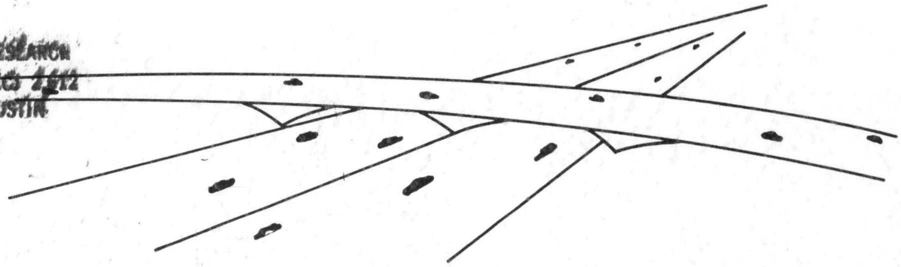

DEPARTMENTAL RESEARCH

Report Number 46-7

OBSERVATION AND ANALYSIS of CONTINUOUSLY REINFORCED CONCRETE PAVEMENT

TEXAS HIGHWAY DEPARTMENT

OBSERVATION AND ANALYSIS OF CONTINUOUSLY REINFORCED CONCRETE PAVEMENT

by

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Research Report No. 46-7

for

Performance Study of Continuously
Reinforced Concrete Pavement
Research Project 1-8-63-46

Conducted by

Texas Highway Department
Highway Design Division, Research Section
In Cooperation With the
U.S. Department of Transportation
Federal Highway Administration
Bureau of Public Roads

July 1968

ACKNOWLEDGEMENTS

The research presented in this report is the result of a cooperate effort between the Texas Highway Department and The University of Texas, Center for Highway Research. The general supervision of Mr. R. L. Lewis, Research Engineer, Texas Highway Department and Dr. W. Ronald Hudson, Research Engineer and Assistant Professor of Civil Engineering, The University of Texas, is gratefully acknowledged.

The able assistance of various members of the Center for Highway Research Staff is also acknowledged.

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ABSTRACT

This report is the result of a cooperate effort between the Texas Highway Department and The University of Texas, Center for Highway Research.

Research project 3-5-63-56, entitled "Development of Methods for Computer Simulation of Beam-Columns and Grid-Beam and Slab Systems" has produced powerful new analytical methods of slab analysis. These analytical tools were used to analyze 21 continuously reinforced concrete pavement test sections.

The Texas Highway Department in Research project 1-8-63-46 has gathered in excess of 15,000 measurements of deflection, radius of curvature, crack width, and temperature on continuous pavements located throughout the State.

Comparisons of the field data with the analytical results indicate that:

1. The slab analysis techniques accurately predict deflections as compared to the Benkelman Beam.

2. Basin Beam measurements indicate an average moment which correlates fairly well with computed moments.

3. The moments indicated by the basin beam are somewhat smaller in magnitude than computed by the finite element method.

I. INTRODUCTION

Pavement Evaluation Needs

Highway engineers are continually looking for ways of comparing and evaluating the pavements which they design and build. In order to make the desired evaluation, factors such as strain, deflection and pressure are field measurements which are usually made on pavement. The AASHO Road Test[1] which involved thousands of strain readings and deflection readings is an excellent example of this type of experiment. In gathering field data for pavement evaluation, the two things that usually govern are the ease and cost of making measurements and the value of the measurements. The value is determined by how well the measurements indicate pavement performance and the pavement's response to load. Strain gages are expensive, installation is always difficult, and maintenance is also a problem. Therefore, a rapid, portable, easy method of measurement is needed.

The first such method is the Benkelman beam which was developed at the WASHO Road Test[2] and used extensively at the AASHO Road Test. A second method is the curvature beam which was initially developed in South Africa[3] and modified by the Texas Highway Department[4] for use on rigid pavement.

Purpose and Scope

The overall purpose of this study is to evaluate the above mentioned two methods of taking quick field measurements, and of particular interest is their application to continuously reinforced concrete pavements since this is where all the data was taken. For comparison purposes analytical techniques developed for evaluating very general orthotropic pavement slabs are used. The finite element method of analysis[5] was developed at The University of Texas in a cooperative research program with the Texas Highway Department and the Bureau of Public Roads.

II. FIELD OBSERVATIONS

The observations made on rigid pavements covered in this paper are deflection and radius of curvature. The deflections were measured by using a Benkelman beam. Radius of curvature was measured by using a small 40-inch beam, called a basin beam, modified by the Texas Highway Department for measuring curvatures on rigid pavements. Hereafter the terms basin beam and curvature beam are used interchangeably. Thus, the two basic pieces of equipment involved in this presentation are the Benkelman beam and the basin beam. The load was applied to the pavement by using an 18 kip single axle stake-type truck.

AASHO Road Test procedures[1] for measuring rigid pavement deflections were used as guidelines for developing the procedures for the Texas experiment.[6] Before actually measuring deflections on a particular site on a slab, the slab was conditioned by making several passes over the area with the deflection truck. The purpose of this conditioning was to establish complete contact between the slab and the subbase or subgrade. Studies of this conditioning procedure have shown that it has less effect on the radius of curvature than on the deflection.[7] However, the conditioning procedure is followed since both deflection and radius of curvature measurements are obtained at the same time.

The deflection basin of a rigid pavement usually extends a considerable distance from the load. Therefore, the Benkelman beam had to be placed with its supporting feet off the edge of the pavement, on the shoulder. This again was in accordance with the procedures used at the AASHO Road Test.[1] The Benkelman beam was placed at an angle of 30 degrees to the longitudinal edge of the pavement pointing towards the truck. The end of the Benkelman beam probe was placed on the pavement one inch from the edge and centered with the axle load. The previously mentioned basin beam was placed parallel to the edge of the roadway between the probe of the Benkelman beam and the truck tire.[4] It was placed about two inches from the edge of the slab and located so that the center or movable point was directly in front of the probe of the Benkelman beam. Figure 3.2 shows in plan view the arrangement of the equipment. After both beams and the axle load have been properly placed, the dial gages on both the Benkelman beam and basin beam were zeroed.

Next the truck is moved from the area of influence or the deflection basin. After removing the load from the deflection basin or the area of influence, the dial gages are read on both the Benkelman and basin beams. These data are recorded on a previously prepared data sheet for deflection and radius of curvature.

All pavement test sections were 2500 feet long with the exception of several experimental pavements on which the test sections were 200 feet long. The test sections were all on in-service continuously reinforced concrete pavements. Data which are used in this paper have been taken from a statewide study of deflection and radius of curvature which the Texas Highway Department has conducted.[6,7]

The same size or number of measurements made on each test section is of significant importance. A special study was conducted to determine the minimum number of data points which could be taken and still have representative data.[4] These statistical analyses showed that 14 data points per 1200-foot section would be significant or 28 per 2500 feet of pavement length.

The average crack spacing of a test section was simply the length of the section divided by the total number of transverse volume change cracks in that section. The 200-foot test sections had preformed crack spacings. At each point at which a deflection and radius of curvature was to be measured the actual crack spacing at that point was to be approximately equal to the average for the entire test section. The 14 or 28 points at which deflection and curvature were measured on a test section were selected and marked.

Other items of data in addition to the deflections and curvatures were the time, slab temperature at the surface, and slab temperature at the bottom.[4]

AASHO Road Test findings on jointed concrete pavements show that slab temperature differential has a significant effect on the magnitude of deflection.[1] Since no continuously reinforced pavements were studied at the Road Test, no specific formula was given for temperature correction. It is believed that a continuous pavement responds nearly like the edge condition on the jointed concrete pavement. This was attributed to the continuity of the steel and better granular interlock of the concrete than the conventional joints. The formula developed at the Road Test[1] for static edge deflection was used to correct the continuously reinforced concrete pavement deflection to a zero degree temperature differential. By doing this, the effects of temperature on deflection were removed. There were no corrections on radius of curvature for temperature.

The field data which is used in this paper is shown in Table 2.1. Included are the concrete strength data and the modulus of subgrade reaction for each section. Also shown in this table are the field deflections and curvatures which will be compared to computed values.

TABLE 2.1

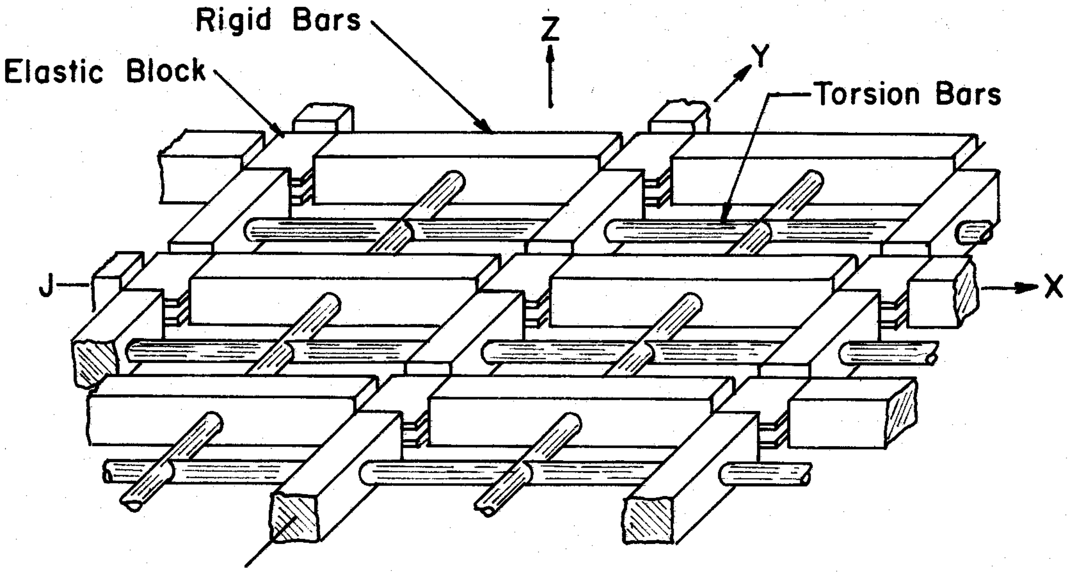
DATA

Problem No.	Concrete Modulus of Elasticity $E_c \times 10^6$	Modulus of Subgrade Reaction k (psi/in)	Deflection Uncorrected for Temp. (in.)	Deflection Corrected for Temp. (in.)	Radius of Curvature (feet)
1001	5.0	250	0.0132	0.0140	13,420
1002	5.0	250	0.0089	0.0091	10,100
1003	5.5	100	0.0176	0.0206	16,924
1004	3.5	250	0.0072	0.0072	14,273
1005	3.5	250	0.0060	0.0075	19,124
1006	5.5	100	0.0256	0.0310	12,375
1007	3.5	150	0.0091	0.0116	13,456
1008	5.5	100	0.0193	0.0200	13,347
1009	3.5	150	0.009	0.0107	15,290
1010	5.5	325	0.0038	0.0042	30,045
1011	3.5	100	0.0123	0.0135	12,856
1012	3.5	250	0.0051	0.0066	29,166
1013	5.5	150	0.0238	0.0240	
1014	5.5	150	0.0200	0.0200	
1015	5.5	150	0.0191	0.0191	
1016	5.5	100	0.0167	0.0161	
1017	5.5	100	0.0119	0.0116	
1018	5.5	100	0.0122	0.0119	
1019	5.5	300	0.0084	0.0084	
1020	5.5	300	0.0049	0.0049	
1021	5.5	300	0.0044	0.0044	

III. ANALYSIS AND COMPARISON

Description of Computer Program

The analysis was performed using a computer program which solves for the deflected shape of freely discontinuous orthotropic pavement slabs subjected to a variety of loads.[5,8] The method is applicable to slabs with freely variable foundation support including holes in the subgrade. The computer program actually solves a finite element model of the slab shown in Figure 3.1. The torsion bars shown represent the real torsional stiffness of the slab. The Poisson's ratio effect and the bending stiffness of the plate are represented by elastic blocks at the node points of the slab. The elastic blocks have a stress-strain relationship equivalent to the real plate and Poisson's ratio equal to that of the plate. Errors resulting from this method are caused by approximating the real slab with a model. The algebraic solution is exact for the model within the computer accuracy. Therefore, the closer the model duplicates the real slab the more precise the answer computed by the method will be. Because of this limitation, extreme caution should be used in properly describing the real slab in terms of a computer model.



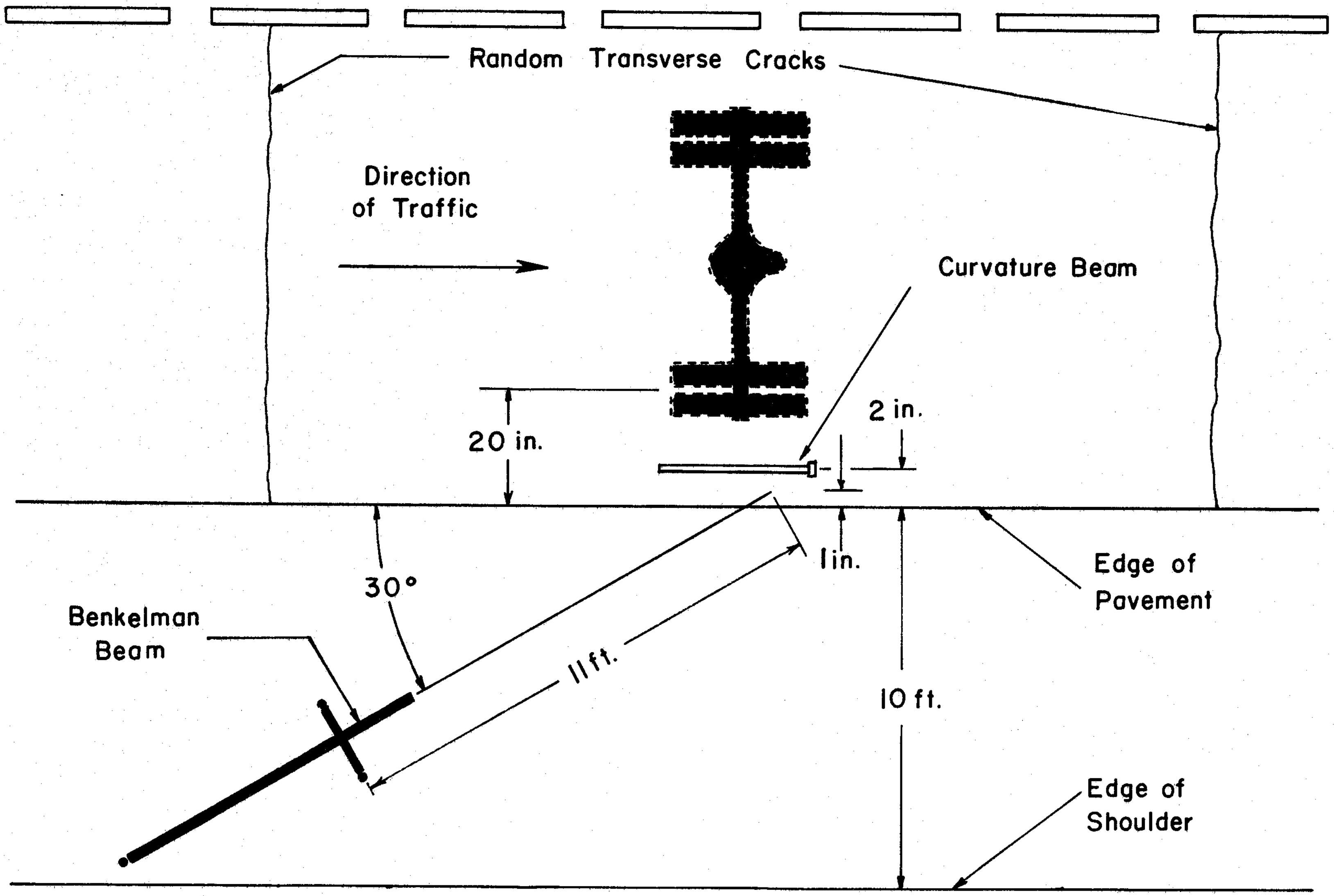
FINITE ELEMENT MODEL OF A PLATE OR SLAB

Fig. 3.1

Modeling Slab Problems

Real Slab. The real slab studied herein is continuously reinforced concrete pavement. The main differences between the numerous sections studied are the average crack spacing and the type of foundation under the pavement slab. Out of all the sections studied, two were six inches thick and all of the others were eight inches thick. The modulus of elasticity of the concrete slabs varied from 3.5 million psi to 5.5 million psi for the various problems. Because no information was available, Poisson's ratio was taken to be 0.15 for all problems.

Figure 3.2 is a plan view of equipment arrangement used while making all of the field measurements on which an analysis is presented herein. This report is concerned with loading in which the axle load was centered between two cracks. The axle load magnitude in all cases was 18 kips. The 40 inch basin beam was placed parallel to and approximately two inches from the edge of the pavement with its mid-point in line with the axle of the truck. The Benkelman beam was located so as to measure the pavement deflection at a point in line with the axle and the probe was placed on the pavement one inch from the edge.



EQUIPMENT ARRANGEMENT

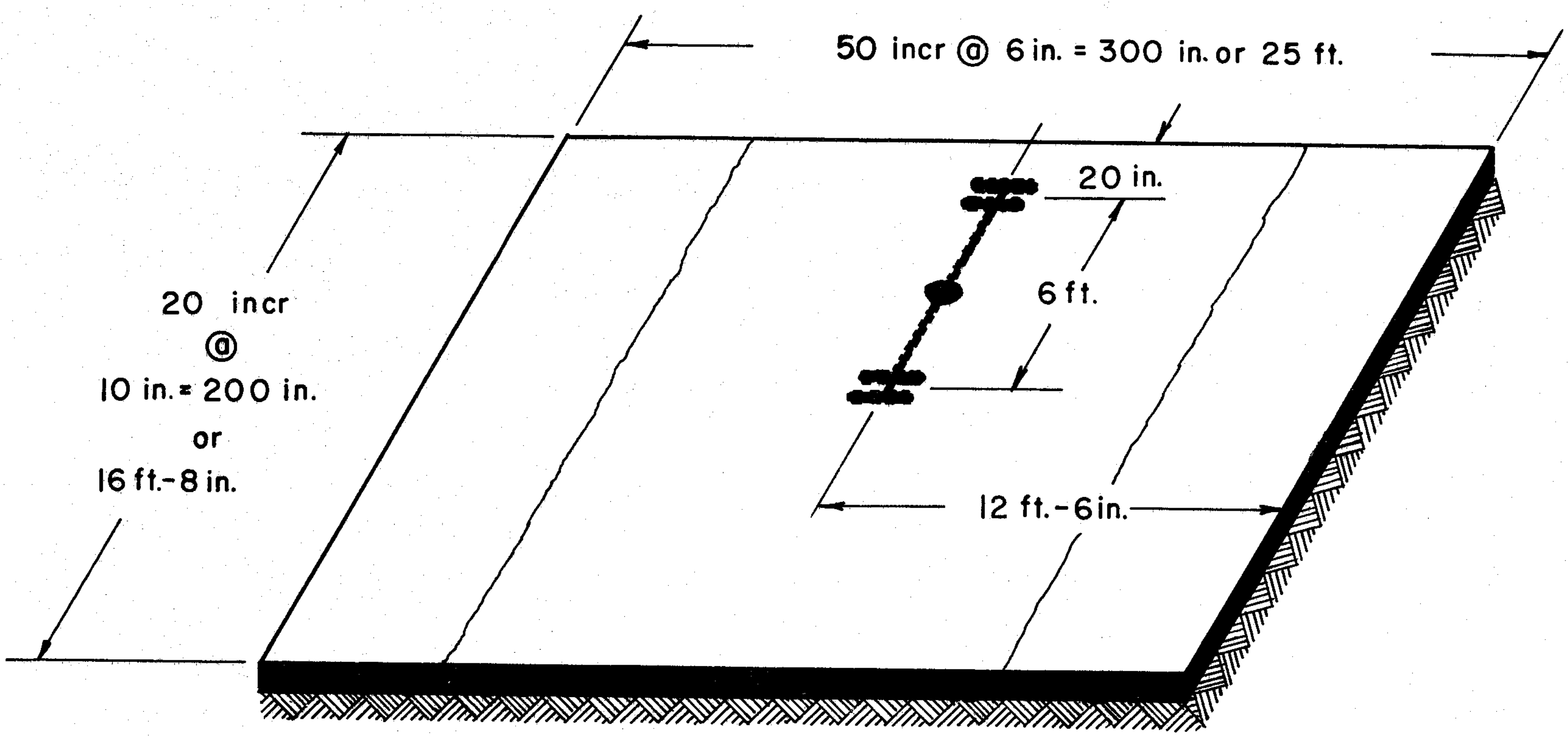
Fig. 3.2

Computer Models. With these pertinent facts about the real slab in mind, adequate computer models were developed. Because of the fixed geometry associated with field procedures and the equipment used, it was very important that increment lengths[5] be chosen that would very closely approximate the actual conditions in the field. Since the deflected shape of the pavement near the edge was of prime importance, it was very important that the increment length chosen parallel to the position of the basin beam should be made as small as practically possible. The increment length perpendicular to the beam was not so critical but had to be chosen so that the position of the wheel loads could be placed as accurately as possible. This accurate modeling of the field conditions is important because the load input values and deflection output values occur only at the mesh points in the computer model.[5]

The next point of consideration was the overall size of the slab which was necessary.[8] Available computer storage and computational time considerations offer two practical limitations. If the load was placed on the center line, the slab had to be long enough so that the effects of the loads were negligible at the ends of the slab. Several trial computer runs were made to determine a maximum size to meet the requirements outlined. The basic model agreed on was 50 six-inch increments along the edge of the pavement and 20 ten-inch increments in the orthogonal direction (see Figure 3.3).

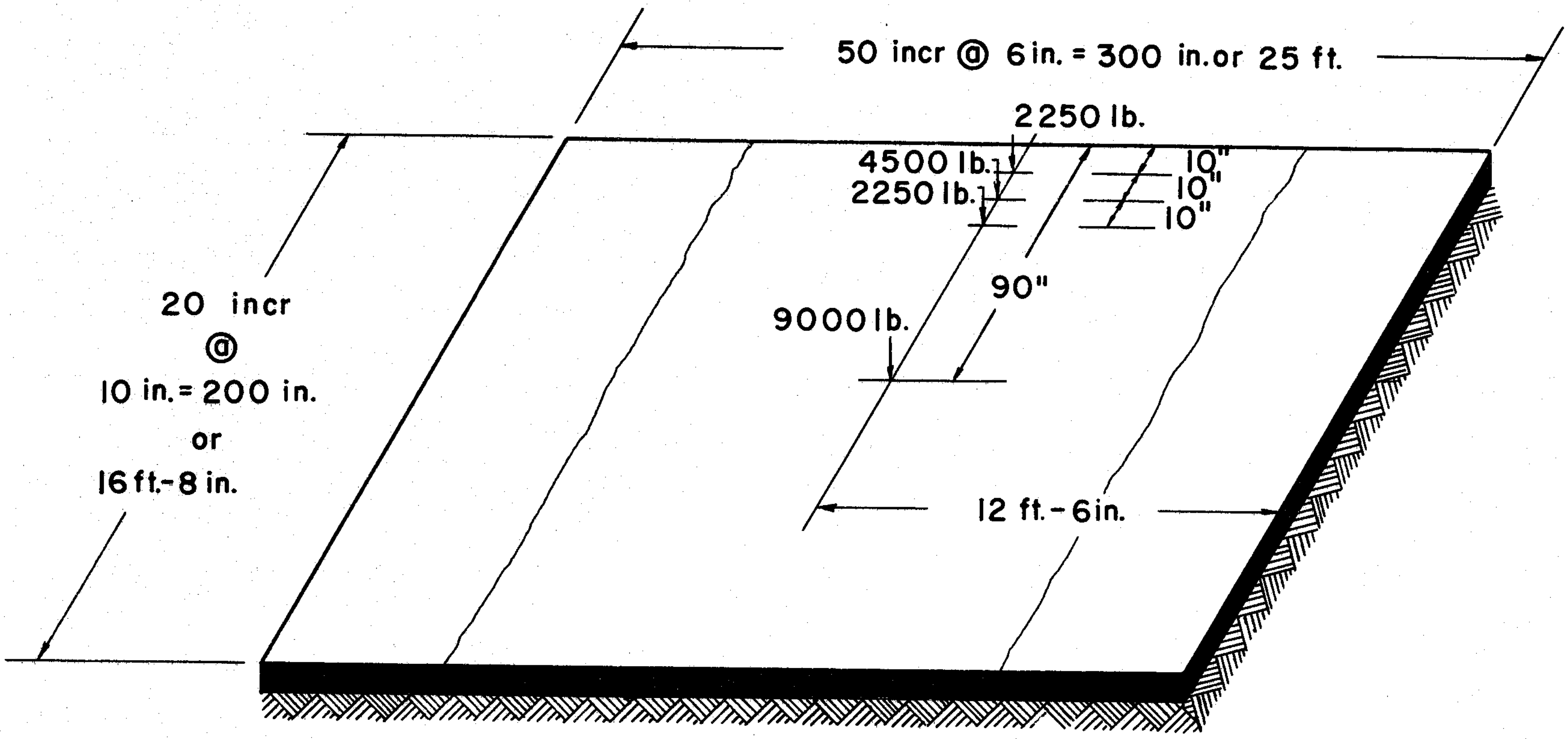
Since the area of primary interest was in the vicinity of the edge wheel load, more emphasis was placed on modeling this load. As shown in Figure 3.2, the center of the dual wheels was 20 inches from the edge of the pavement. The wheels actually extend several inches from either side of this point. The nine kip wheel load was spread over three adjacent increments as shown in Figure 3.4. The inside wheel load was concentrated at a point ninety inches from the edge of the pavement since its effect on the area of interest was minor. Also it should be noted that the front axle of the load configuration was not considered. Previous solutions on problems such as this had shown that its effect in the area of interest was quite minor; therefore, neglected in this analysis.

The transverse volume change cracks which are characteristic of the pavement type being analyzed were treated in the computer model as partial hinges, i.e. the cracks will transmit all of the internal shear force across themselves but only a small amount of the moment. This was accomplished



COMPUTER MODEL OF SLAB

Fig. 3.3



COMPUTER MODEL OF LOAD

Fig. 3.4

by reducing the bending stiffness perpendicular to the crack at each mesh point along the crack by 75 per cent. The amount of reduction in stiffness was arrived at by comparing field and computer deflection data for the condition where the rear axle is over a crack for reduction in bending stiffness ranging from 40 to 100 per cent.

The slab support used was that of a uniform Winkler foundation; that is to say, the foundation was modeled by an elastic spring under each mesh point with a support value.

$$S = h_x h_y k$$

Where S = support value
h_x = increment length, x direction
h_y = increment length, y direction
k = modulus of subgrade reaction

Deflection Analysis and Comparison

Deflection measurements were made in the field on continuously reinforced concrete pavements using the Benkleman beam. The deflections were measured at a point one inch from the edge of the pavement along a line extended from the rear axle of the load vehicle. This is clearly indicated in Figure 3.2. The raw field data was corrected for temperature using methods developed at the AASHO Road Test and used extensively in other studies conducted by the Texas Highway Department.[6,7] The correction for temperature is only a small adjustment of the actual or raw field data. In Figure 3.5, the temperature corrected field deflections are compared to the uncorrected field deflections. Based on past studies, it was believed necessary to use the corrected data in the following analysis for the simple reason that temperature is a variable which does have some effect and cannot be considered in the analytical method.

Each of the real pavements for which field data was obtained was carefully modeled so that the analytical technique[5,8] which is very briefly described in this report could be used to solve for theoretical deflections, curvatures, moments, etc. The foundation springs used in this method of analysis were calculated from available information about the subbase and subgrade; i.e. the various different types of subbases were assumed to have K values in their respective ranges.

After all the solutions were run for all the various pavements using the analytical method,[8] the data or information from the output provided by the computer program were reduced to such a form that comparisons could be made between the analytical method and the field measurements.

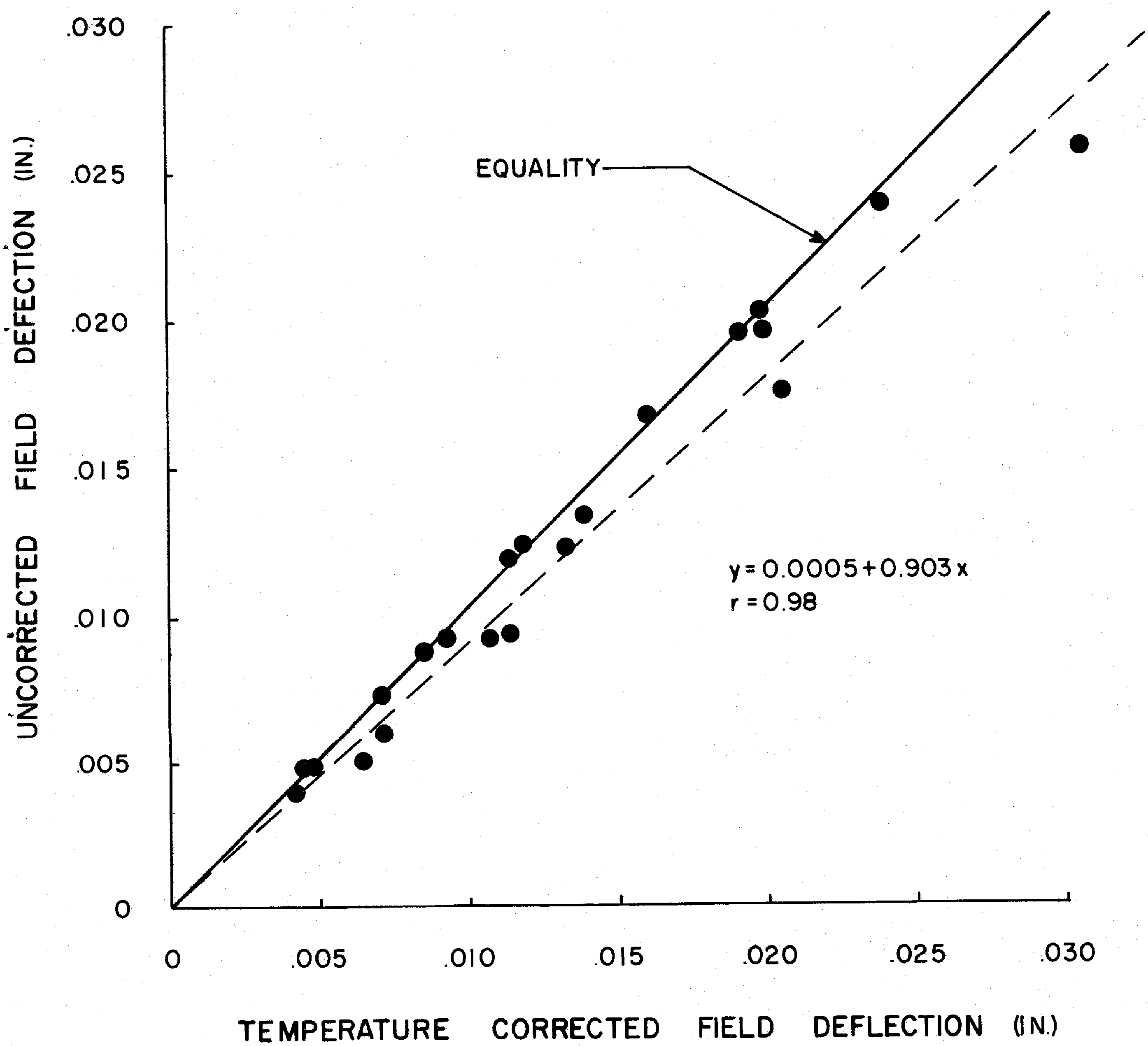
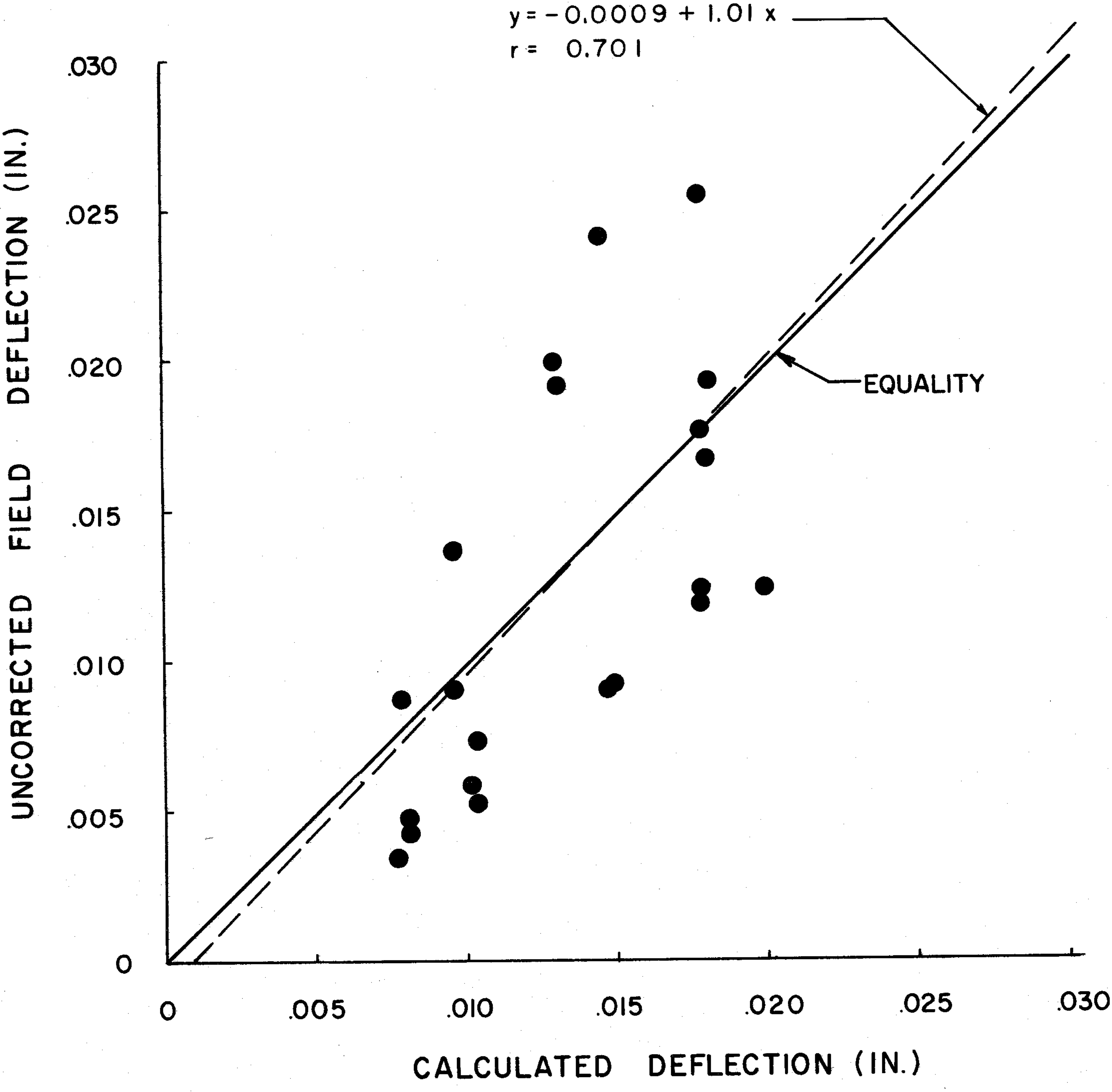

.030
.025
.020
.015
.010
.005
0
UNCORRECTED FIELD DEFECTION (IN.)
EQUALITY
y = 0.0005 + 0.903 x
r = 0.98
0
.005
.010
.015
.020
.025
.030
TEMPERATURE CORRECTED FIELD DEFLECTION (IN.)

Fig. 3.5

The raw field data, temperature corrected field data, and the calculated deflections are all listed in Table 2.1, p. 8. The raw field deflection data is compared with the computer calculated deflections in Figure 3.6. The indicated scatter is fairly large; however, there is reasonable correlation between the measured and the calculated deflections. Figure 3.7 shows the temperature corrected field deflections as compared to the calculated deflections. Here, the scatter seems to be about the same as that in Figure 3.6 where the uncorrected field deflections were compared to the calculated deflections. The correlation found in each of these two comparisons is about the same. The greatest limitation of the calculated deflections is probably that of the support value or "k". The "k" values were estimates based on the type of subbases and subgrade that the pavements had. No test values were available, merely the types of subbases and whether they were stabilized with additives or not. The range of supports were assigned values of "k" which were thought to be relative; therefore, it is believed that these results were honestly arrived at and do indicate reasonable correlation. Table A.1 in the Appendix defines the values of "k" used in analytical evaluation.



y = -0.0009 + 1.01 x
r = 0.701
EQUALITY
.030
.025
.020
.015
.010
.005
0
UNCORRECTED FIELD DEFLECTION (IN.)
0
.005
.010
.015
.020
.025
.030
CALCULATED DEFLECTION (IN.)

Fig. 3.6

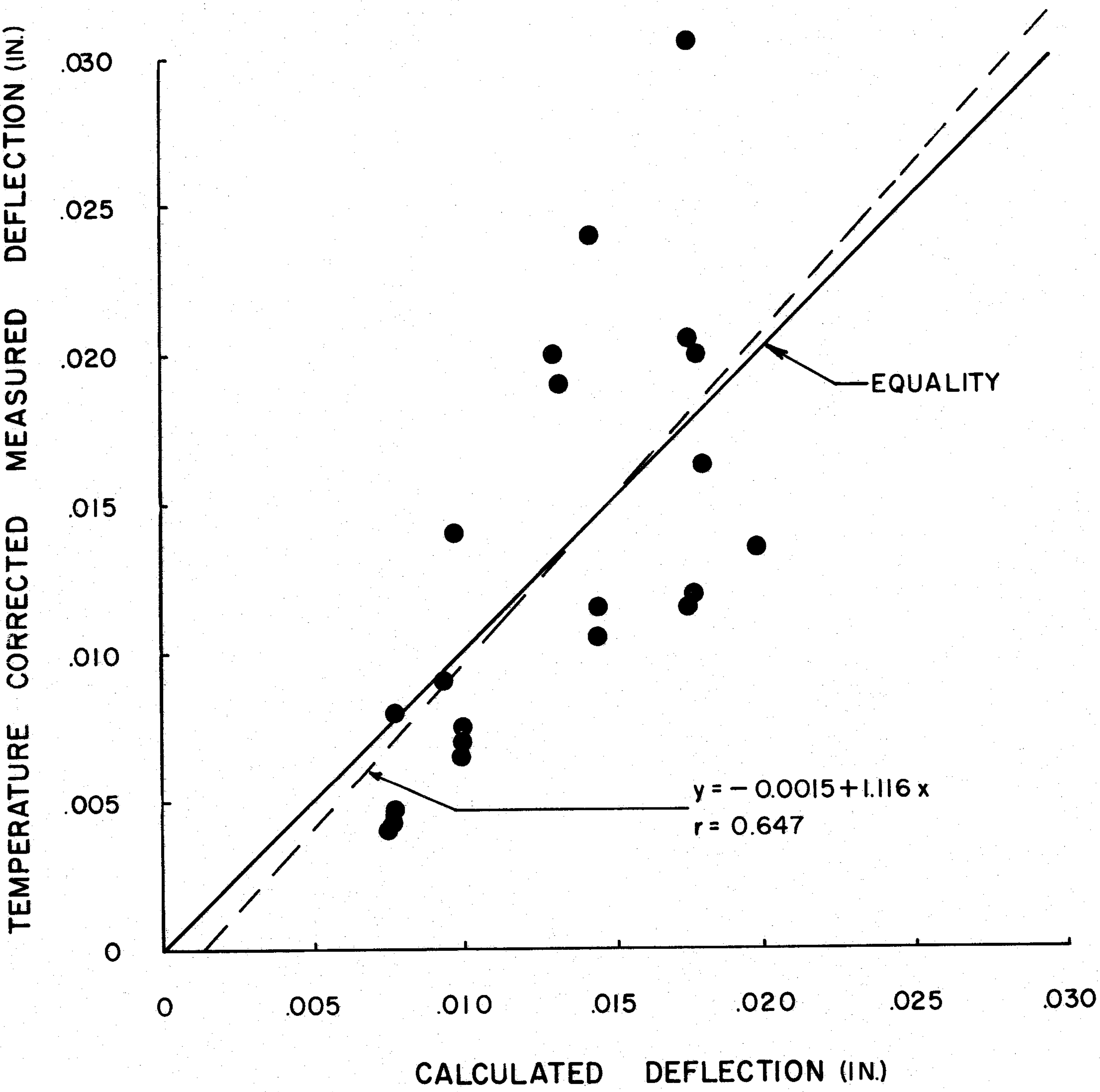

TEMPERATURE CORRECTED MEASURED DEFLECTION (IN.)
.030
.025
.020
.015
.010
.005
0
EQUALITY
y = − 0.0015 + 1.116 x
r = 0.647
0
.005
.010
.015
.020
.025
.030
CALCULATED DEFLECTION (IN.)

Fig. 3.7

Radius of Curvature Evaluation

Experimental Data. The basic field data which is used in this portion of this investigation was that of radius of curvature data as obtained by the Texas Highway Department through the use of the curvature beam shown in Figure 3.8. Another view of the curvature beam as it is used is shown in Figure 3.9. The curvature beam operates on the assumption that the pavement slab deflects in a circular shape. The curvature beam is simply a fixed beam 40 inches long with a movable dial gage probe in the center, 20 inches from either end.

From the physical geometry of the curvature beam, the radius of curvature can be determined as is shown in Figure 3.10.

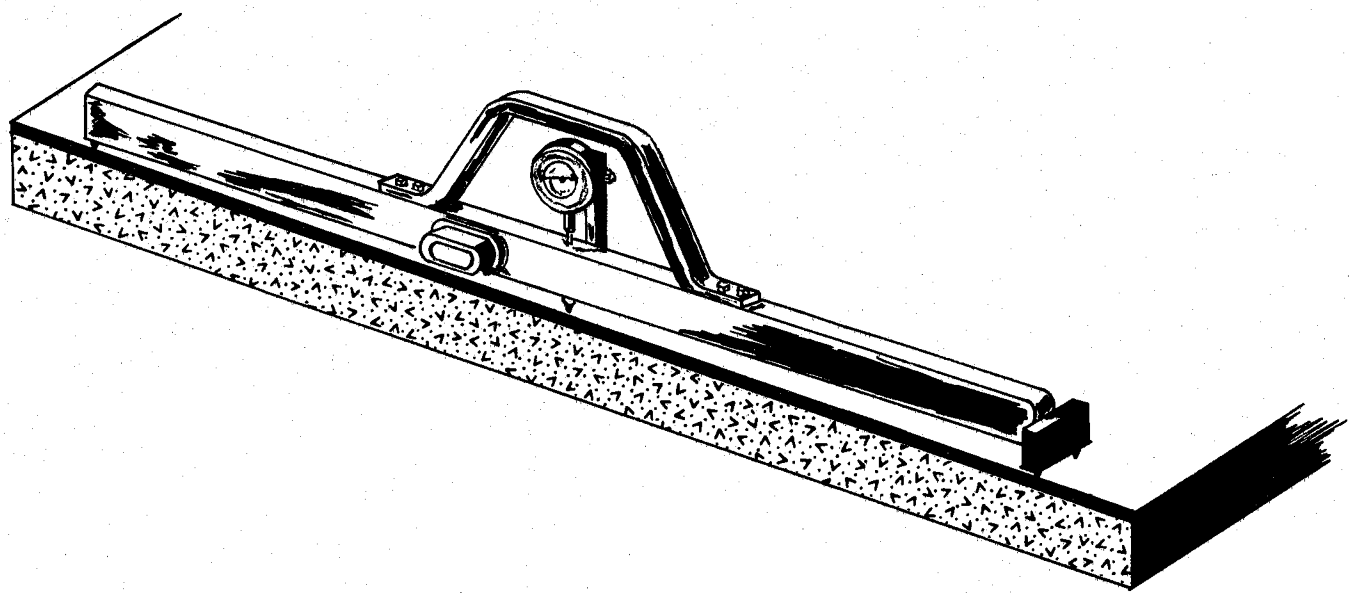
$$R = \frac{16\ 2/3}{\Delta}$$

Where: R = radius of curvature, ft.

Δ = differential deflection, inches.

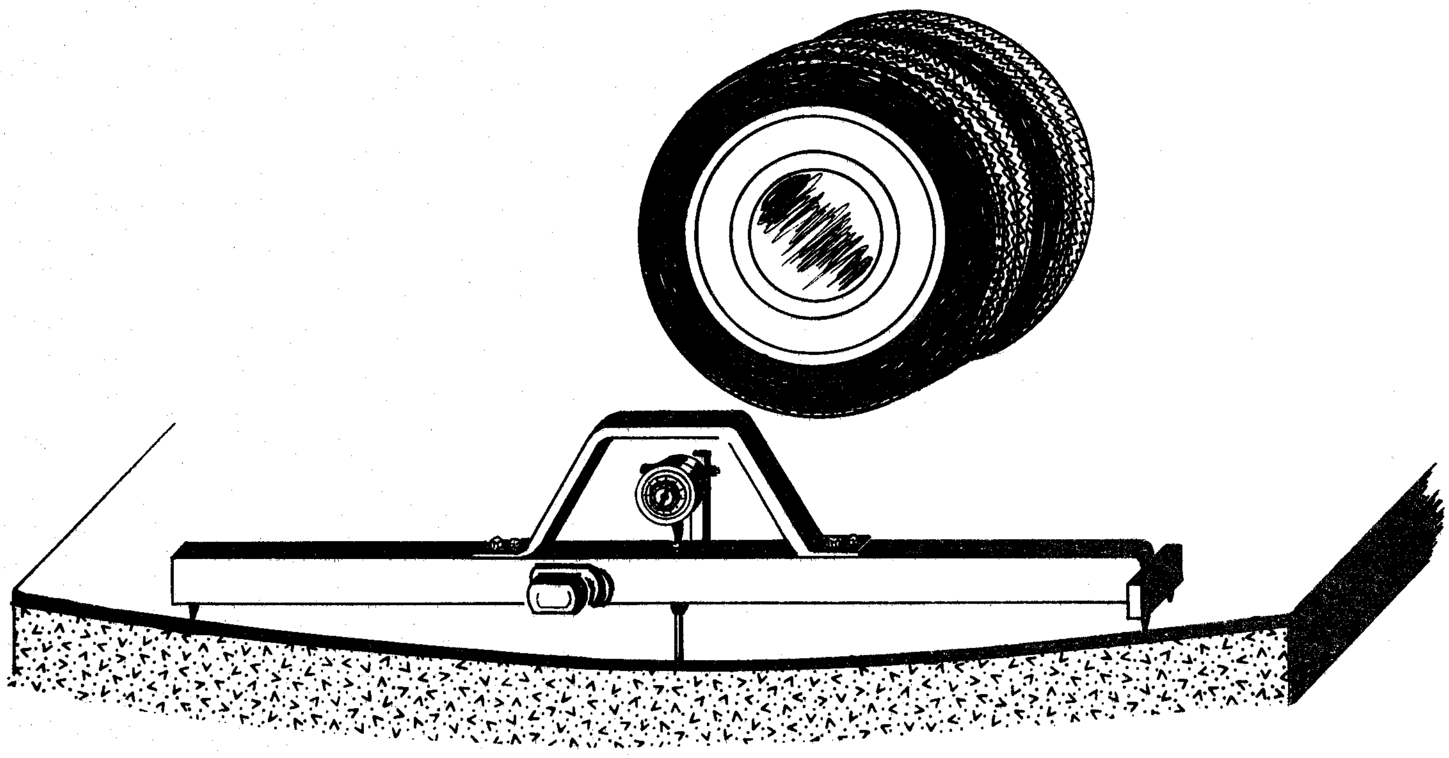
An extensive discussion on the development of the curvature beam is presented in Reference 4.

For this study all field data that was taken with the basin beam or curvature beam was reduced to radius of



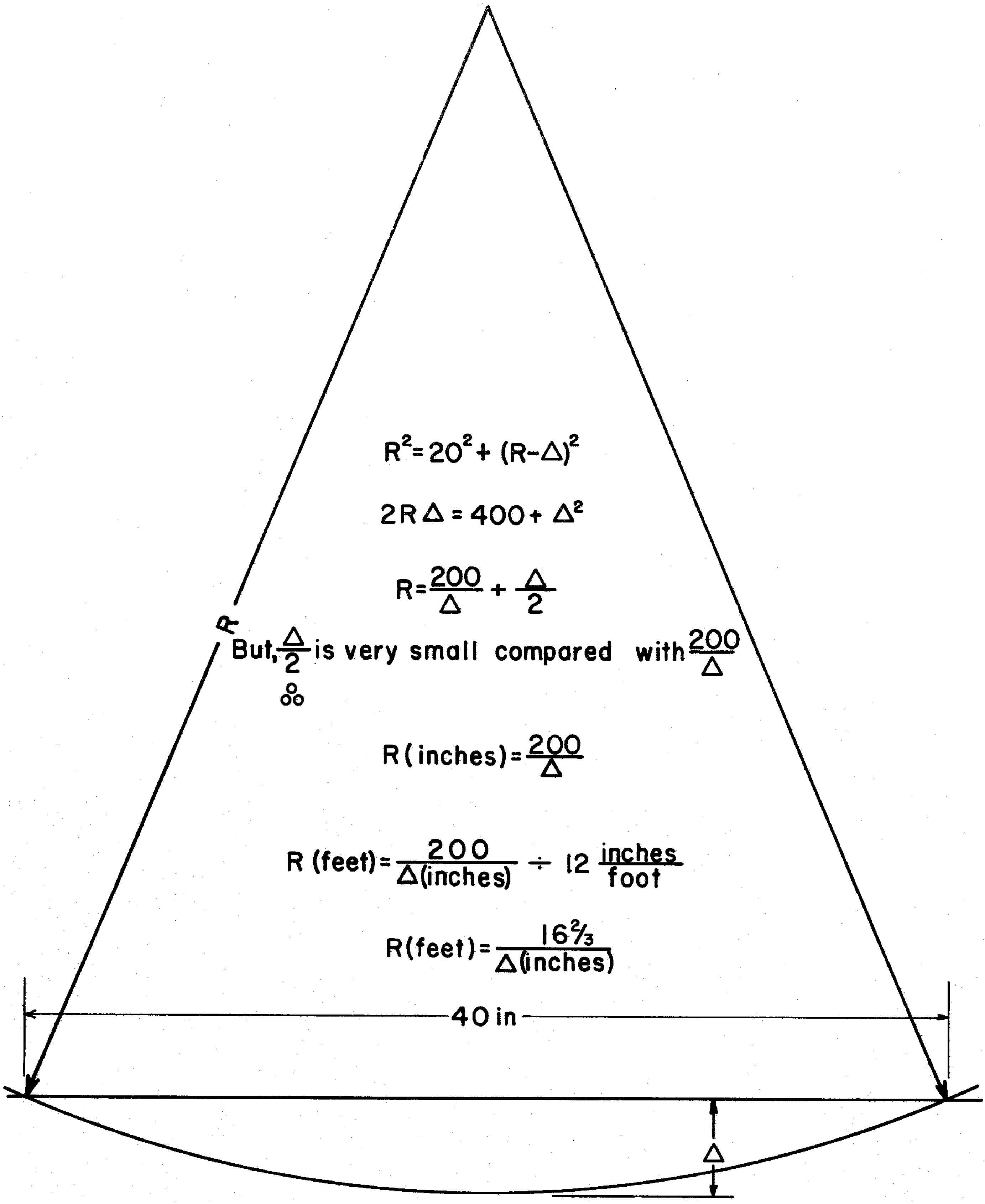
CURVATURE BEAM

Fig 3.8



CURVATURE BEAM IN OPERATION

Fig. 3.9



DERIVATION OF CIRCULAR RADIUS OF CURVATURE FROM BASIN BEAM

Fig. 3.10

curvature by means of the above equation. All subsequent analyses and comparisons of analytical and field evaluations are based upon the radius of curvature values as computed from field data using the above equation.

Analytical Evaluation. After a brief examination of the data which was provided by the basin beam, it was apparent that the moments computed from the measured curvatures did not represent the maximum condition for the load configuration which was used. Therefore, it was necessary to view the entire picture to see if the curvature as displayed by the curvature beam could be duplicated using the analytical technique. Several approaches to curvature were made and each of these approaches was in turn compared to the experimental or measured curvatures.

The first analytical evaluation of the radius of curvature was that from the maximum moment under the load, i.e. the radius of curvature values were calculated from the basic strength of materials relationship.

$$R = \frac{D}{12\ BM}$$

WHERE: R = radius of curvature, feet.

D = bending stiffness per inch of slab, $\frac{\text{in.-lb.}}{\text{in.}}$

BM = bending moment, in.-lb.

Now for each real pavement studied, the radius of curvature was calculated from the maximum moment found underneath the load next to the edge. A graphical comparison of this analysis with the experimental data is shown in Figure 3.11. From the graph it is quite evident that the curvature measured by the basin beam is not the minimum curvature or the maximum stress condition which would exist underneath the load. This comparison indicates that the curvature beam gives a relative measure of the true curvature which exists in the pavement where loaded.

The second evaluation compared the radius of curvatures computed from the maximum moment in the slab at the edge. This is the position where the curvature beam was placed while taking measurements in the field. These curvatures were compared to the field curvatures as is shown in Figure 3.12. The graph indicates that the measured curvature is more nearly equal to the curvature calculated from the maximum moment under the beam than the curvature calculated from the maximum moment under the load.

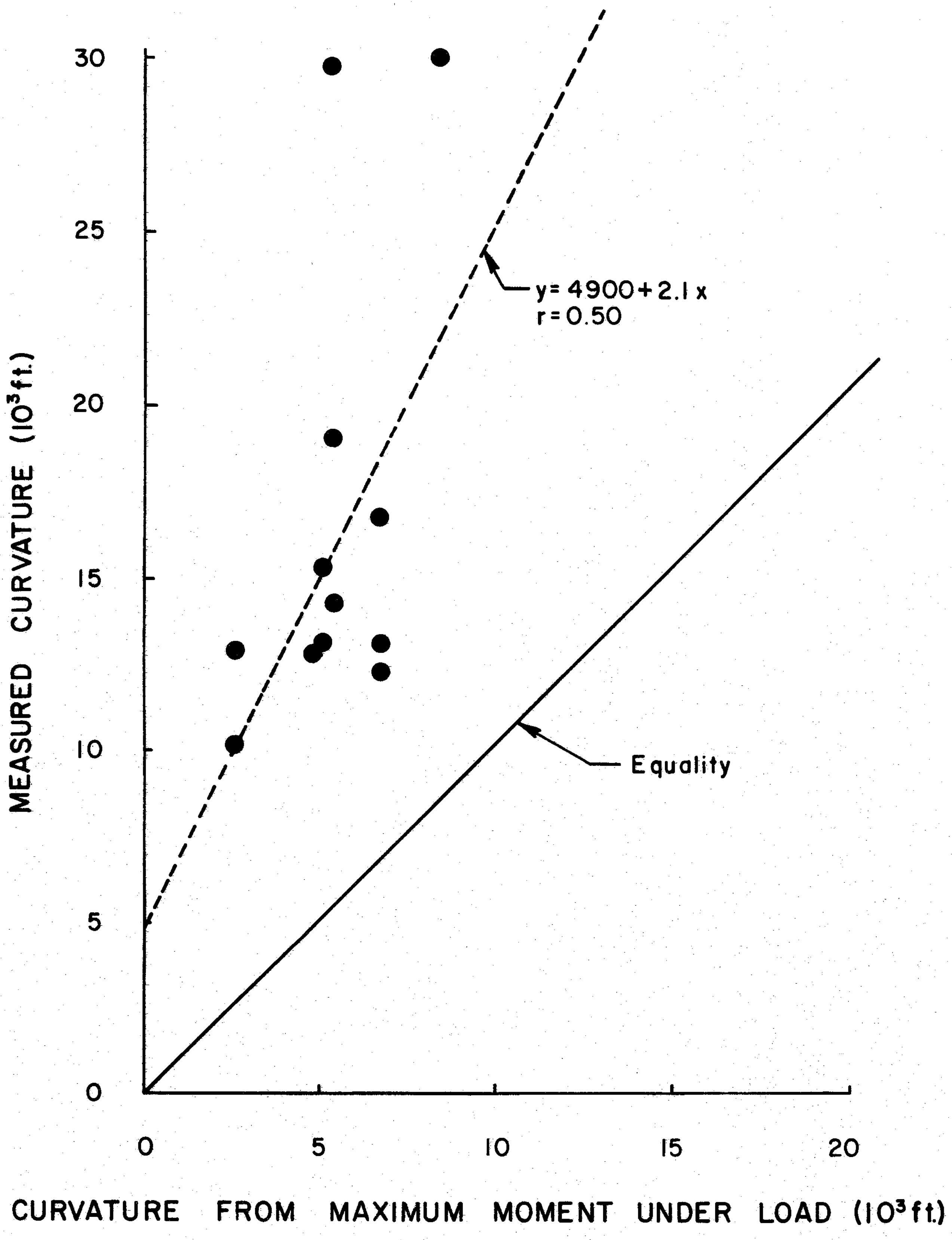
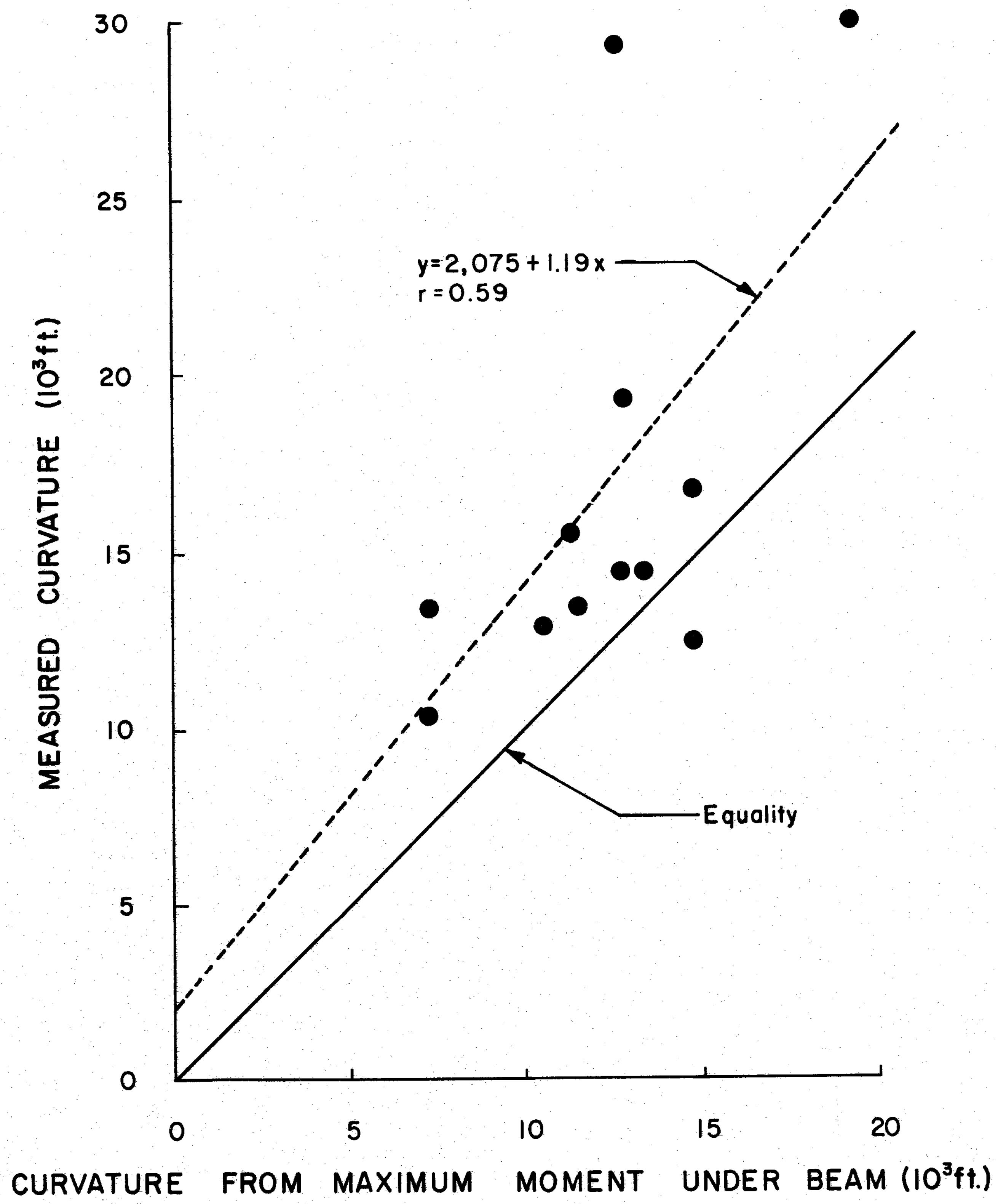

30
25
20
15
10
5
0
MEASURED CURVATURE (10³ft.)
y= 4900+2.1 x
r=0.50
Equality
0
5
10
15
20
CURVATURE FROM MAXIMUM MOMENT UNDER LOAD (10³ft.)

Fig 3.11



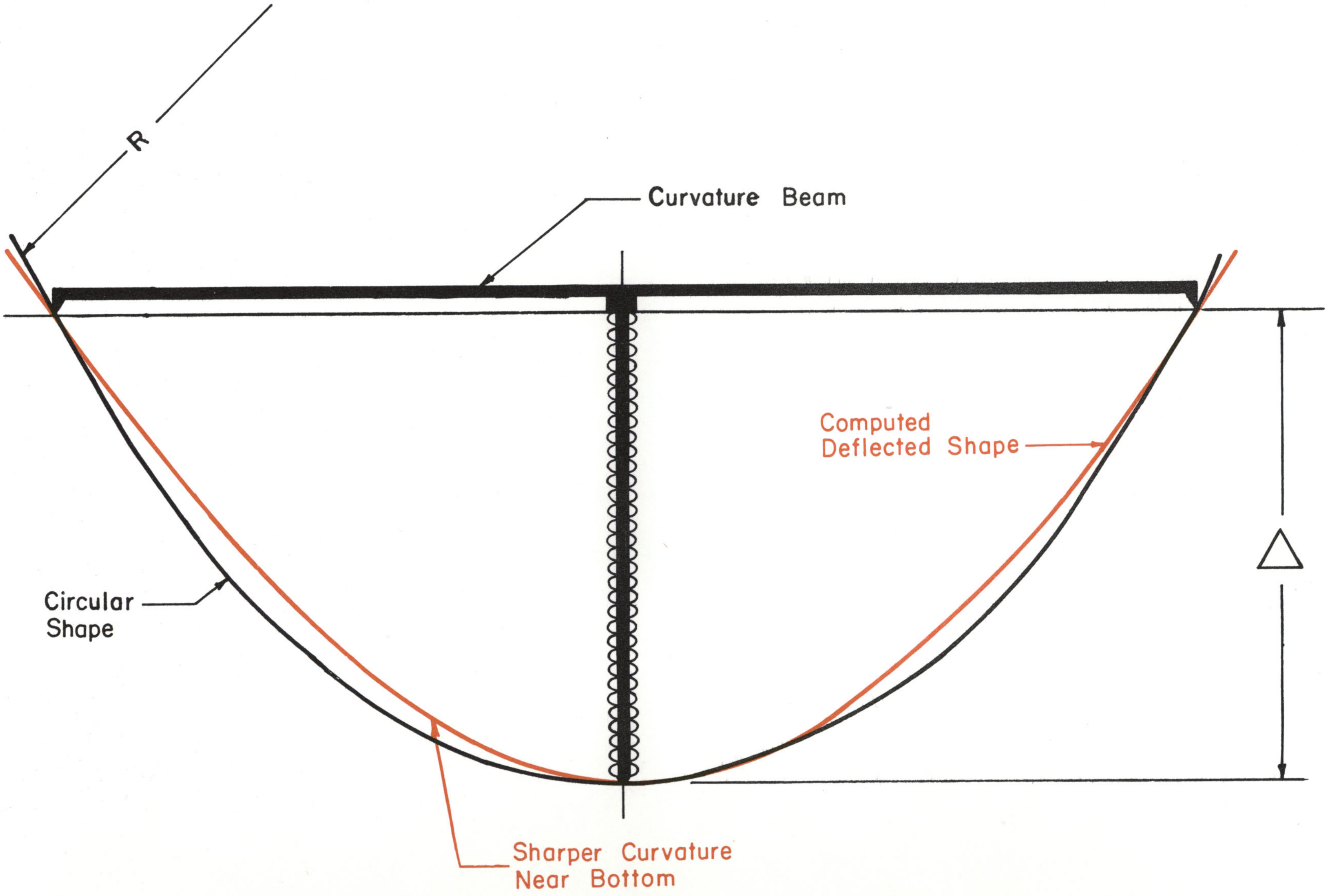
30
25
20
15
10
5
0
MEASURED CURVATURE (10^3 ft.)
y=2,075 + 1.19x
r = 0.59
Equality
0
5
10
15
20
CURVATURE FROM MAXIMUM MOMENT UNDER BEAM (10^3 ft.)

Fig 3.12

However, it is significant that the curvature from the maximum moment under the beam is not that measured in the field.

The third evaluation of the radius of curvature values were those from the geometry of the deflected slab. For each of the pavements studied a profile of deflection at the edge was plotted. In general each of these was a basin-type curve. In each of these profile plots the 40 inch basin beam was drawn to the appropriate scale. The beam was placed on each graph with its center point at the center of the basin, i.e. the 0,0 coordinate. A typical plot of this type is shown in Figure 3.13. The vertical distance between the horizontal line simulating the basin beam and the bottom of the basin simulates the Ames dial reading of the basin beam. All of the deltas or differential deflections were obtained from the computer results in this fashion and the corresponding radius of curvature was calculated from the same formula used to compute the field radius of curvature values, i.e.

$$R = \frac{16.67}{\Delta}$$



COMPARISON OF COMPUTED DEFLECTED SHAPE
AND CIRCULAR SHAPE OF LOADED PAVEMENT

Fig. 3.13

Figure 3.14 shows the curvatures computed by this method correlated to the measured curvatures. This plot indicates that the curvature measured in the field is not equal to that determined from the deflection profile. It is believed that the curvature beam results indicate some average value of the moment or radius of curvature under the beam, thus this is the next method of comparison

A typical graph of the moment under the basin beam or curvature beam according to computer results is shown in Figure 3.15. The bending moment at -20in. is the moment at a point at which the basin beam rests on the pavement surface. The bending moment at the mid-point is the moment in the slab under the center of the basin beam. Thus, it can be stated that the average bending moment under the basin beam is approximately equal to one-half of the bending moment at -20 in. plus one-half the bending moment at the mid-point. Thus in equation form:

$$BM_{Avg} = \frac{BM_{-20} + BM_{Mid}}{2}$$

Thus, using the average moment, a radius of curvature can be calculated from the equation:

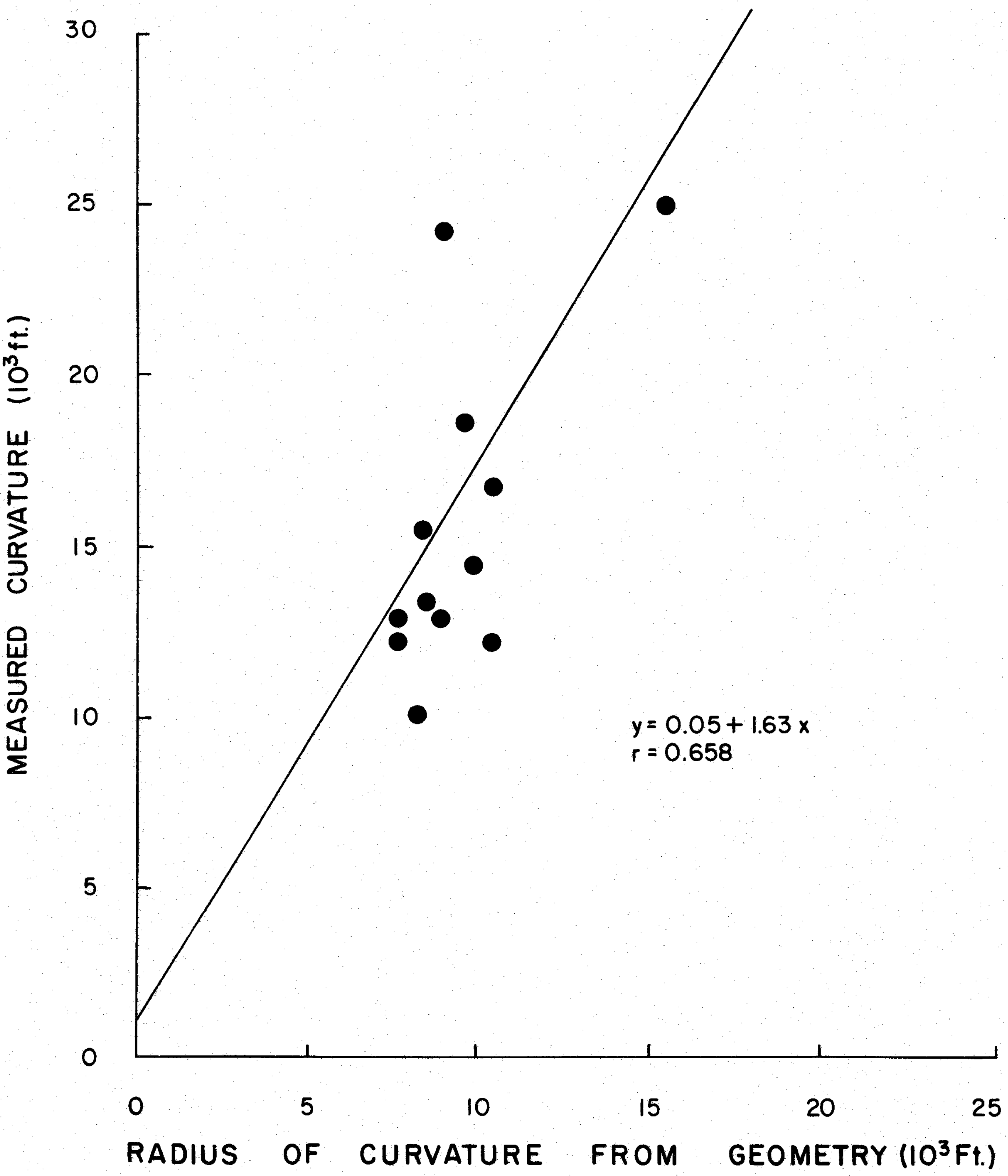
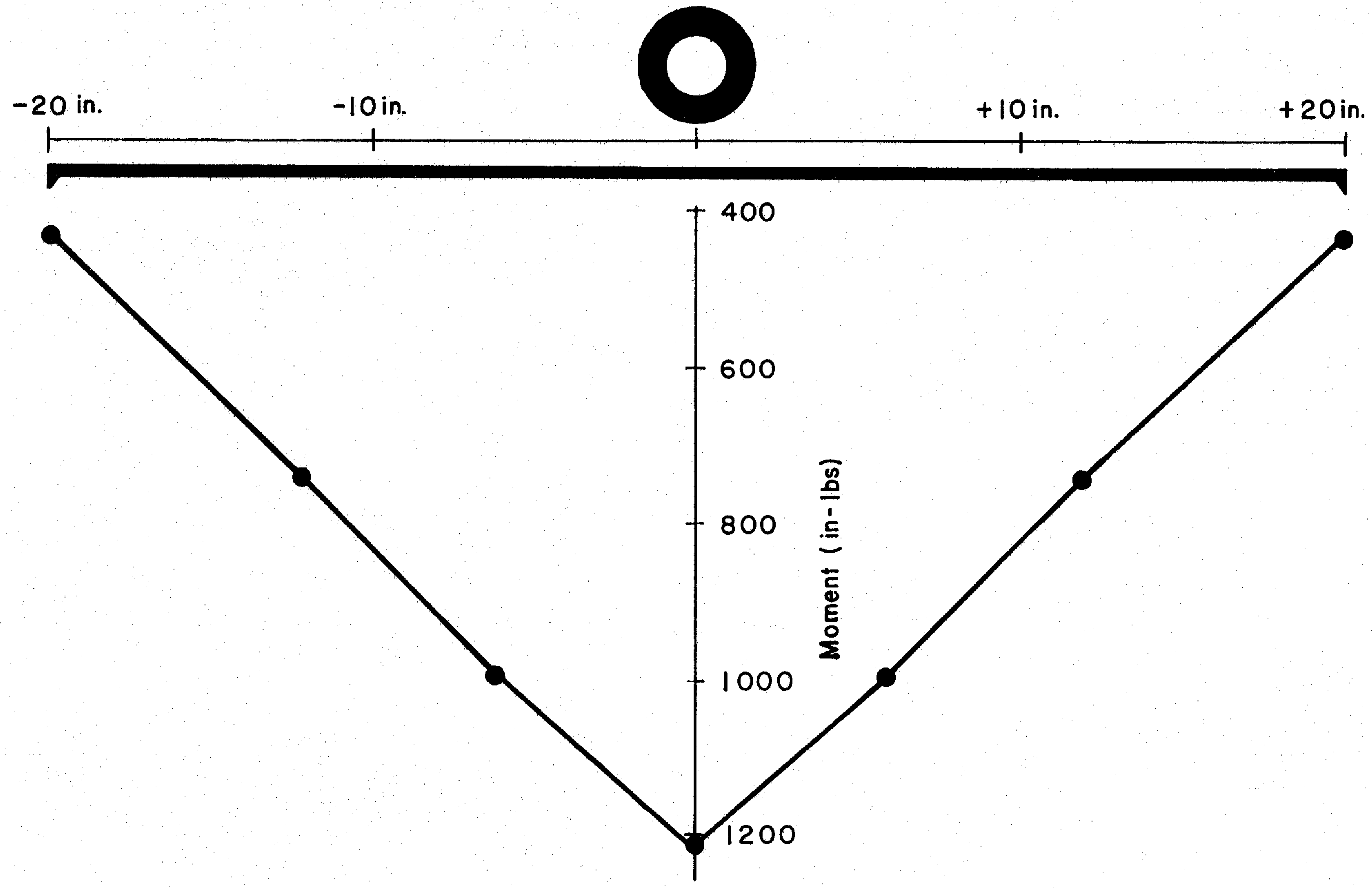

30
25
20
15
10
5
0
MEASURED CURVATURE (10³ft.)
y = 0.05 + 1.63 x
r = 0.658
0
5
10
15
20
25
RADIUS OF CURVATURE FROM GEOMETRY (10³ Ft.)

Fig 3.14



TYPICAL MOMENT DISTRIBUTION UNDER CURVATURE BEAM

Fig. 3.15

$$R = \frac{D}{12\ BM}$$

The radius of curvature values were calculated using the average bending moment for each of the pavements in the study. A graph of these computed curvatures versus the measured curvatures is shown in Figure 3.16. Figure 3.16 indicates that reasonable correlation does exist between the measured radius of curvature and the computed radius of curvature found by using the average computed moment. As pointed out in the typical bending moment plot in Figure 3.15, the maximum moment under the basin beam is generally one and one-half to two times as great as the average moment. This points out the fact that the basin beam results do indicate moments which are generally much smaller than the maximum moment that really exists in the pavement. To substantiate this, Figure 3.17 is exhibited in which the moment under the axle load is plotted. It indicates that the maximum moment is under the load and the placement of the beam 18 inches from the center of the load shows that a moment something other than the maximum would be obtained in the field.

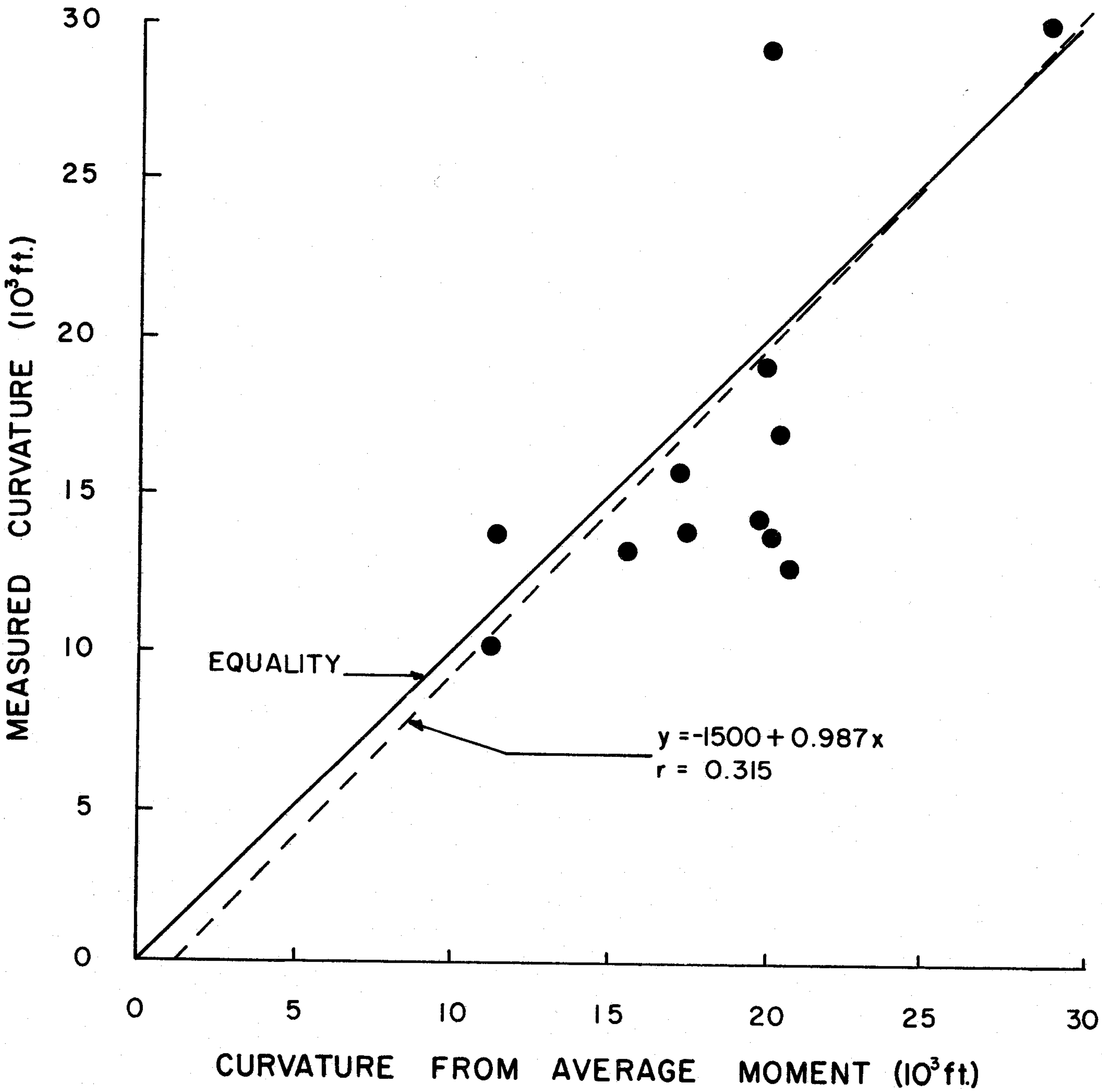
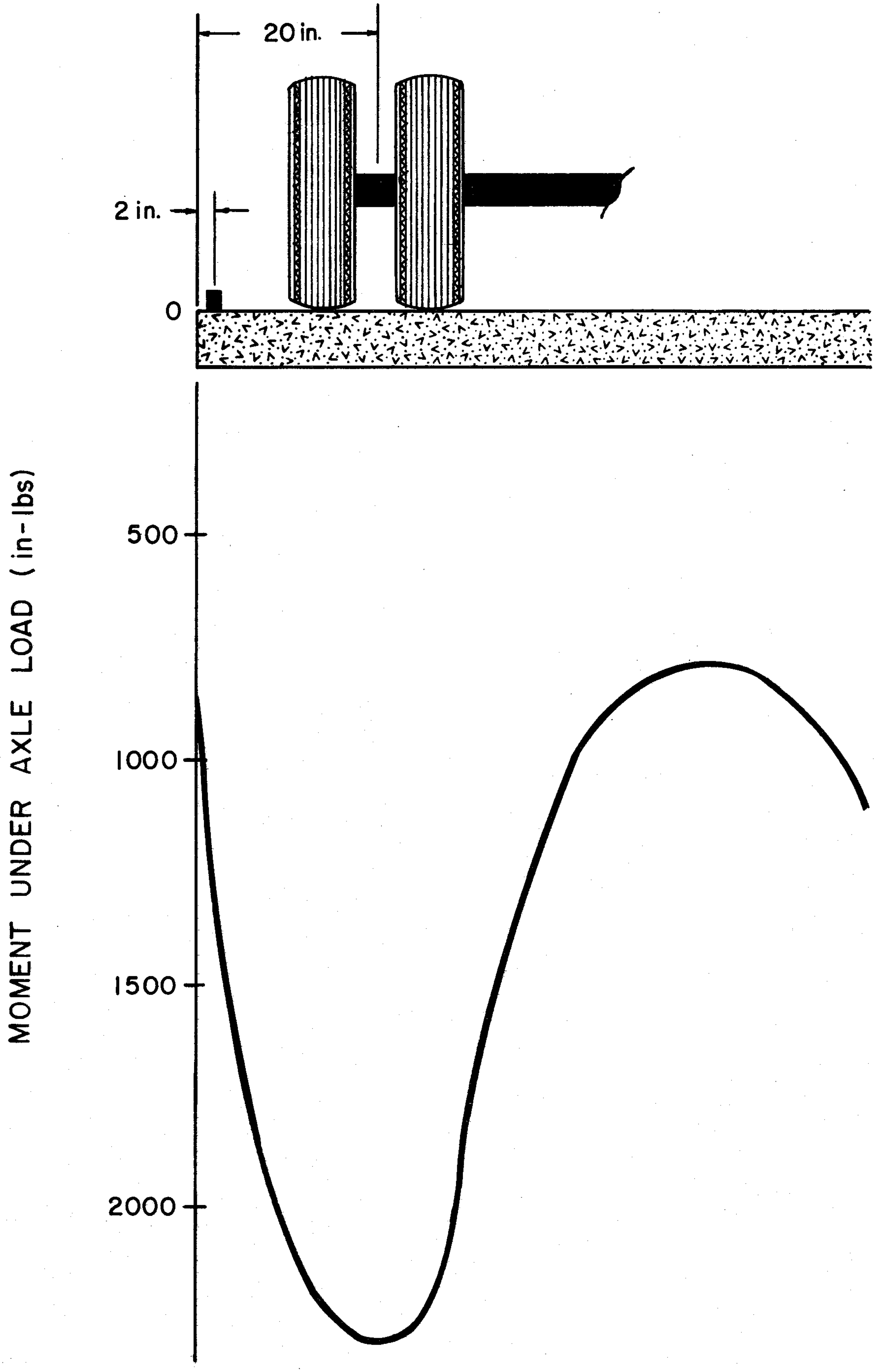

30
25
20
15
10
5
0
MEASURED CURVATURE (10³ft.)
EQUALITY
y =-1500 + 0.987x
r = 0.315
0
5
10
15
20
25
30
CURVATURE FROM AVERAGE MOMENT (10³ft.)

Fig. 3.16



MOMENT DISTRIBUTION UNDER AXLE LOAD

Fig. 3.17

SUMMARY

Continuously reinforced concrete pavements can be studied using the finite element method of slab analysis. With the strength characteristics of the subgrade, subbase and the concrete together with the geometrical configurations of the slab, the volume change cracks and the longitudinal steel, the pavement can be modeled effectively in the computer.

A comparison of field data and analytical results on a limited number of test sections in this study warrant the following conclusions:

1. This method of slab analysis predicts accurate deflections as compared to Benkelman beam deflections.

2. Basin beam measurements indicate an average moment over the length of the beam which was 40 inches.

3. Curvatures calculated from the average moment correlate fairly well with the curvatures predicted by the basin beam.

4. The moments indicated by the basin beam are smaller in magnitude than those which have been calculated using this method of analysis.

This comparison of observations and analyses of rigid pavements has been based on a limited number of test sections and a limited amount of data. It is an initial attempt to use some of the analytical methods being developed for use in practical applications.[9] Hence, it is truly an embryo study and should be extended. This investigation could serve as background material for further research with a planned experiment. A planned experiment would help to more accurately model the real slab in the computer. Data could be taken in conjunction with the coding of the computer problems. The equipment arrangement used in taking data could be such that it would be geometrically compatible with the grid system used in the defining of the slab in this method of analysis.

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APPENDIX A

PAVEMENT SUPPORT DESCRIPTIONS

TABLE A.1

PAVEMENT SUPPORT DESCRIPTIONS

Subgrade Texas Triaxial Classification	Subbase	Modulus of Subgrade Reaction
Poor 5.5 +	Crushed Stone	100
	Sand Shell with Lime treated Subgrade	150
	Asphalt Stabilized	200
	Lime Stabilized	200
	Cement Stabilized	250
Fair 5.0 - 5.5	Fine Grain	100
	Crushed Stone	150
Good 4.0 - 5.0	Fine Grain	100
	Crushed Stone	150
	Asphalt Stabilized	250
	Lime Stabilized	250
	Cement Stabilized	300-325