2
3	Subbase	D_3	S_3
4	Subgrade	D_4	S_4

It is not a practice of the Texas Highway Department to measure the compressive strength of asphaltic surfacing materials by the method previously specified for determining S; therefore, the values of S_1 for 323 test sections were unknown. Nevertheless, use of the deflection equation required at least an estimated value of laboratory strength for the surfacing layer. The value selected for use for all test sections was obtained by substituting in Equation 3 the value of F for asphaltic concrete given in Table 5 (.5305) and solving for S. The value found by this means was 1108 psi, which lies between the measured compressive strengths for lime-stabilized crushed in limestone (430 psi) and cement-stabilized crushed limestone (2270 psi) given in Table 5. It should be pointed out in this connection that the asphaltic concrete used in in the test sections was unusually "tender" when laid, and may not be representative of much of the surfacing materials on existing highways in Texas at the time it was tested.

The strength data originally available for subsurface layers on the great majority of the highway sections were Texas Triaxial Class data. However, a relationship was found to exist between triaxial class and the laboratory strength, S, so that triaxial class data could be converted to S data with reasonable accuracy. Details are given in Appendix B.

(2) In 1964 deflections were measured by means of the first model of the Dynaflect, shown in Figure 9. These measurements were made at 15 points on each section, averaged, and the average converted to an estimate of the static deflection that would be

-22-

caused by an 18-kip single axle load (9000-lb. wheel load), based on the results of field correlation studies relating Benkelman Beam to Dynaflect deflections (See Appendix A).

(3) From the data for each test section log $\hat{C}_r$ was computed using Equation 7. (Log $\hat{C}_r$, rather than $\hat{C}_r$ itself, was used because of the propensity of the deflection error to be proportional to the deflection (See Appendix A).

(4) The values of log $\hat{C}_r$ were written on a map, each value being placed at the location of the test section from which the estimate was computed.

(5) Contours of equal values of log $\hat{C}_r$ were drawn on the map. The fact that the contours could be drawn was taken as evidence that the quantity, log $\hat{C}_r$, was not randomly distributed geographically, but was in fact related to location.

(6) Areas bounded by successive contours of log $\hat{C}_r$ were regarded tentatively, as regions, and the average value of log $\hat{C}_r$ within each region was taken to be the logarithm of the regional factor, C_r.

Paragraphs numbered 1 through 6 above describe what will be termed for discussion purposes as the Main Experiment. The geographical distribution of the sections in the Main Experiment is shown in Figure 10, where the location of each of the 323 test sections is indicated on a Texas map.

Figure 11 shows contours of log $\hat{C}_r$ (which defined 5 regions) drawn free-hand on a Texas map in accordance with the procedures outlined above. Also shown on the map (as small dots) are the locations of the test sections, each of which contributed data from which one value of log $\hat{C}_r$ was computed. The exact location of the contours are not considered definite, and where they pass through areas sparsely populated by test sections, the lines are dashed to warn of uncertainty as to their true position.

The contour interval, chosen arbitrarily, was 0.25, and each contour line was taken as the boundary of a region. The result was the division of the state into five regions, two of which were subdivided into several widely separated subregions.

Each region or subregion was assigned a number from 1 to 5, the particular number assigned depending upon the value of log $\hat{C}_r$ on the contours forming its boundaries. Table 7A gives the values on the limiting contours of each region, the number of test sections in each region, the average of the values of log $\hat{C}_r$
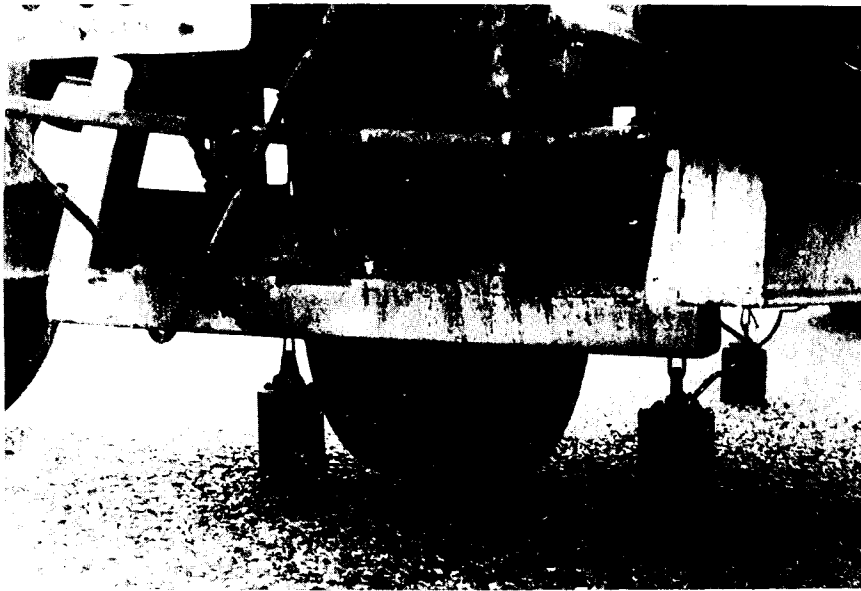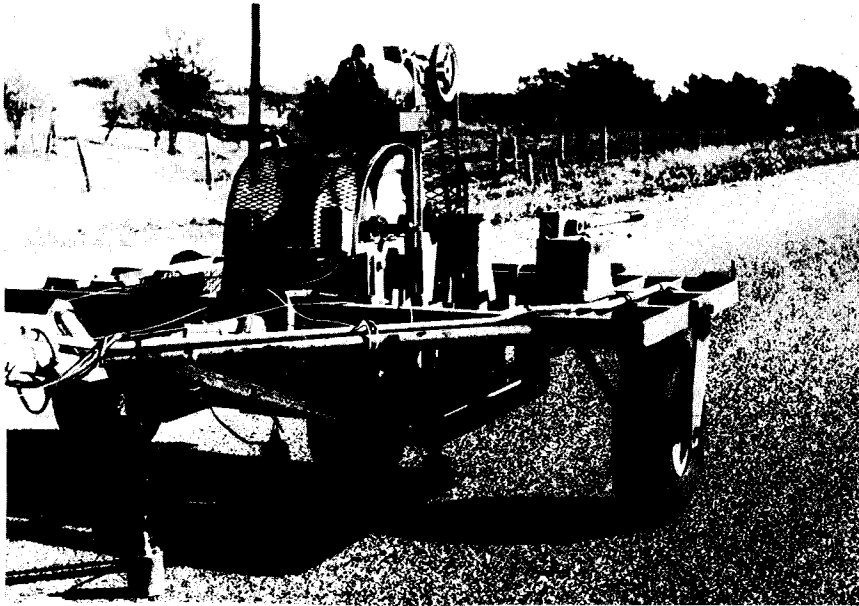
Figure 9: DYNAFLECT -- ORIGINAL MODEL.
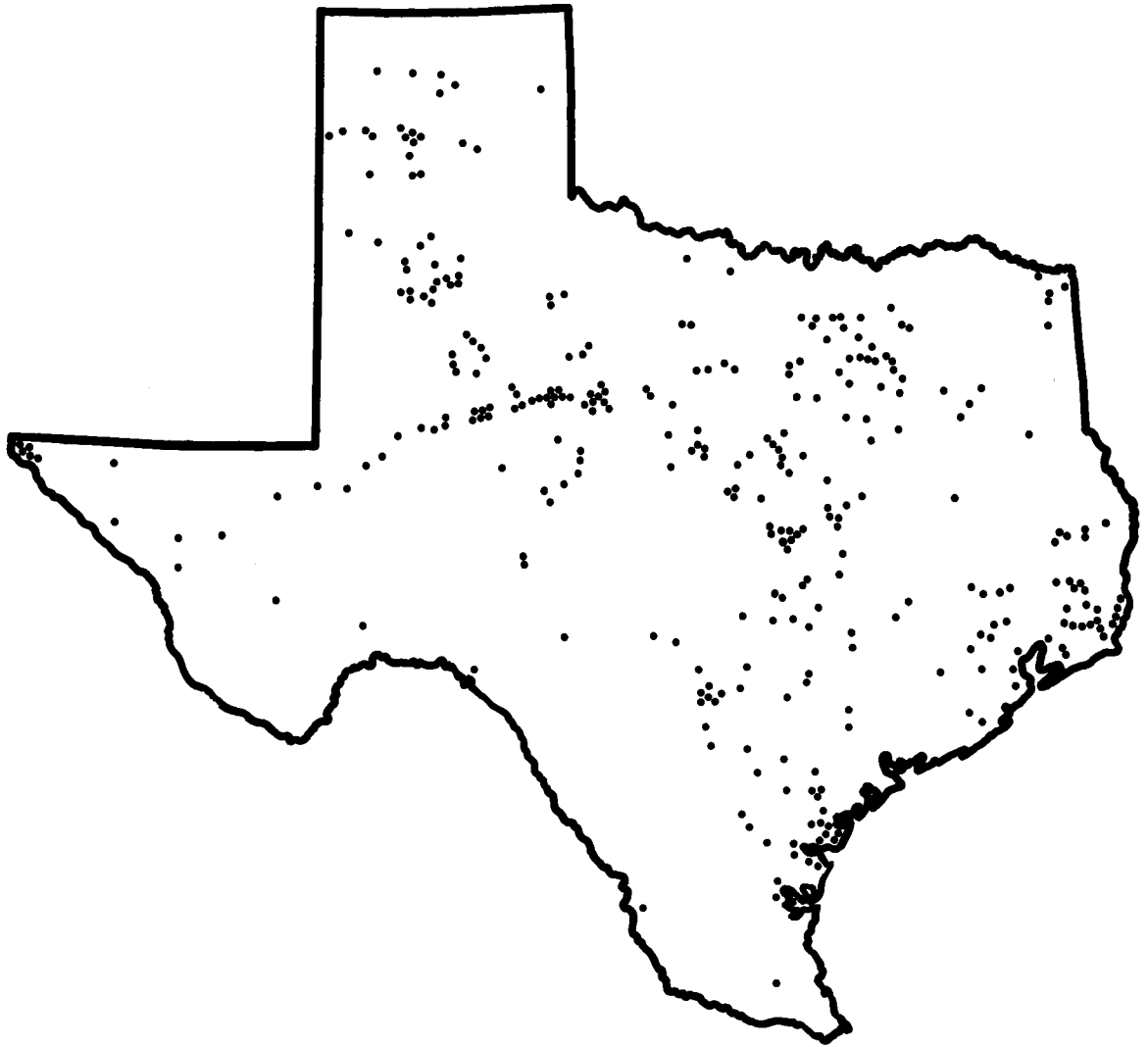The lower photograph shows a
close-up of the load wheel.

Figure 10: OUTLINE OF TEXAS WITH LOCATION
OF TEST SECTIONS SHOWN.

REGION   Cr

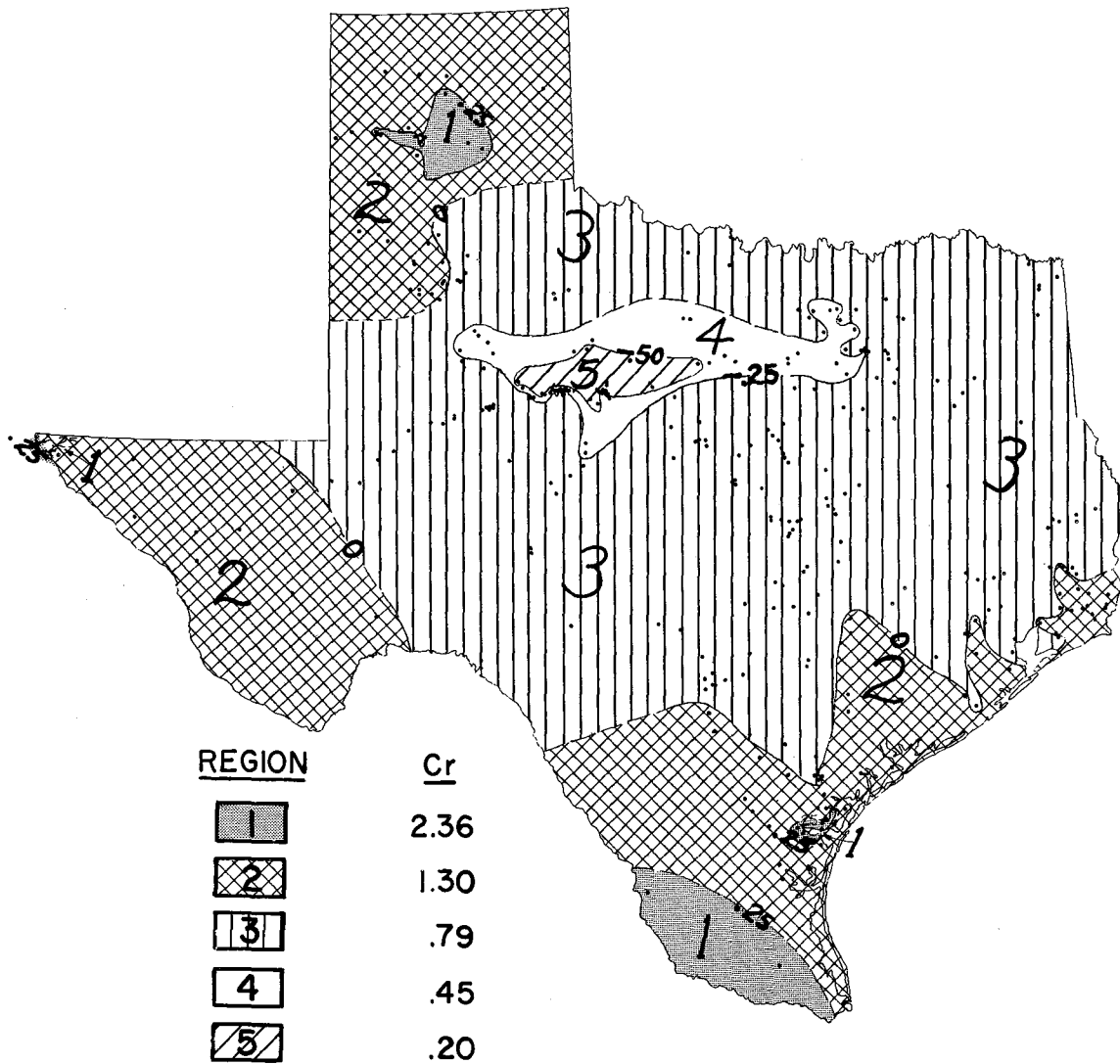|	
1	2.36
2	1.30
3	.79
4	.45
5	.20

Figure 11: REGIONAL MAP OF TEXAS.
Regions define areas of
equivalent pavement behavior.

occurring within the region, and the corresponding anti-log, which was taken as the regional factor.

In Table 7B the averages are given, for each region, of the layer compression coefficients, F_i (for $C_r = C_o = 1$), the layer depth coefficients, X_i, the measured deflections, W_r, the calculated deflections for the test facility conditions, W_o, and the regional factors. As evidenced by the table, there are no significant trends in the averaged design data except that of the subgrade strength, F_4, and this trend is in the wrong direction--the subgrades tend to get weaker as the regions get better.

The engineering implications of the wide variation in the regional factor, C_r, become clear if one considers the following examples:

From Table 7A it can be seen that the deflection observed on a section in Region 1 can be expected to exceed the deflection that would be observed on a section of similar design at the A&M Pavement Test Facility by a factor in the neighborhood of 2.4 (since $C_1 = 2.389$). On the other hand a section in Region 5 would be expected to have a deflection only 20% of that observed on a section of similar design at the test facility ($C_5 = 0.204$). By the same reasoning it can be concluded that (since $C_1/C_5 = 11.7$) a section of a given design in Region 1 would be expected to deflect an amount more than ten times the deflection of a section having the same design parameters, but located in Region 5.

In view of the engineering implications just described, it became important to show that variations in the regional factor, C_r, were neither merely the result of chance nor the result of systematic operational errors. Some evidence that the variations in log $\hat{C}_r$ are related to locatlity was mentioned in Paragraph 5 above. More evidence is presented in Table 8, which gives the results of an analysis of variance. It was concluded from this analysis that the differences in log $\hat{C}_r$ between regions was highly significant when compared to the variation of log $\hat{C}_r$ within regions. The same conclusion was reached subjectively from an examination of the histograms shown in Figure 12, where the number of sections having a log $\hat{C}_r$ outside the range encompassed by each region is compared graphically with the number inside the range.

The analysis of variance given in Table 9A supplied statistical evidence that the four widely separated subregions of Region 1 did in fact belong to the same region, while the analysis shown in Table 9B supported the hypothesis that the three subregions of Region 2 belonged to the same region.

In March, 1966, a second set of deflection measurements were made with the 1966 model of the Dynaflect which is shown in Figure 5 of Section 4. The purpose of the second set of measurements was to determine if some type of systematic error contributed to the variations observed in the first set of data. For this investigation measurements were remade on 56 of the test sections scattered over the state of Texas. The second set of measurements and the design information associated with these 56 test sections will be termed the 1966 Experiment to distinguish it from Main Experiment, the larger set of data for 323 sections from which the regional boundaries were established. A summary of the data from the 1966 Experiment is given in Tables 10A and 10B which can be compared directly with Tables 7A and 7B. This comparison shows a very close agreement between the two sets of data. The results of an analysis of variance for the 1966 Experiment is given in Table 11.

It was concluded from the analyses described in this section that the regional hypothesis was valid, that the regions found by the main experiment were in fact highly significant, and that the wide variation in the regional factor warranted an intensive investigation of the underlying causes.
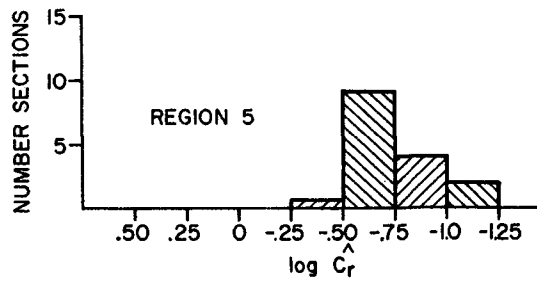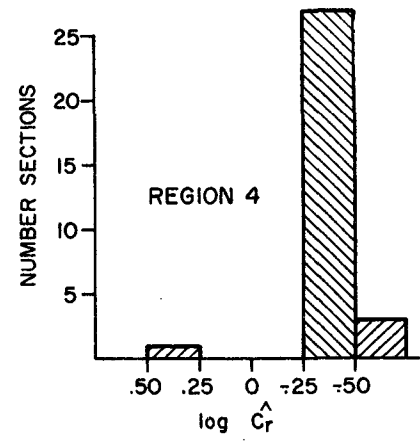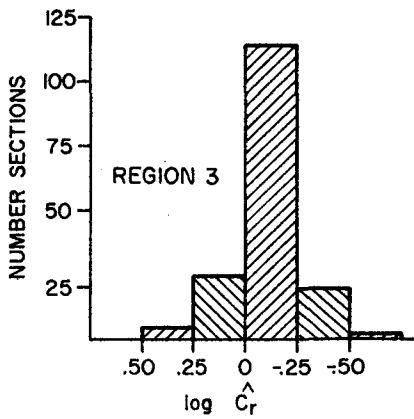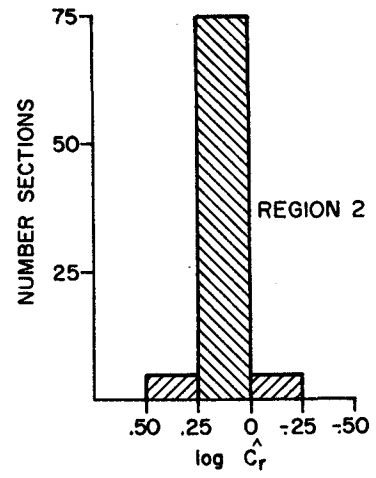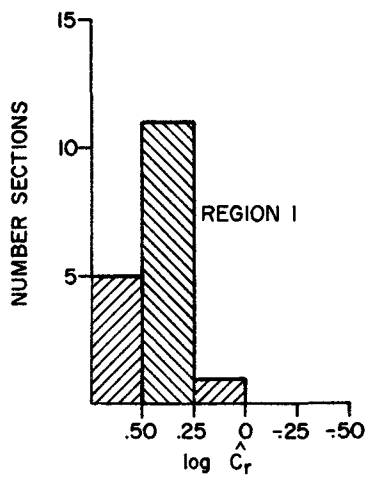
Figure 12:   HISTOGRAMS SHOWING DISTRUBUTION
OF LOG $\hat{C}_r$ WITHIN REGIONS.

TABLE 7A

Summary of Main Experiment Data

(From Which Location of Regional Boundaries
and Values of Regional Factors Were Estimated)

| | Limiting Contours of Log $\hat{C}_r$ | | | | |
| | Lesser Value | Greater Value | No. Sections | Average Value of Log $\hat{C}_r$ | Regional Factor, C_r |
Region, r					
1	0.25	>0.25	14	.3732	2.389
2	0	0.25	86	.1116	1.291
3	-0.25	0	176	-.1024	0.797
4	-0.50	-0.25	31	-.3436	0.456
5	<-0.50	-0.50	16	-.6905	0.204
All			323	-.0747	0.840

TABLE 7B

Main Experiment-Regional Averages of F_i, X_i, W_r and W_o

Region	Compression Coefficients*				Depth Coefficients				W_r	W_o	C_r
	F_1	F_2	F_3	F_4	X_1	X_2	X_3	X_4			
1	0.53	13.73	22.63	71.00	.01381	.02163	.00338	.00986	52.8	22.1	2.389
2	0.53	14.99	26.11	85.47	.01245	.02219	.00409	.00996	33.3	25.8	1.291
3	0.53	15.01	27.02	104.82	.01268	.02218	.00407	.00976	23.5	29.5	0.797
4	0.53	16.79	26.40	122.61	.01298	.02215	.00458	.00897	15.1	33.1	0.456
5	0.53	15.92	23.11	135.63	.01099	.02318	.00386	.01066	7.4	36.3	0.204

*Computed with $C_r = C_o = 1$.

TABLE 8

Main Experiment—Analysis of Variance - Log $\hat{C}_r$
(All 5 Regions)

Source of Variation	SS	DF	MS	F	F(.005)
Total	22.1398	322	.0687570		
Between Regions	14.7333	4	3.68333	158.15	3.85
Within Regions	7.40644	318	.0232907		

TABLE 9A

Main Experiment--Analysis of Variance - log $\hat{C}_r$

(Subregions of Region 1)

Source of Variation	SS	DF	MS	F	F(.05)
Total	.138168	16			
Between Subregions	.019237	3	.006412	0.70	3.41
Within Subregions	.118930	13	.009148		

TABLE 9B

Main Experiment--Analysis of Variance - log $\hat{C}_r$

(Subregions of Region 2)

Source of Variation	SS	DF	MS	F	F(.05)
Total	.89365	82			
Between Subregions	.015712	2	.007856	0.72	3.11
Within Subregions	.877939	80	.010974		

TABLE 10A

Summary of 1966 Experiment Data
(Compare with Table 7A)

Region, r	Limiting Contours of Log $\hat{C}_r$		No. Sections	Average Value of Log $\hat{C}_r$	Regional Factor C_r
	Lesser Value	Greater Value			
1	0.25	>0.25	3	.3092	2.038
2	0	0.25	10	.0494	1.121
3	-0.25	0	34	-.0697	0.852
4	-0.50	-0.25	8	-.3151	0.484
5	<-0.50	-0.50	2	-.7016	0.199
All			56	-0.0870	0.818

TABLE   10B

1966 Experiment

Regional Averages of F_i, X_i, W_r and W_o

(Compare with Table 7B)

Region	No. Sections	Compression Coefficients*				Depth Coefficients				W_r	W_o	C_r
		F_1	F_2	F_3	F_4	X_1	X_2	X_3	X_4			
1	3	0.53	14.19	28.79	74.44	.01776	.01800	.00432	.00860	44.867	20.743	2.038
2	10	0.53	12.82	34.45	106.77	.01487	.02066	.00437	.00878	32.970	29.240	1.121
3	34	0.53	14.34	28.39	100.67	.01527	.02186	.00343	.00813	23.153	26.583	0.852
4	8	0.53	15.15	23.64	118.20	.01291	.01950	.00794	.00833	16.912	34.472	0.484
5	2	0.53	16.01	20.22	196.70	.01484	.01975	.00594	.00815	8.300	46.588	0.199

*Computed with $C_r = C_o = 1$.

TABLE 11

1966 Experiment--Analysis of Variance - log C_r

(All Regions)

Source of Variation	SS	DF	MS	F	F(.005)
Total	4.0634	56	.072561		
Between Regions	1.83866	4	0.459664	10.74	4.24
Within Regions	2.22477	52	.042784		

REFERENCE LIST

1.   "The AASHO Road Test, Report 5, Pavement Research," Special Report 61E, Highway Research Board of the National Academy of Sciences-- National Research Council, Washington, D. C., 1962.

2.   *Manual of Testing Procedures*, Texas Highway Department, Materials and Tests Division, Austin, Texas, February, 1966.

3.   Scrivner, F. H. and Moore, W. M., "Evaluation of the Stiffness of Individual Layers in a Specially Designed Pavement Facility from Surface Deflections," Research Report 32-8, Pavement Design Department, Texas Transportation Institute, Texas A&M University, College Station, Texas, June, 1966.

4.   Scrivner, F. H. and Moore, W. M., "An Electro- Mechanical System for Measuring the Dynamic Deflection of a Road Surface Caused by an Oscillating Load," Research Report 32-4, Pavement Design Department, Texas Transportation Institute, Texas A&M University, College Station, Texas, December, 1964.

5.   Scrivner, F. H. and Moore, W. M., "Standard Measurements for Satellite Road Test Program -- Measurements Team," Report I, Pavement Design Department, Texas Transportation Institute, Texas A&M University, College Station, Texas, June, 1966, (pp. 53-61).

6.   Scrivner, F. H. and Moore, W. M., "A Tentative Flexible Pavement Design Formula and Its Research Background," Research Report 32-7, Pavement Design Department, Texas Transportation Institute, Texas A&M University, College Station, Texas, February, 1966.

7.   Manke, P. G., "Pulse Velocities in Flexible Pavement Construction Materials," Highway Research Board Record 131, 1966 (pp. 128-153).

Appendix A

CORRELATION OF DYNAFLECT
WITH BENKELMAN BEAM DEFLECTIONS

In 1963, prior to the routine use of the Dynaflect in this project, an extensive correlation study[4] was made on 35 test sections on existing highways in an effort to determine if deflections measured by the original model of the Dynaflect (Figure 9) were related to deflections induced by heavy wheel loads and measured by the Benkelman Beam. The testing procedure that was used is described below.

On each test section measurements were made at 14 locations in the outer wheel path. The load wheel of the Dynaflect (see Figure 9) was placed on a designated location, the output of the geophones was recorded, and the instrument removed. The exact point on the pavement where the load wheel had been applied was marked with a painted cross. Immediately thereafter a 2-axle truck, with the rear axle loaded to 18,000 lbs., was positioned with the right rear wheel centered over the cross. A Benkelman Beam was then positioned with its probe on the cross, the truck was driven forward about 50 feet, and the rebound deflection was recorded. The truck was then backed to its previous position, a second rebound deflection was measured, the two measurements were averaged, and the average was used as the Benkelman Beam deflection for that location.

The value recorded for the Dynaflect was the average output of two geophones placed on the pavement 9.5 inches to the right and left of the center of the load contact area. The geophone output actuated a pen that inked a line on a moving paper tape. While the cyclical load was being applied and the pavement was in steady-state vibration, the circuitry was such that the displacement of the pen from its neutral (no load) position, was proportional to the amplitude of the combined output of the two geophones, and therefore to the average deflection of the pavement at two points 9.5 inches each side of the load.

Values of the Dynaflect pen displacement, in units of one-quarter inch, were plotted against corresponding Benkelman Beam deflections in milli-inches, as shown in Figure 13. The correlation coefficient was 0.91.

The slope of the line fitted to these data and shown in the figure provided a factor which could be used to convert measurements made by the original Dynaflect Model to estimates of the deflections caused by a 9000-lb. wheel load. The standard deviation of the data from this line was .0069 inch.
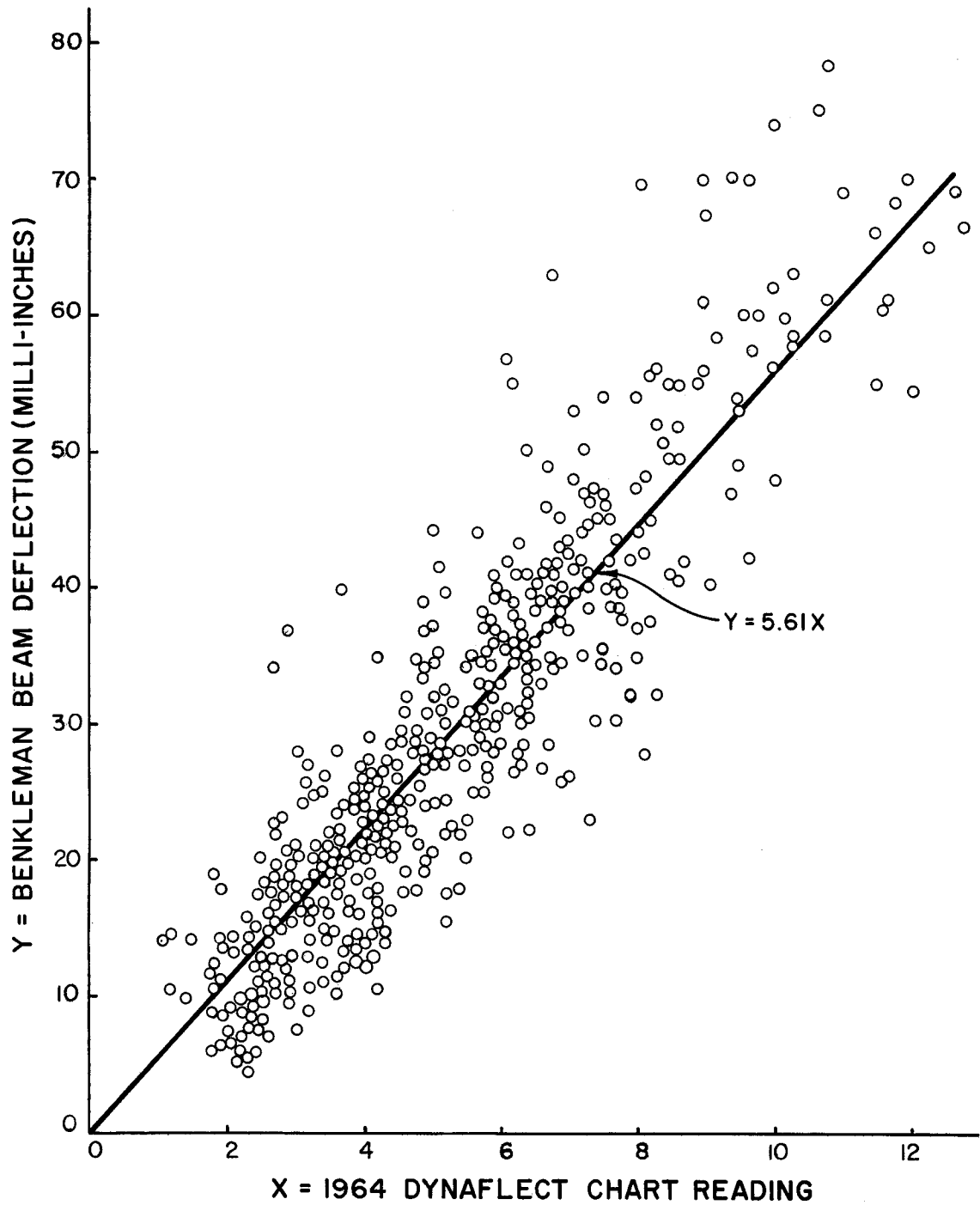
Figure 13:   BENKELMAN BEAM VERSUS ORIGINAL
             DYNAFLECT.

The later (1966) model of the Dynaflect (see Figure 5) was equipped with a meter indicating deflections directly. Comparisons with the older model, made on a number of Texas highways, led to a factor of 22.4 which, when multiplied by the deflection registered by the geophone located between the load wheels (Geophone No. 1 of Figure 6) gave an estimate of the deflection caused by a 9000-lb. wheel load.

Some confirmation of the factor 22.4 used with the 1966 Model Dynaflect was obtained by a study[5] made in May and June of 1966 in Florida and Minnesota. The results are plotted in Figure 14. As may be seen, the line drawn in the figure with a slope of 22.4 appears to fit the data fairly well.

The Minnesota data were gathered on 10 test sections. On each section Dynaflect and Benkelman Beam deflections were observed at 11 locations, a number sufficient to permit the determination, with some confidence, of the standard deviation within each section associated with each of the two instruments. These data are plotted in Figure 15 against the corresponding section means for each with a measured deflection to be proportional to the magnitude of the deflection. It was because of this tendency that $\log \hat{C}_r$, rather than $\hat{C}_r$ itself, was used in the analyses discussed in Section 8.
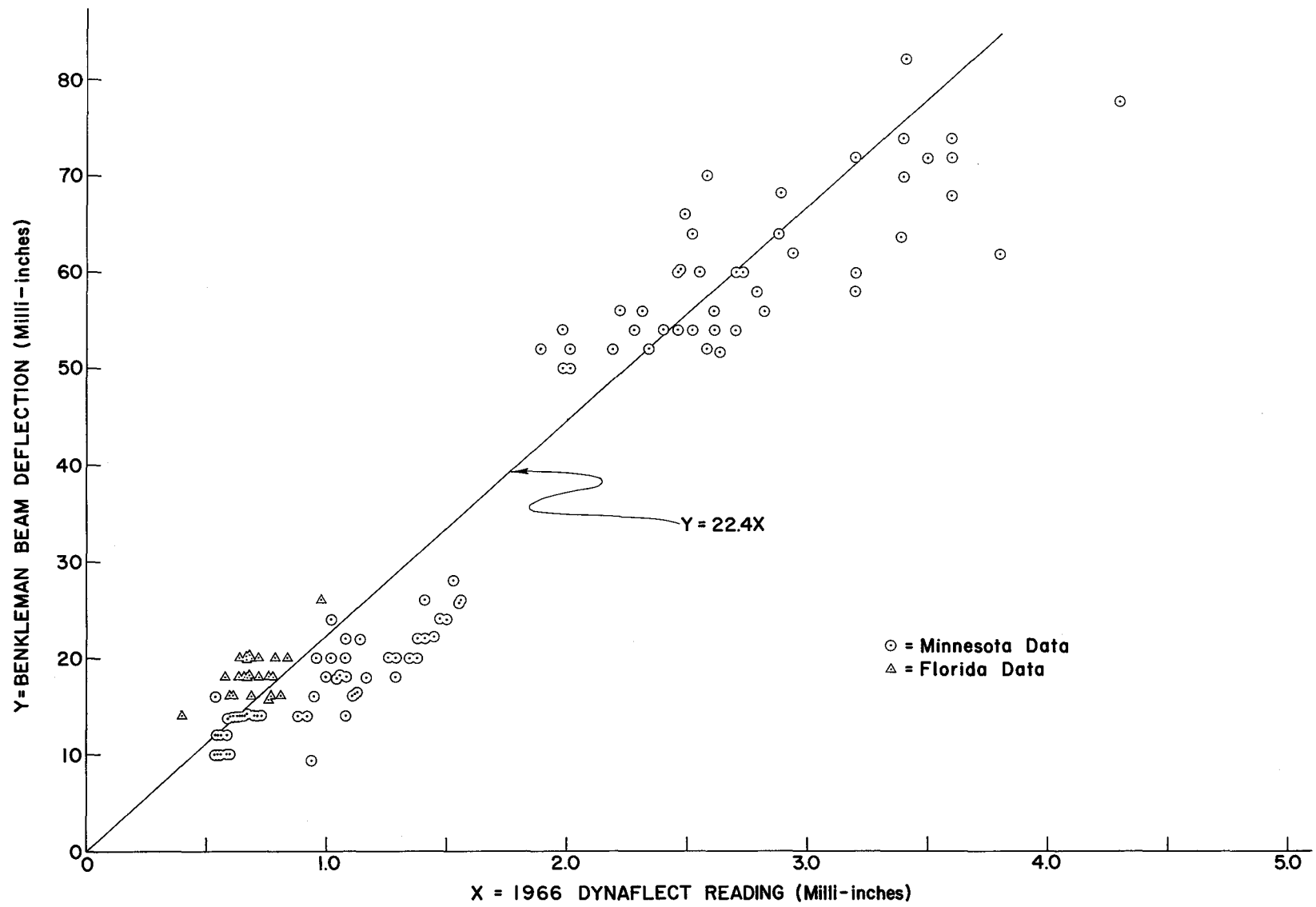
Figure 14:   BENKELMAN BEAM VERSUS 1966
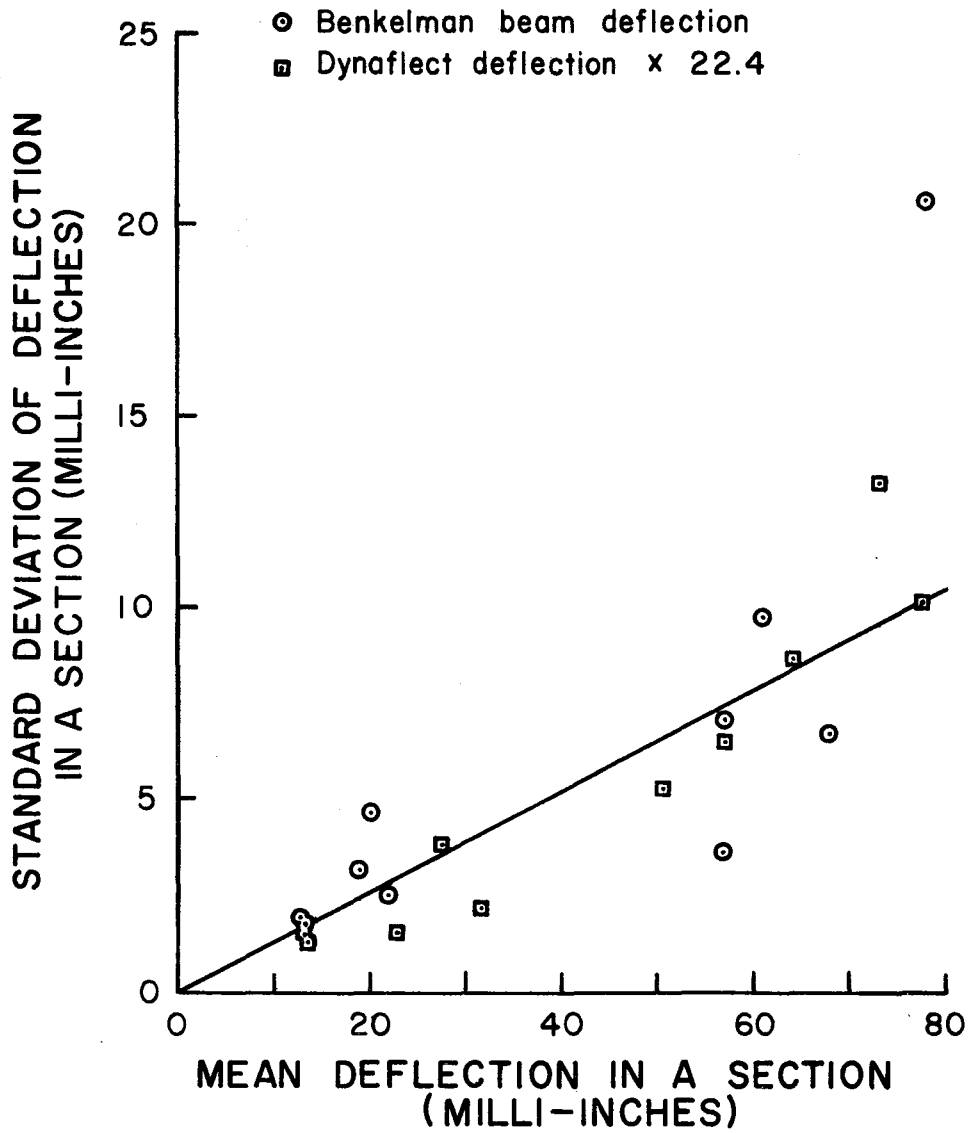   DYNAFLECT.

Figure 15: WITHIN-SECTION STANDARD DEVIATION
VERSUS MEAN DEFLECTION. Trend
line was drawn through origin and
mean of data.

Appendix B

COMPRESSIVE STRENGTH AT 5 PSI LATERAL PRESSURE ESTIMATED
FROM TEXAS TRIAXIAL CLASS

The Texas Triaxial Class of a material is obtained from the Mohr's rupture envelope for the material. The latter, in turn, is obtained from triaxial tests made on specimens of the material at a variety of lateral pressures, including a pressure of 5 psi. It is not surprising, then, that an approximate relationship should exist between triaxial test results at a lateral pressure of 5 psi (the S-data used in this report) and Texas Triaxial Class data.

An opportunity to develop the relationship between the variables S and T (where T represents Texas Triaxial Class) arose when the Highway Department District 17 Laboratory made test data for the triaxial classification of 106 materials available to this research. In Figure 16 the value of S is plotted against the value of T for each of these materials. The curved line fitted to the data has the following equation:

$$S = 9.300 + 0.4539 (8-T)^3 \qquad (1)$$

where T is restricted to the interval, $0.5 \leqslant T \leqslant 6.5$.

The data plotted in Figure 16 are from tests conducted in the years 1959-62. In 1964 additional triaxial classification data became available from 113 materials taken from 39 existing highway sections scattered over the state and tested in connection with this project. These later data are plotted in Figure 17. Also shown in this figure is a reproduction of the curved line plotted in Figure 16 and representing Equation 1. It is apparent that the relationship between S and T developed from the District 17 data also fits the later data.

From this study it was concluded that in cases where the Texas Triaxial Class is known the "Laboratory strength," S, could be estimated with reasonable accuracy.

(The discerning reader, if a Texas Highway Department engineer, may question several points plotted in Figures 16 and 17 with values of T less than 2.0. These values were obtained by use of a special classification chart that included an extra line in the Class 1 area of the chart. This chart was presented in Reference 6, and is reproduced in Figure 18).
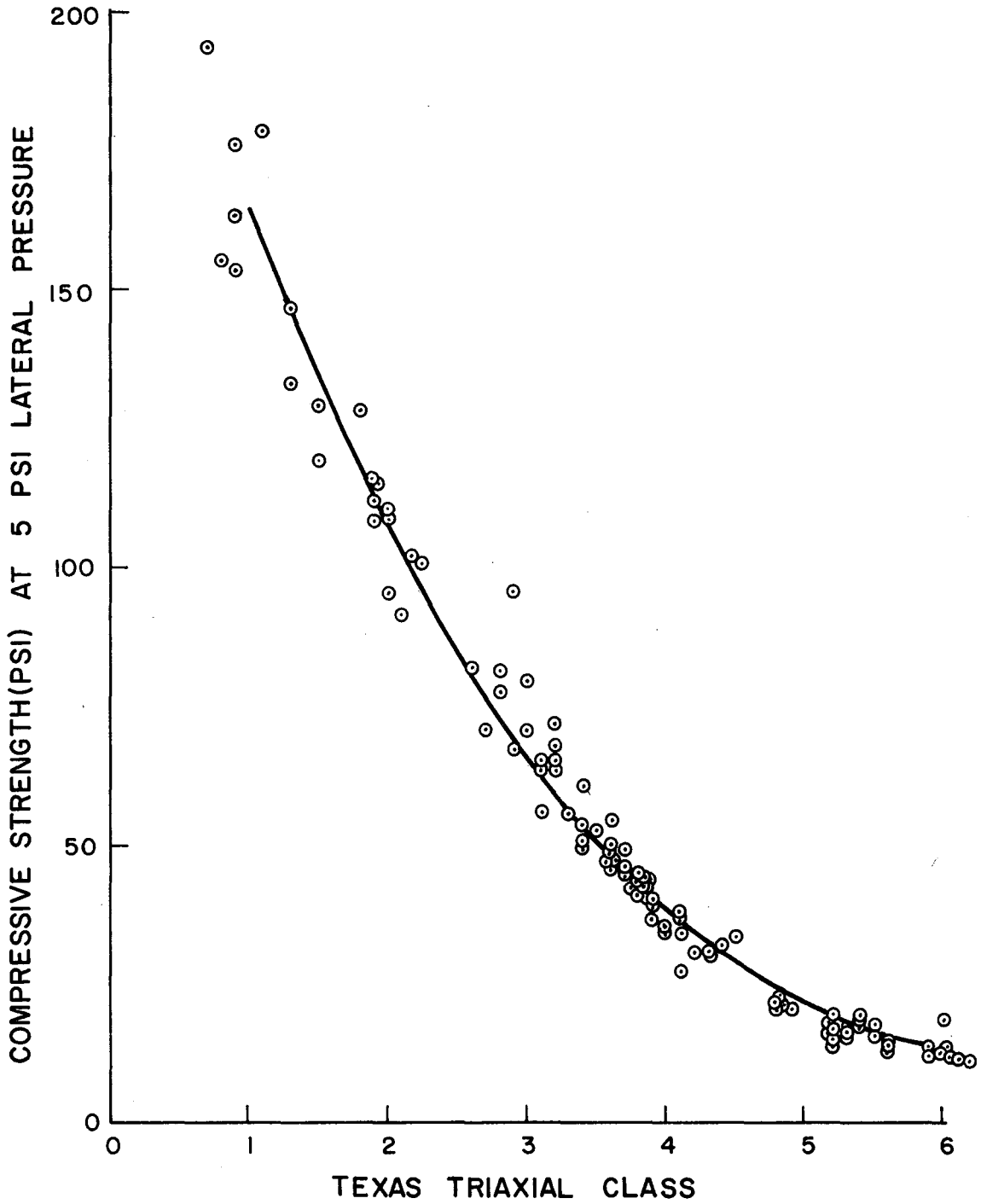
Figure 16: 1959-62 TEST RESULTS FOR TEXAS
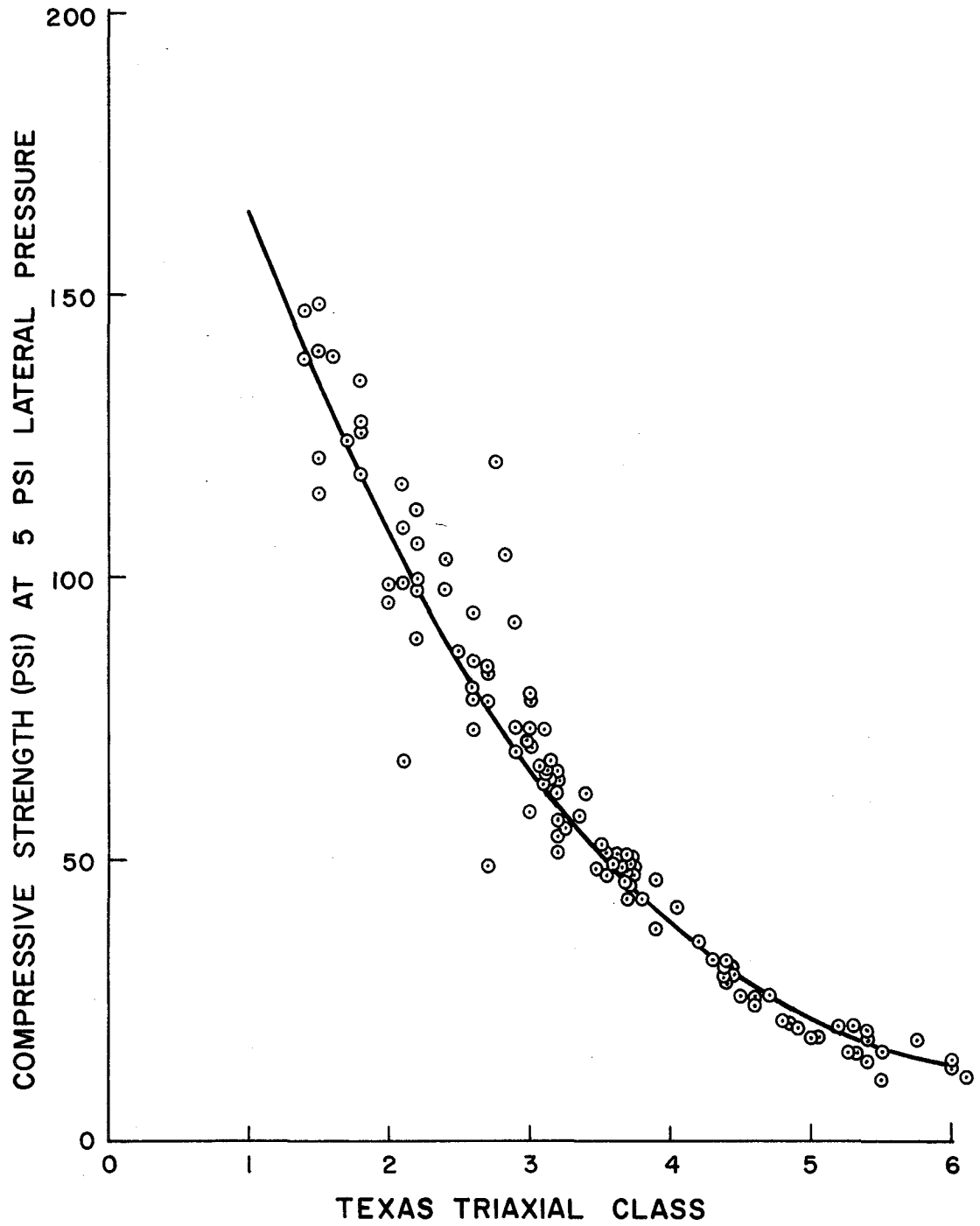TRIAXIAL CLASSIFICATION OF 106
MATERIALS IN DISTRICT 17.

Figure 17: 1963-64 TEST RESULTS FOR TEXAS
TRIAXIAL CLASSIFICATION OF 113
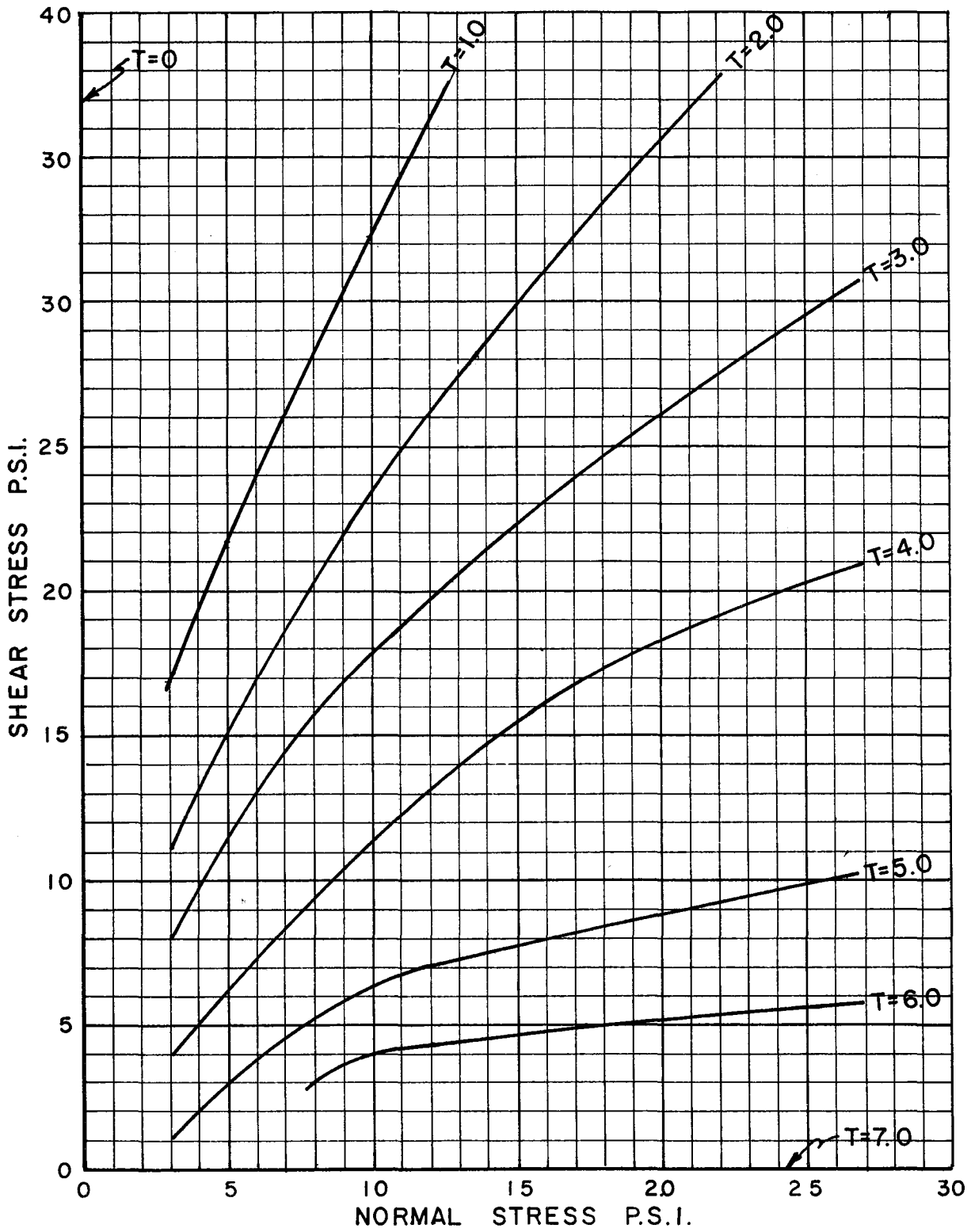MATERIALS IN 13 DISTRICTS.

Figure 18: RECOMMENDED FLEXIBLE PAVEMENT
MATERIALS CLASSIFICATION CHART.
A Class 1.0 line has been added.