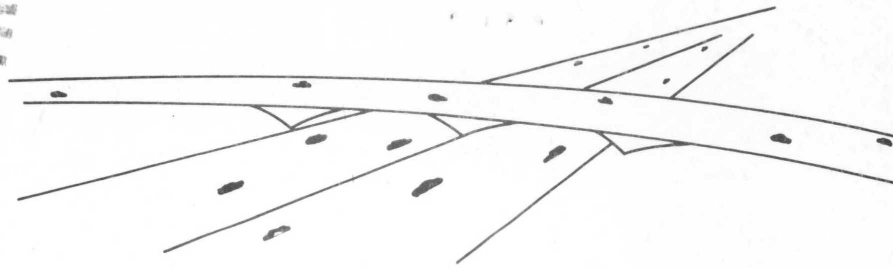

DEPARTMENTAL RESEARCH

Report Number: 46 — 6

A LABORATORY STUDY OF THE VARIABLES THAT AFFECT PAVEMENT DEFLECTION

TEXAS HIGHWAY DEPARTMENT

A LABORATORY STUDY OF THE VARIABLES THAT AFFECT PAVEMENT DEFLECTION

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Research Report No. 46-6
Performance Study of Continuously Reinforced Concrete Pavement

Research Project 1-8-63-46

Conducted by
Highway Design Division, Research Section
Texas Highway Department
In Cooperation with the U.S. Department of Commerce,
Bureau of Public Roads

August 1966

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ABSTRACT

The Texas Highway Department conducted a study entitled, "A Performance Study of Continuously Reinforced Concrete Pavement". One phase of this project was to study the factors influencing deflection and their effect on the performance of continuously reinforced concrete pavement. The preliminary results of field studies indicated that low modulus of elasticity concrete pavement deflected substantially less than high modulus of elastiticy concrete pavement. This result is contrary to established theory. For this reason a laboratory model was constructed in order that certain variables could be studied. The variables considered were load, surface thickness, subgrade and slab surface materials with varying modulus of elasticity. Special emphasis was placed on the study pertaining to pavement surface materials with varying modulus of elasticity. Additionally, the model study results for all variables correlate with theory, with the exception of the modulus of elasticity, which was also found in the field studies made in Texas.

The study also indicates that a model is a useful tool for preliminary study of variables which are important considerations in highway pavement design.

Report On

A LABORATORY STUDY OF THE VARIABLES THAT AFFECT PAVEMENT DEFLECTION

I. INTRODUCTION

In the early part of 1963, the Texas Highway Department initiated a research study entitled, "A Performance Study of Continuously Reinforced Concrete Pavement". One phase of this project was to study the factors influencing pavement deflection and their effect on the performance of continuously reinforced concrete pavement. The preliminary results of these deflection studies indi-- cate that low modulus of elasticity concrete pavement deflects substantially less than does high modulus of elasticity concrete pavements (1,2) which is contrary to the established theory. (3,4,5)

The need for more knowledge as to how the various variables affects deflection of pavement is apparent. This study of the known variables which affect pavement deflection, with special emphasis of modulus of elasticity of the pavement slab, is a laboratory effort to learn more about this phenomenon. The primary variables which are considered in this report are modulus of elasticity of the slab, thickness of simulated pavement, subgrade, and load.

Objectives

The objectives of this study are as follows:

1. To develop a device that will simulate deflections obtained on pavements in the field due to wheel loads.

2. Investigate the pavement deflection characteristics in terms of variables known to effect deflection, with special emphasis on the modulus of elasticity of the pavement slab.

Background

Westergaard developed a deflection formula for interior load on a pavement which is as follows:[3]

$$d = \frac{P}{8KL^2}$$

in which:

d is the deflection on the pavement under the load in inches,

P is the concentrated interior load on the pavement in pounds,

K is the foundation modulus in pounds per cubic inch,

$$L = \sqrt[4]{\frac{Eh^3}{12(1 - u^2)K}}$$, radius of relative stiffness of the pavement in inches,

E is the modulus of elasticity of the concrete in pounds per square inch,

h is the pavement thickness inches, and

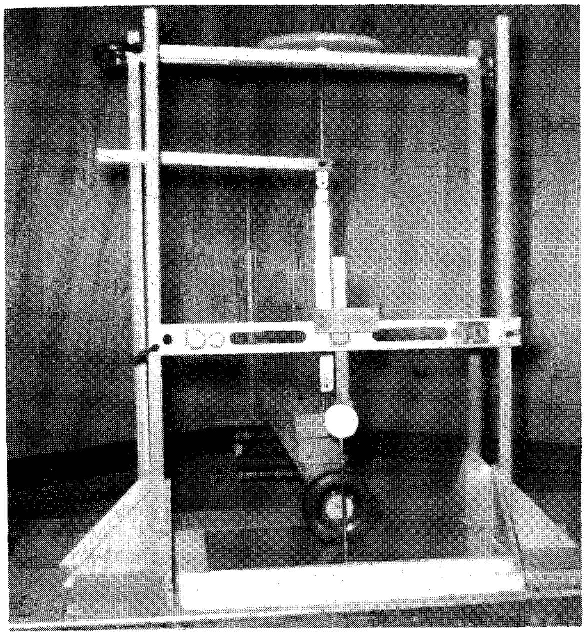
u is Posson's ratio of the pavement.

Note that the above formula indicates that pavement deflection should vary inversely with modulus of elasticity of the pavement slab material. This is contrary to the results obtained in the field as mentioned earlier in this report.

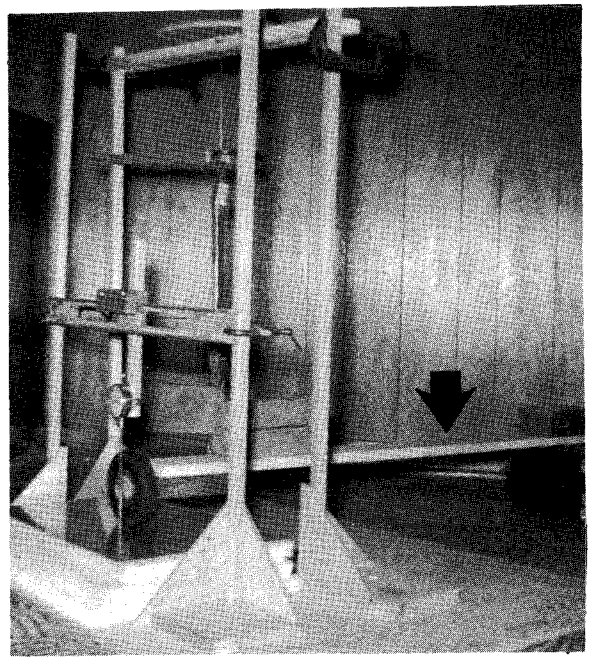
II. DESCRIPTION OF EXPERIMENT

The laboratory test equipment was developed to correlate field conditions to the degree possible, and to the accuracy required so that measurements could be accurately reproduced. This was accomplished by constructing a model having a separate loading and measurement structure (see Figure 1). The loading device was constructed so that the load could be varied as desired. The load was indicated in pounds on a scale. The load was applied to the simulated pavement through a single wheel with a rubber tire 4.75 inches in diameter and a one inch wide tread mounted on axle hinged 48 inches from the center of the wheel (see Figure 2).

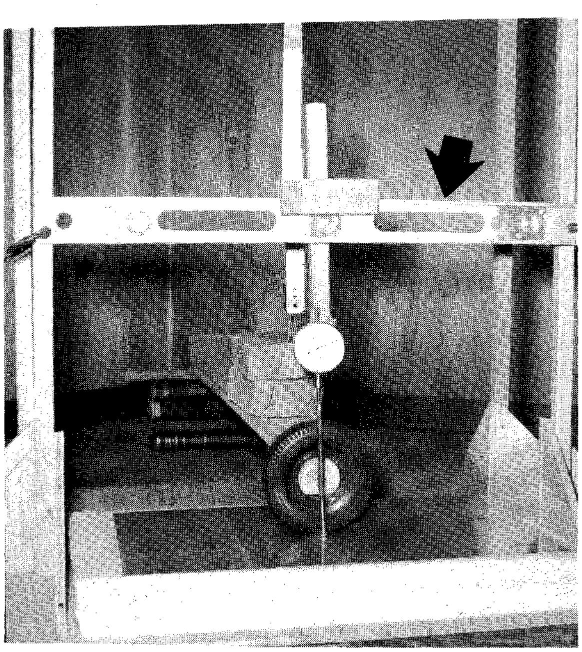
The deflection measurement device was mounted on a separate structure, the cross-bar being an aluminum carpenter's level as shown in Figure 3. The level served as an accurate stationary reference from which measurements could be taken along the model slab. This permitted measurements of the entire deflection basin. The dial guage used was capable of measuring to an accuracy 0.001 of an inch.



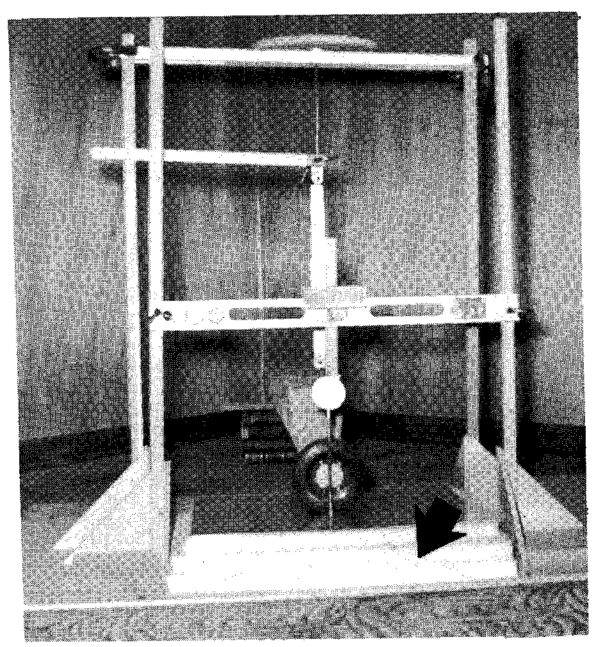
Deflection Measurement Model
Figure 1



48 Inch Axle
Figure 2



Deflection Measurement
Reference
Figure 3



Synthetic Foam Rubber
Subgrade
Figure 4

The simulated support material was a fine pore synthetic foam rubber one inch thick. The thickness of the subgrade was varied by adding one inch layers of the foam rubber as shown in Figure 4. The support characteristics were varied by changing the number of layers.

Pavement surface was simulated by using steel, copper, aluminum, magnesium, and plexiglass flat plates 12 inches by 18 inches in size. All of the plates were 0.022 inch thick, with the exception of the plexiglass and steel, which were 0.021 and 0.024 inch, respectively. Additionally, a magnesium flat plate 0.026 inch thick and a plexiglass plate 0.125 inch thick were used for making certain comparisons discussed in detail later in this report.

In order to evaluate the effect of pavement thickness relative to deflection, magnesium and plexiglass plates, identical in all other respects, of varying thickness were used.

In order to determine if slab surface friction had a bearing on deflection measurements, the surface of the steel, copper and aluminum were lacquered to equalize the coefficient of friction. However, it is emphasized that all other measurements shown in the report were made without lacquered surfaces.

III. EXPERIMENTAL PROCEDURE

Load

The load was applied mechanically at a small uniform rate, varying from zero to five pounds. Zero load measurements were taken for each set of deflection measurements to serve as a reference. The loads were applied in succession from one to five pounds. The deflection measurement for each load was subtracted from the zero load reading to obtain the total pavement deflection for both interior and edge loads.

Deflection Measurements

The simulated pavement interior load was applied with the wheel in the center of the slab. Deflection measurements were taken starting on the center of the slab, and one-fourth inch from the center line of the tire. In addition, slab deflection basin measurements were taken in both directions from the center, parallel to the wheel, and in 1.29 inch increments to a point 7.75 inches away.

The edge pavement deflection load was applied with the tire parallel to the edge and 1.25 inches from the edge of the pavement slab. Deflection basin measurements were taken in the same way as described above for the interior pavement load, except being on the edge of the slab.

In order to compensate for any difference in pavement deflection due to possible warping in the thin sheets, measurements were taken on one side of the surface material and then turned over and the measurements repeated. The average of the two were used as the final reading. This procedure was used throughout the experiment.

<u>Thickness of Simulated Pavement</u>

As indicated previously in this report, the thickness of the pavement slab was evaluated by using magnesium and plexiglass with identical properties and differ only in depth. The plexiglass and magnesium slabs used were 0.021, 0.125 and 0.022, 0.026 inch, respectively. Therefore, for evaluating deflection, all variables were constant except for thickness. Two materials were used in the evaluation to determine if the results correlated.

The plexiglass and steel slabs used were not 0.022 inch thick, but mere 0.021 and 0.024 inch. In order to correct the measurements taken, Westergaard's formula was used. This procedure is justified in that the deflection measurements of the magnesium slabs, 0.022 and 0.026 inch, were taken. The same procedure as described above was used to correct the measurements from 0.026 to 0.022 inch. These values on the average differed from actual measurements approximately six per cent greater than measured values. In the case of the magnesium slab the correction for thickness was 0.004 inch, for the steel slab it was 0.002 and for the plexiglass it was 0.001. Therefore, it is reasonable to assume that the corrections made for the steel and plexiglass slabs were considerably more accurate.

Modulus of Elasticity

The modulus of elasticity was varied in the pavement slab materials by the use of various metal surfaces. The surfaces being stainless steel, copper, aluminum, magnesium and plexiglass. The respective modulus of elasticity being 27.92×10^6 psi, 16.72×10^6 psi, 4.70×10^6 psi, 8.13×10^6 psi, and 0.34×10^6 psi. (For background information on the modulus of elasticity values used see Appendix, Page A-1.) The modulus of elasticity spread in the metals used to simulate the road surfaces was believed to be sufficient to study its effect upon pavement deflection. The total range would encompass the general range of modulus of elasticity for concrete.

Simple Span Deflection

In order to investigate the effects of the modulus of elasticity of the various materials on deflection in unsupported conditions, measurements were taken for simple beams resulting from dead weight. The span used was 17.5 inches long. The maximum dead weight deflection value in turn was used to determine the modulus of elasticity for each material. Thence, considering the beam weights as zero, the maximum deflection of each simple beam was calculated assuming a given concentrated load (see Appendix, Page A-2).

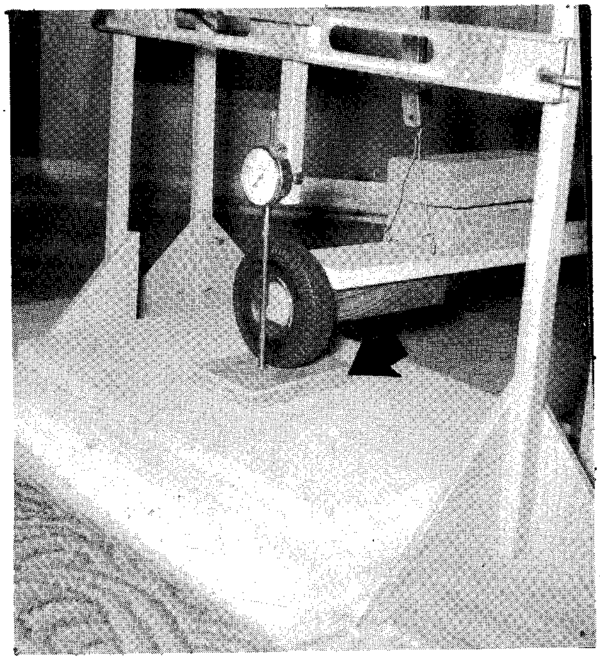
Subgrade

The subgrade material was simulated by using synthetic foam rubber. The thickness of the subbase material was one, two, and three inches and extended well beyond the outer edges of the simulated pavement slab.

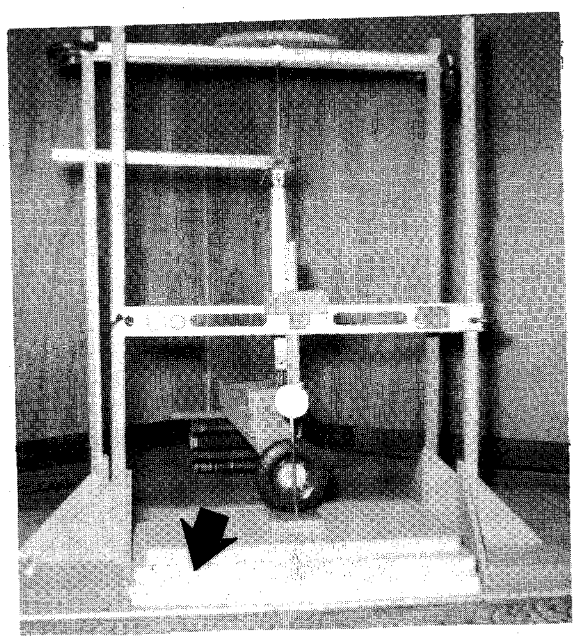
The subgrade modulus (K = pounds per cubic inch) was determined by applying a load to the foam rubber subgrade through a rigid plate with a surface area of 17.3 square inches as shown in Figures 5 and 6. The subgrade modulus of the foam rubber subgrade was found to be as follows:

Foam Rubber Subgrade Thickness	Subgrade Modulus in Pounds Per Cubic Inch
1	14.45
2	6.67
3	3.85

As a comparison, the K value for a poor soil is about 100 pounds per cubic inch. Page A-3 in the Appendix shows the test data gathered to obtain the above K values of deflection of the subgrades versus the load applied. The average K value for each material as enumerated was used for calculating the theoretical deflections.



Rigid Plate Used to Determine
Subgrade Modulus
Figure 5



Subgrade, Synthetic
Foam Rubber
Figure 6

IV. PRESENTATION OF RESULTS

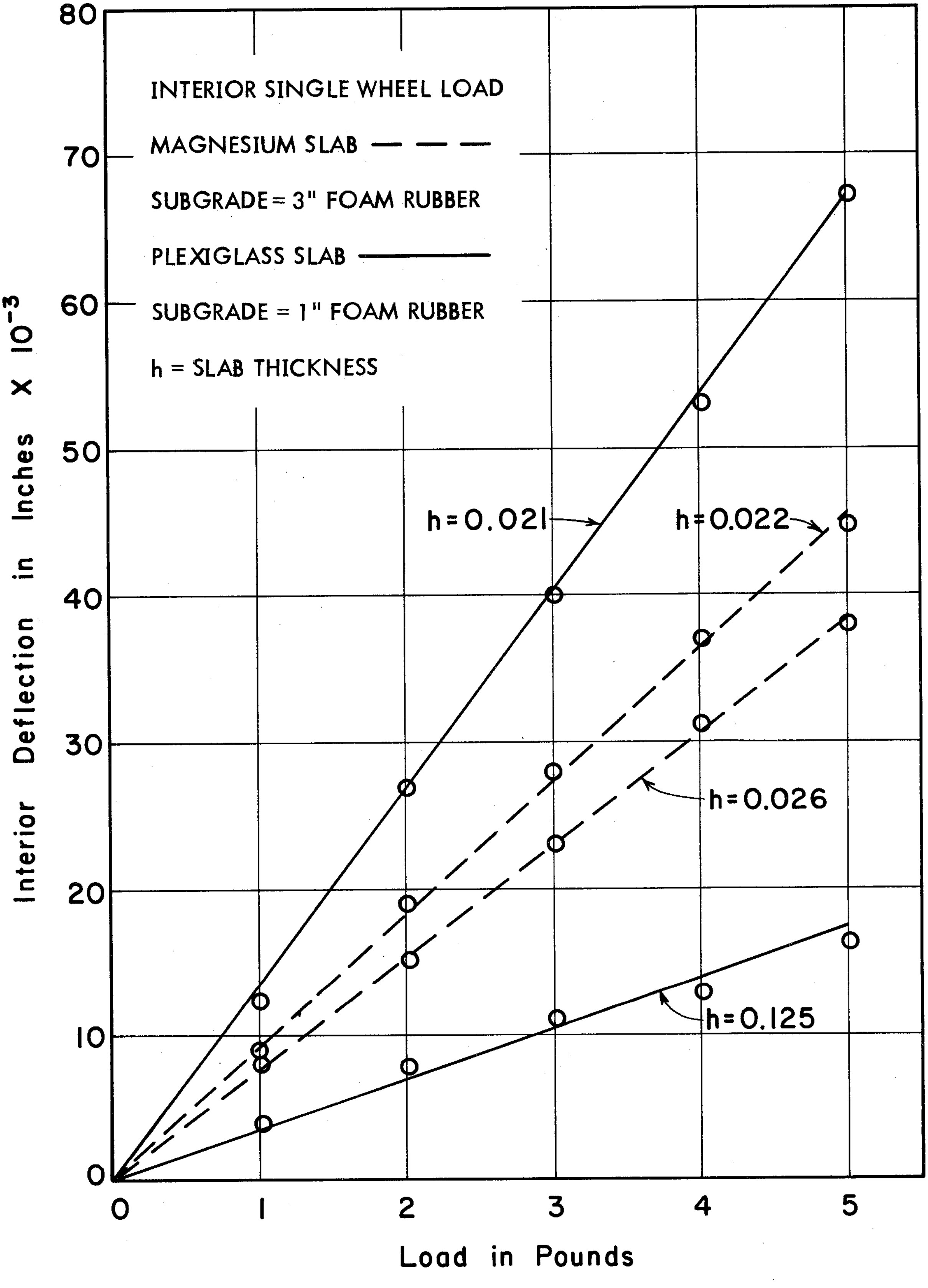
The results of the response of the various pavement slabs used due to a single wheel load in terms of deflection and deflection basin measurements are presented in this chapter. The measurements are used in evaluating the characteristics of the pavement deflection in relation to load, pavement thickness, subgrade, and the modulus of elasticity of the simulated road surface.

Load

The results for pavement interior and pavement edge loads show that deflection of surface is a direct function of load and varied linearly as found in other investigations.[2,3,4,5] Comparable results were obtained on all materials considered in this study. Figure 7 presents the results for magnesium and plexiglass surface. It was found for the magnesium plate on a three inch foam rubber subgrade that the interior deflection equations are $d = 9 P \times 10^{-3}$ inches and $d = 7.7 P \times 10^{-3}$ inches for a 0.022 inch and a 0.026 inch plate, respectively.

Edge Versus Interior Deflection

The results of this study show that the deflection at the pavement edge position is considerably greater



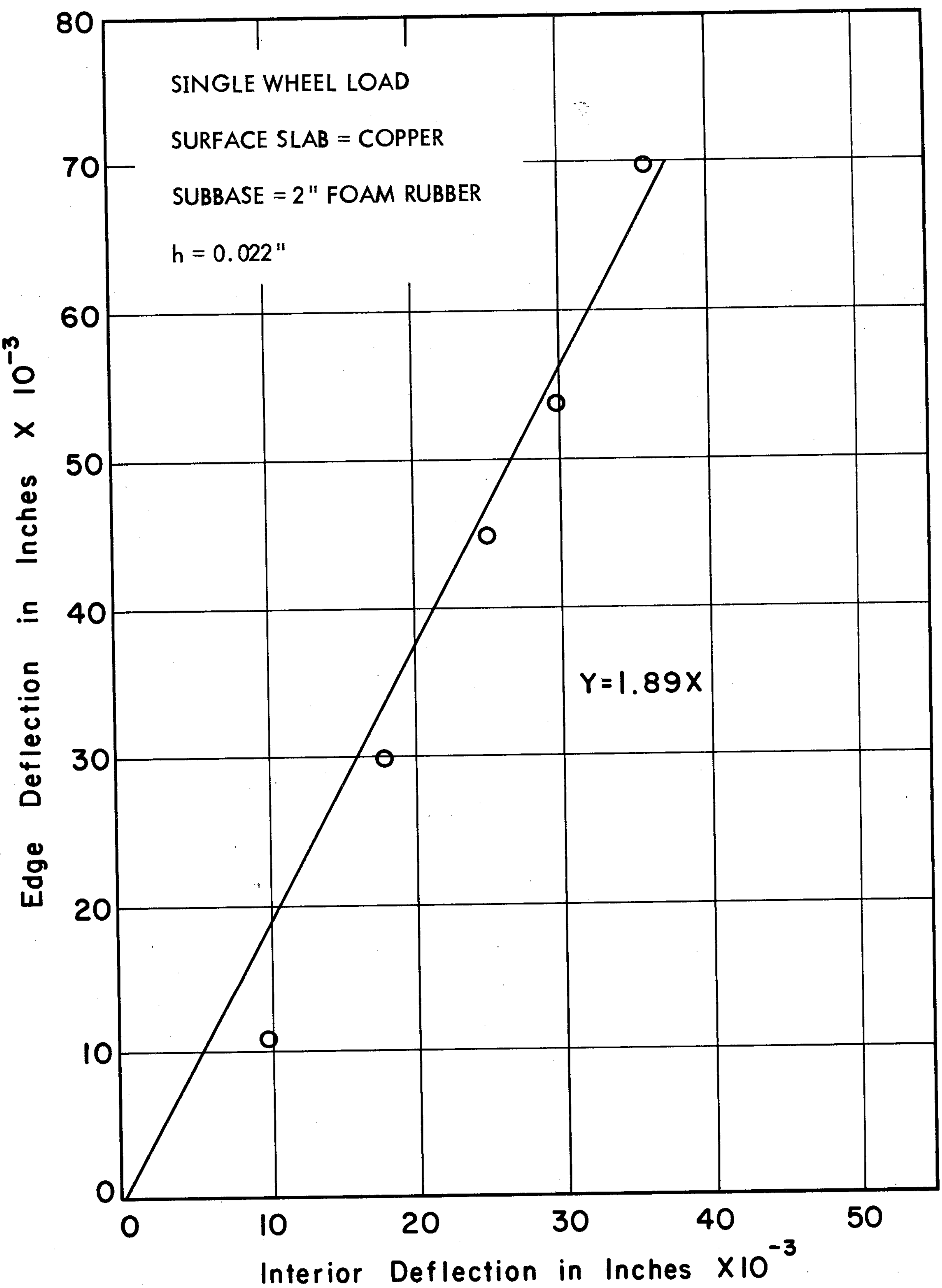
DEFLECTION VS. LOAD

FIGURE 7

than interior pavement position as expected. Figure 8 shows that for the copper pavement the deflection at the pavement edge position is 1.89 times as great as at the center pavement position. It is interesting to note that in a field study conducted by the Texas Highway Department on in-service jointed concrete pavements, the edge deflection ranged from 1.7 to 2.0 times the interior.[6] These pavements had a uniform overlay over each pavement. The laboratory values are within the range experienced in the field.

Pavement Thickness

Figure 7 indicates that deflection decreases for a given load as the slab thickness is increased. Magnesium and plexiglass was used in the evaluating this variable. For the plexiglass surfaces, 0.125 and 0.021 inch thick, the deflection equations are shown to be $d = 3.5\ P \times 10^{-3}$ and $d = 13.4\ P \times 10^{-3}$, respectively. The results clearly indicate, as found in other investigations, that the pavement slab thickness is a variable. Furthermore, as the pavement thickness increases for a given surface, the pavement deflection decreases.[2,7]



COMPARISON OF DEFLECTION FOR EDGE AND INTERIOR LOADINGS

FIGURE 8

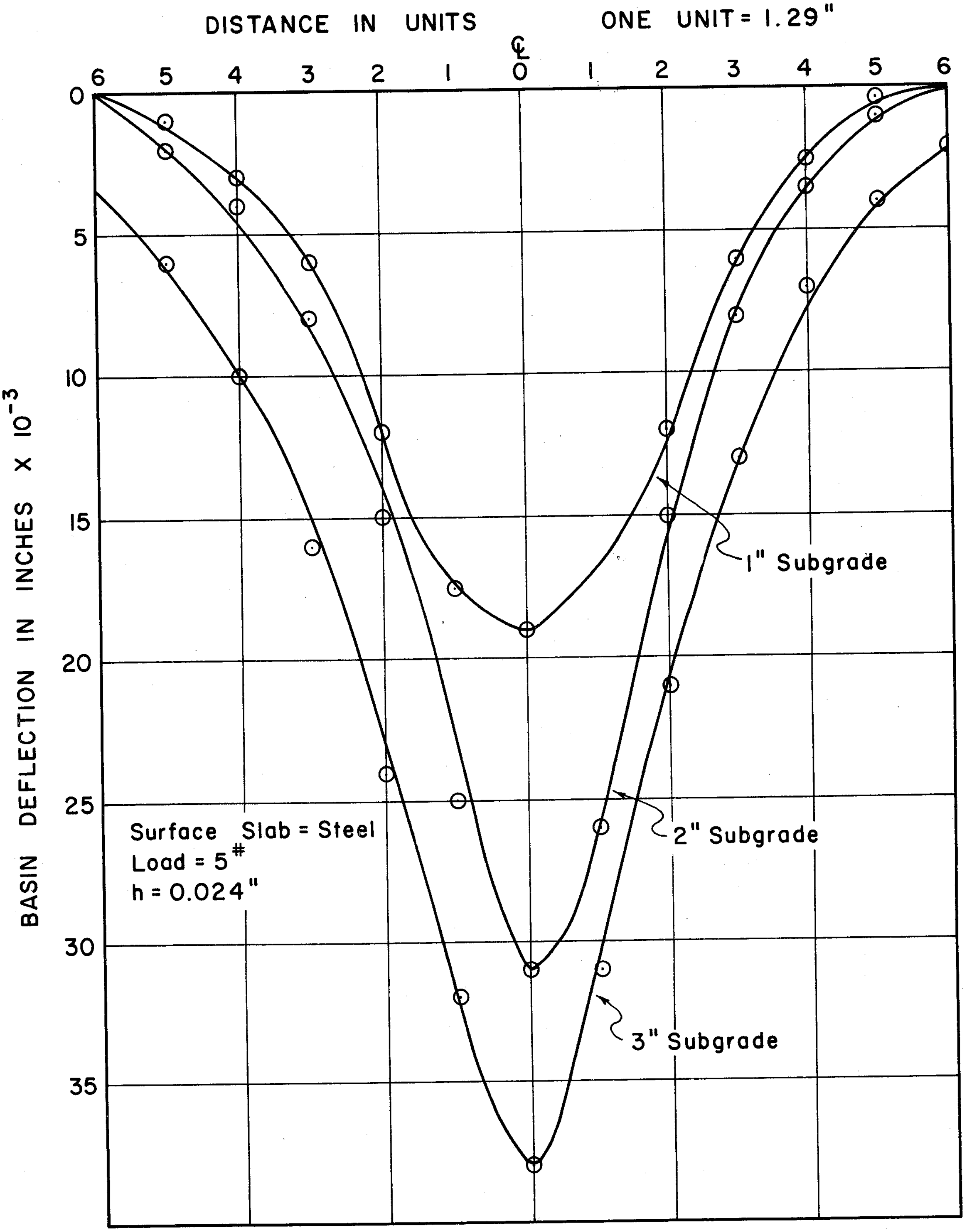
Subgrade

The pavement subgrade support value was varied by using three different thicknesses of sponge rubber. The pavement deflection basin for the stainless steel surface is shown in Figure 9 for one, two, and three inch subgrades. Measurements are taken from the center to six inches on either side of load. The graph clearly shows that as the subgrade modulus is decreased, the deflection increases; and hence pavement deflection varies inversely with the subgrade modulus.

Modulus of Elasticity

Figures 10, 11 and 12 show the effect of the modulus of elasticity on pavement deflection for loads from 1 to 5 pounds as measured by the model. These figures are for different subgrades which varied from 1 to 3 inches of foam rubber respectively. On each graph the deflection of the steel plate was adjusted theoretically by use of Westergaard's formula to 0.022 inch in thickness as was discussed earlier in the report.

Relatively speaking, in going from the flexible range (E less than 1,000,000 psi) to the semi-rigid range (E greater than 1,000,000 psi), the deflection decreases



EFFECT OF VARYING DEGREES OF SUBGRADE SUPPORT ON DEFLECTION BASIN

Figure 9

h = PAVEMENT SLAB THICKNESS

p = LOAD IN POUNDS

SUBGRADE = 1" FOAM RUBBER

PAVEMENT SLAB = 12"x18"

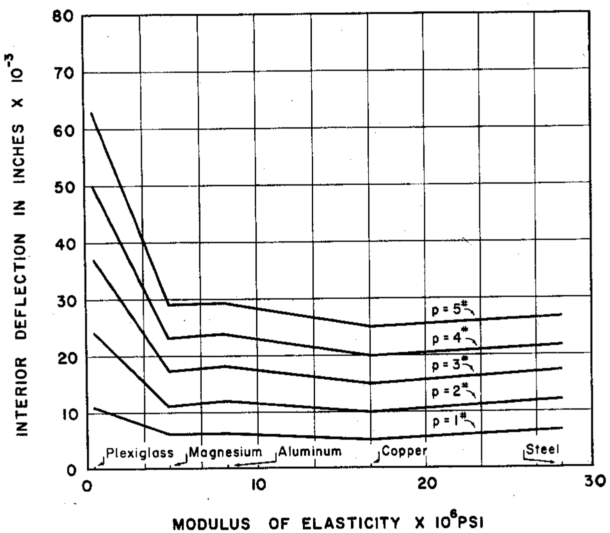
STEEL E = 27.92×10^6 psi h = 0.024" (CORRECTED BY WESTERGAARD FORMULA TO h = 0.022")

COPPER E = 16.72×10^6 psi h = 0.022"

ALUMINUM E = 8.12×10^6 psi h = 0.022"

MAGNESIUM E = 4.7×10^6 psi h = 0.022"

PLEXIGLASS E = $.34 \times 10^6$ psi h = 0.021" (CORRECTED TO 0.022")



DEFLECTION VS. MODULUS OF ELASTICITY
MEASURED READINGS

FIGURE 10

h = PAVEMENT SLAB THICKNESS

p = LOAD IN POUNDS

SUBGRADE = 2" FOAM RUBBER

PAVEMENT SLAB = 12"x18"

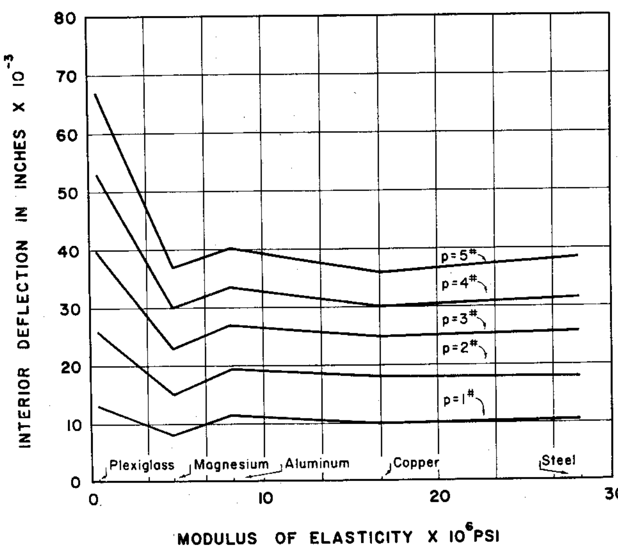
STEEL E = 27.92×10^6 psi h = 0.024 (CORRECTED BY WESTERGAARD FORMULA TO 0.022")

COPPER E = 16.72×10^6 psi h = 0.022"

ALUMINUM E = 8.12×10^6 psi h = 0.022"

MAGNESIUM E = 4.70×10^6 psi h = 0.022"

PLEXIGLASS E = $.34 \times 10^6$ psi h = 0.021" (CORRECTED TO 0.022")



DEFLECTION VS. MODULUS OF ELASTICITY
MEASURED READINGS

FIGURE 11

h = PAVEMENT SLAB THICKNESS

p = LOAD IN POUNDS

SUBGRADE = 3" FOAM RUBBER

PAVEMENT SLAB = 12"x18"

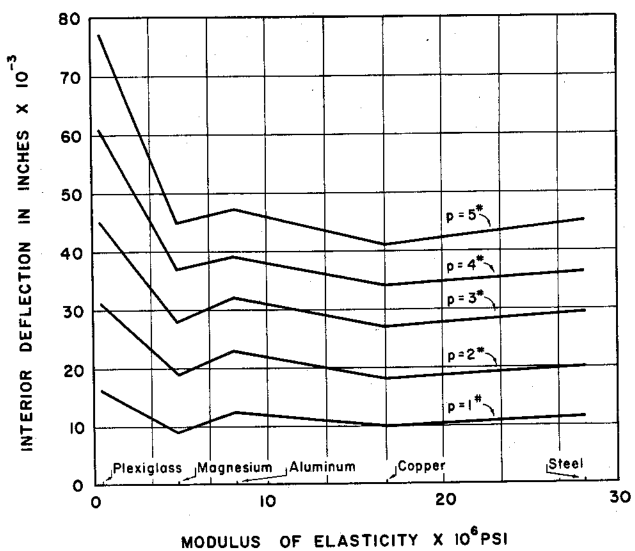
STEEL E = 27.92×10^6 psi h = 0.024" (CORRECTED BY WESTERGAARD FORMULA TO 0.022")

COPPER E = 16.72×10^6 psi h = 0.022"

ALUMINUM E = 8.13×10^6 psi h = 0.022"

MAGNESIUM E = 4.70×10^6 psi h = 0.022"

PLEXIGLASS E = $.34 \times 10^6$ psi h = 0.021" (CORRECTED TO 0.022")

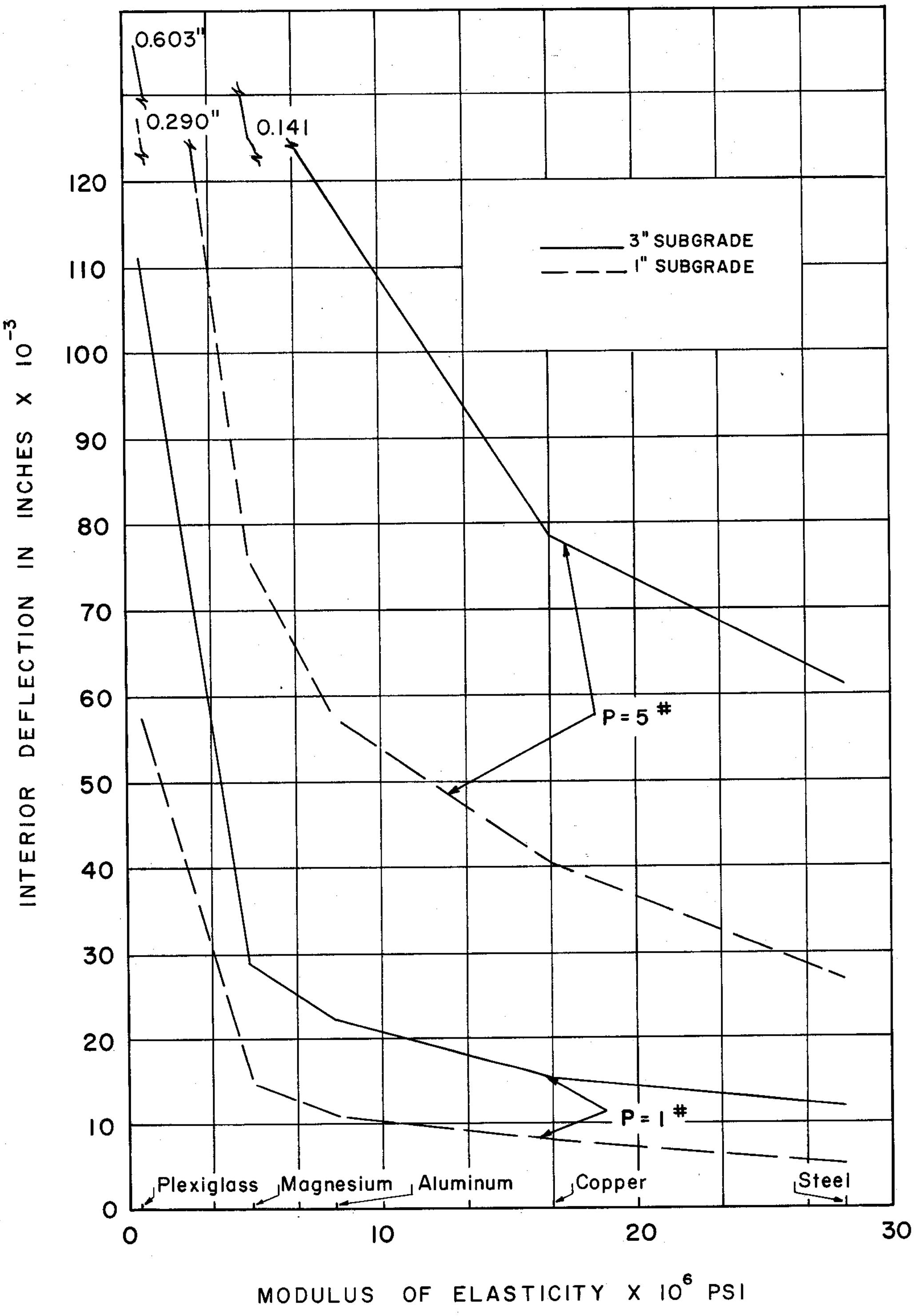


DEFLECTION VS. MODULUS OF ELASTICITY
MEASURED READINGS

FIGURE 12

rapidly with an increase in modulus of elasticity. As the modulus of elasticity increases from the level of magnesium to that of aluminum, the deflection increases. From the level of aluminum through copper and steel the deflection remains approximately equal or increases slightly with an increase in modulus of elasticity. Generally speaking, this observation applies over all ranges of loads and support conditions. Note that the deflection reduction in the range of magnesium is accentuated as the load is increased and as the support value is decreased.

For comparison purposes the pavement deflection for the various materials was calculated theoretically by the use of Westergaard's formula. The Possion's ration used for each material was 0.33, with the exception of plexiglass, which 0.25 was used. The results for the 1 pound and 5 pound loads and for 1 inch and 3 inch subgrade supports are presented in Figure 13. The results are typical of the data and show the general trend. Note that as the modulus of elasticity is increased the pavement deflection decreases. This observation holds over the entire range of loading and support conditions although the effect is reduced as the modulus increases and the support value increases.



DEFLECTION VS. MODULUS OF ELASTICITY

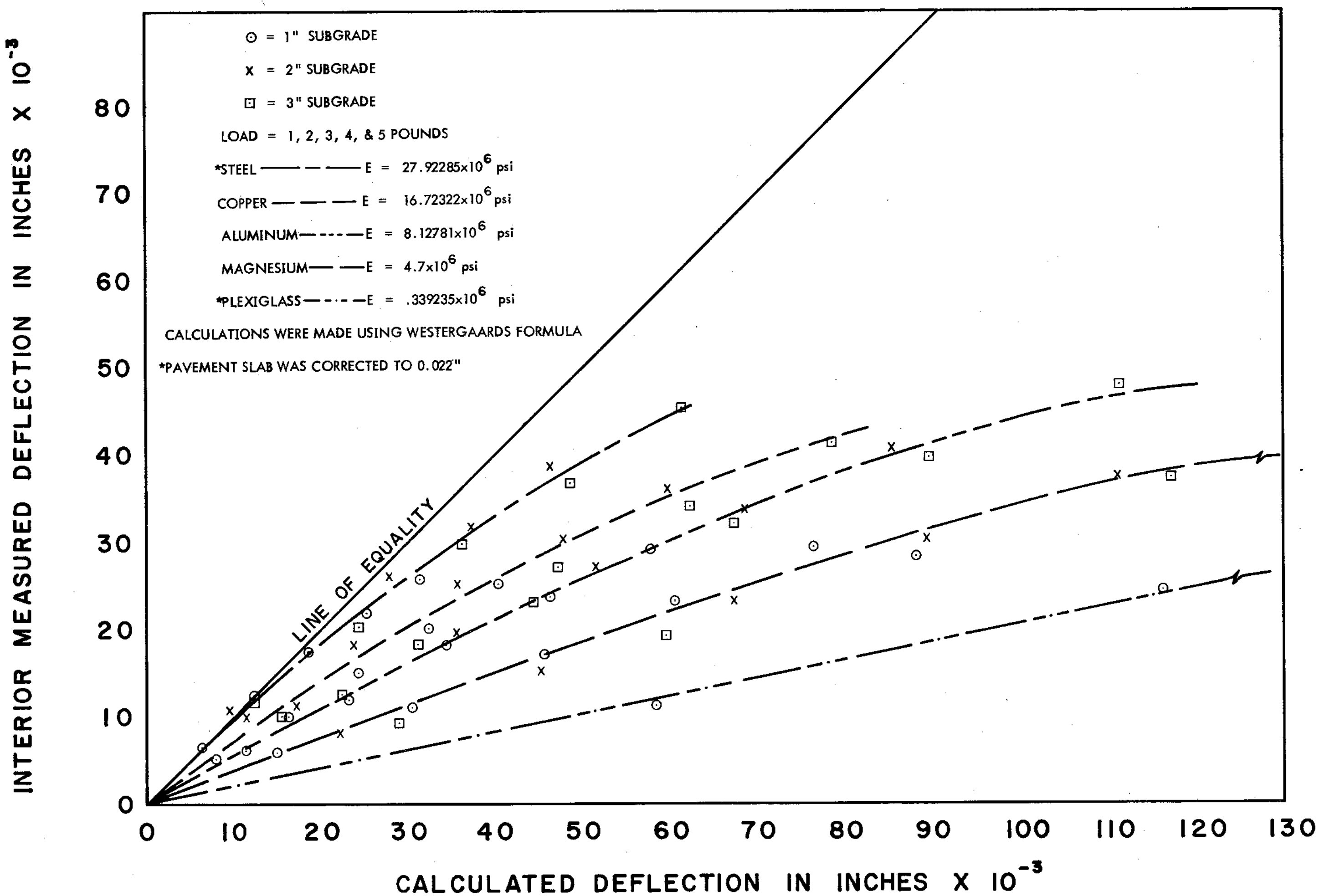
CALULATED VALUES

FIGURE 13

Figure 14 is a comparison of the measured and calculated deflections. The various lines on the graph represent the different modulus of elasticity. The points along these lines are for the various load increments and subgrade support conditions. The 45 degree or line of equality is also placed on the graph. Note that in all cases the calculated deflection is considerably larger than the measured deflection. In addition it may be observed that as the modulus decreases the calculated deflection becomes progressively larger than the measured deflection.

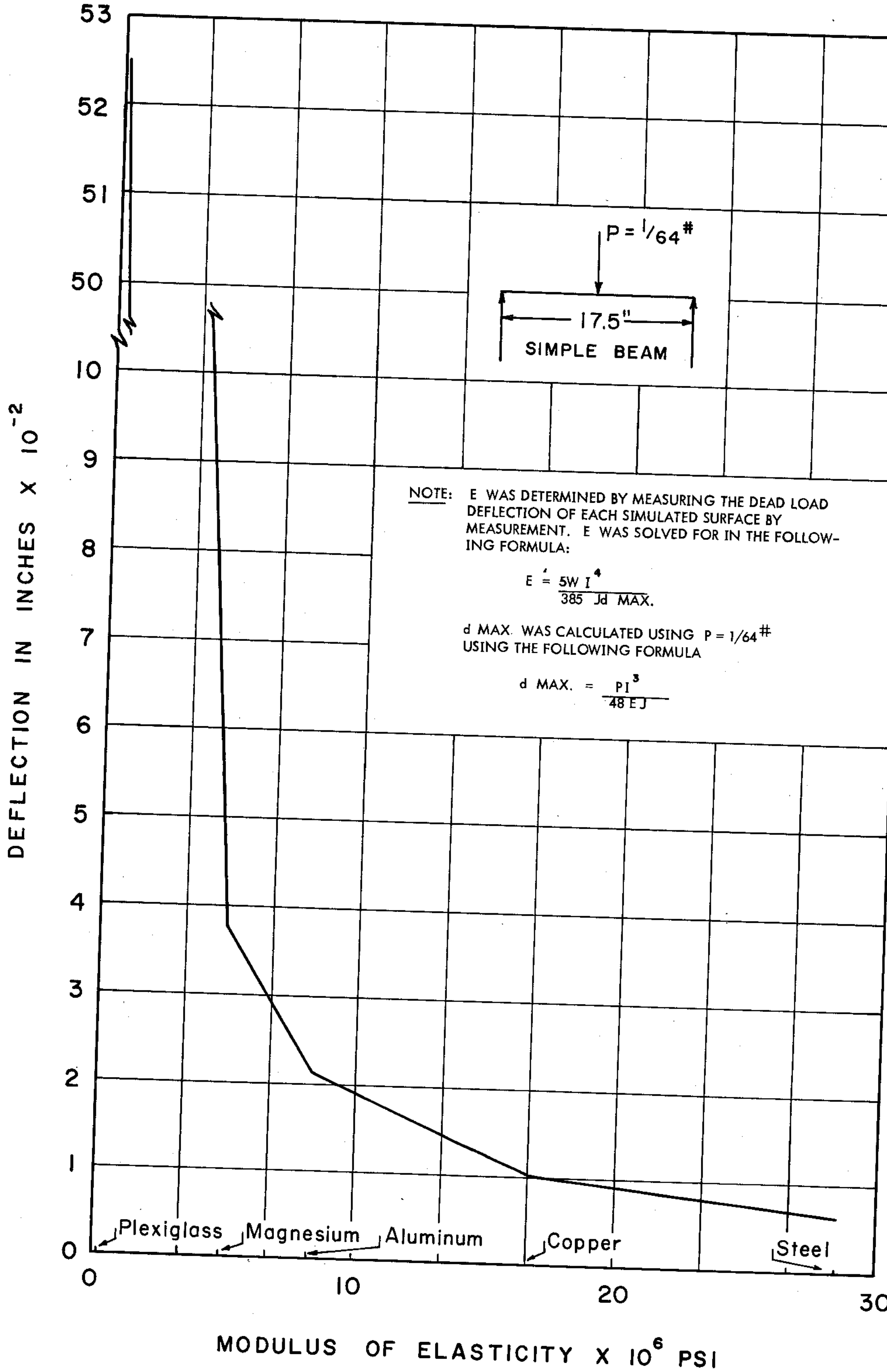
Using the same plates, a test was conducted with the plates being used as a simple span beam. The results of this investigation are presented in Figure 15. Note that in the case of the simple beam the measured values agree with that predicted by theory, but in the case of a slab on-grade, a pavement deflects different as would be expected from theory.

In order to determine if the surface friction of the slabs was a factor in deflection measurements, the steel, copper and aluminum surfaces were lacquered. This was done



MEASURED VS. CALCULATED DEFLECTION

FIGURE 14



DEFLECTION VS. MODULUS OF ELASTICITY

PAVEMENT SLAB AS A SIMPLE BEAM

FIGURE 15

to eliminate this possible variable. The results were relative to the measurements taken without lacquered surfaces. That is, the lacquer strengthened or reduced deflection relatively on each slab.

V. DISCUSSION OF RESULTS

The primary variables investigated in this study relative to pavement deflection were wheel load, pavement thickness, subgrade support, and modulus of elasticity of pavement materials. The results of this experiment show that each of these variables react with model studies in the same manner as indicated by theories and as measured under field conditions with the exception of the modulus of elasticity of the pavement material. Although the findings in connection with this latter exception disagree with the theoretical analysis, they are in agreement with field measurements conducted by the Texas Highway Department as previously mentioned.

The data on Figures 10, 11, and 12 indicate that in the range of modulus of elasticity from 1×10^6 to 5×10^6 psi, the deflection starts to increase as the modulus of elasticity is increased. From the range of 5 to 8 million the data shows conclusively that deflection increases as modulus increases. Therefore, it may be stated on the basis of this data that at some point greater than 1×10^6 psi to a modulus of approximately

8×10^6 psi, the deflection increases as the modulus of elasticity increases. It is within this range that the concrete pavements studied in this research project fall. The one referenced experimental pavement had two significant levels of modulus of elasticity ranging from 2.5×10^6 psi to 6×10^6 psi. As pointed out previously, the data from this field experiment shows that the deflection increased as the modulus of elasticity increased which is in agreement with the limited laboratory studies.

It is difficult to preconceive how a sheet of magnesium which is flexible in comparison to a more rigid sheet of steel will deflect less under a given load than the steel plate when placed on a subgrade. Using the same plates as simple beams the magnesium deflects considerably more than the steel plate as would be expected. It is important to emphasize again, however, that these model test results correlate with field measurements.

It is not possible for the authors to explain this phenomenon. However, it appears that with certain combinations of pavement material, wheel loads, and subgrade support the total capability of the pavement structure is increased which in turn reduces the pavement deflection appreciably. There are several factors not accounted for in the theoretical analysis that could result in these observations, these being as follows:

1. Friction between the slab and the subgrade induce membrane stresses which are not accounted for in theory.
2. The foundation is not acting as a set of independent springs as assumed by Westergaard and others, but is acting as an elastic body or a set of interconnected springs.
3. A combination of the above two hypothesis may result in the secondary deflections induced on the weaker slabs to bring the foundation interconnections into play more strongly than for the stiffer materials thus reducing the effect of modulus of elasticity in the range of concrete pavements.

The test model developed indicates it is possible to correlate field results to laboratory experiments. Measurements can be accurately reproduced by adopting standard procedures and techniques. Consistent test results can be partially attributed to use of a very long wheel axle, the rate of road application, the stable subgrade material, high quality materials and a stable measuring device.

VI. CONCLUSIONS AND RECOMMENDATIONS

Conclusions

1. On the basis of this experiment it is concluded that the variables considered correlate with Westergaard's theory, with the exception that deflection of the pavement surface does not, under all conditions, increase with a decrease in the modulus of elasticity of the pavement slab.

2. That a model can be constructed which is capable of correlating field pavement deflection measurements.

Recommendations

1. It is recommended that a pavement deflection formula be derived which will more accurately correlate actual field measurements as related to the modulus of elasticity of the pavement surface.

2. It is recommended that laboratory test models be considered, if feasible, for preliminary studies to aid in solving problems in pavement design.

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A P P E N D I X

MODULUS OF ELASTICITY

The modulus of elasticity of each material was determined by measuring the dead weight deflection of each material, as a simple beam, over a 17.5 inch span. The dead weight deflection was measured for each surface side, and the average of the two was used. Using these values, the modulus of elasticity was calculated as follows:

$$E = \frac{5\,w\,l^4}{385\,J\,d\,max}$$

in which:

E = Modulus of elasticity in psi

W = Pounds per inch of length

l = Length of span in inches

J = Moment of inertia through the center of gravity in inches to the fourth power

d max = Maximum deflection in inches.

The modulus of elasticity measured and Handbook values are shown in Table A-1.

MODULUS OF ELASTICITY IN PSI

Materials	Measured Values $\times 10^6$	Handbook Values $\times 10^6$
Steel	27.72	30.00
Copper	16.77	16.00
Aluminum	8.12	10.00
Magnesium	4.69	6.25
Plexiglass	0.34	-

TABLE A.1

SIMPLE SPAN DEFLECTION

In order to determine the simple span beam deflection, the following formula was used:

$$d\ max = \frac{P\ l^3}{48\ E\ J}$$

Where:

E = Modulus of elasticity calculated from beam dead weight deflection in psi

l = Length of span in inches

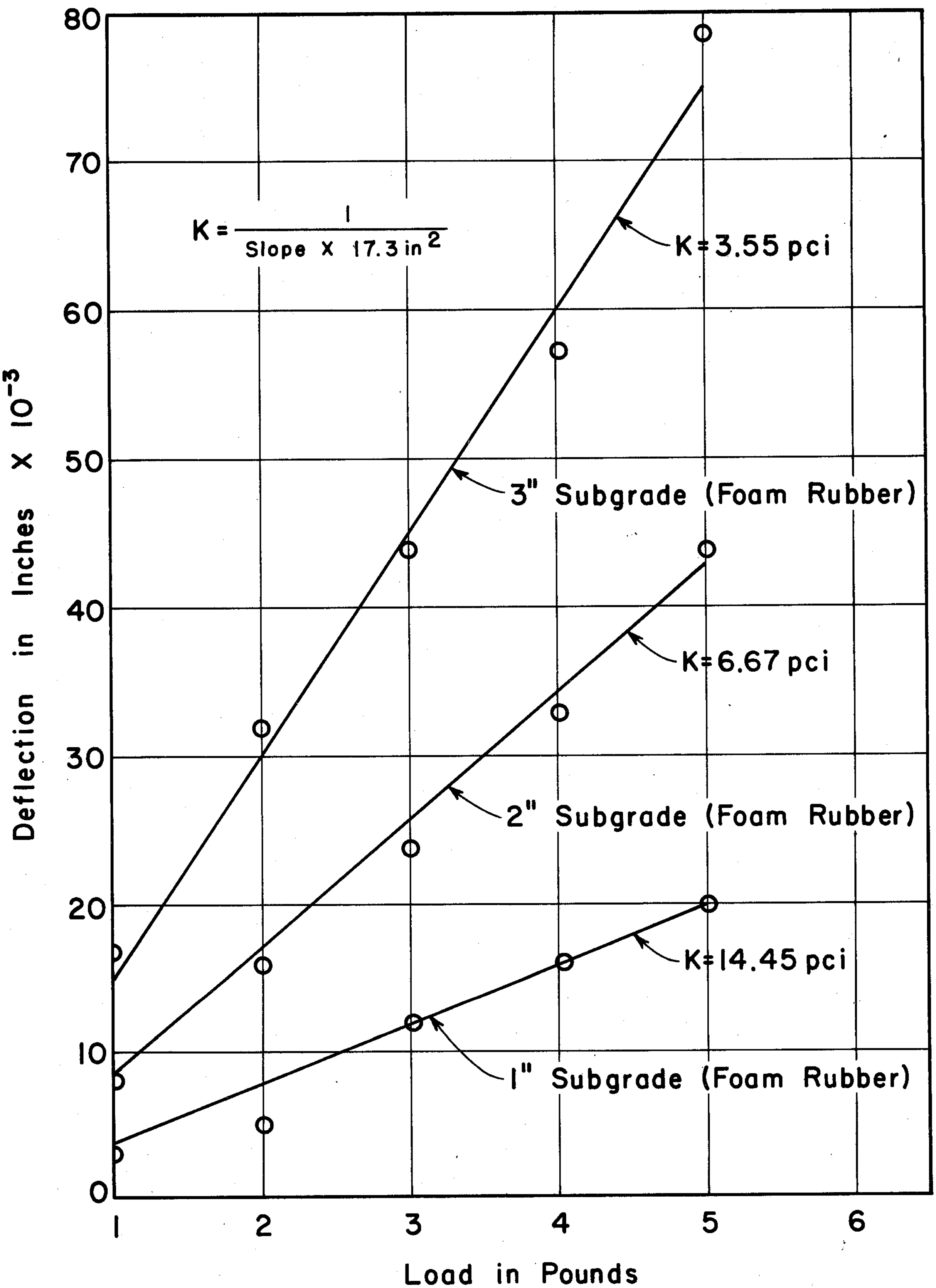
P = Concentrated load in pounds

J = Moment of inertia through the center of gravity in inches to the fourth power

d max = Maximum deflection in inches.

The value for P was arbitrarily selected as 1/64 pound. The deflection values determined are shown below:

Steel	=	0.00638 inches
Copper	=	0.01066 "
Aluminum	=	0.02193 "
Magnesium	=	0.03790 "
Plexiglass	=	0.52556 "



DEFLECTION VS. LOAD DATA USED IN DETERMINING THE SUBGRADE MODULUS

FIGURE A.3