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16. ABSTRACT

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Data from ten different roadways throughout California are presented as part of the correlation study. The program involved the determination of deflection for a section of roadway, the sampling of all soils and aggregates to a depth of 30 inches and the resiliometer testing of the soils and aggregates at test pressures. These pressures were determined from a theoretical depth pressure relationship for the configuration and loading of the wheel of the deflection truck used.

Presented also in the report is a procedure which can be used to predict the probable deflection of a proposed roadway based upon resilience tests of preliminary soils and aggregate samples. The predicted deflection can be compared with limiting deflection criteria to determine whether the proposed structural section is satisfactory to preclude fatigue cracking.

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THE EFFECT OF RESILIENCE-DEFLECTION RELATIONSHIP ON THE STRUCTURAL DESIGN OF ASPHALTIC PAVEMENTS

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INTERNATIONAL CONFERENCE
ON STRUCTURAL DESIGN OF
ASPHALT PAVEMENTS

ANN ARBOR, MICHIGAN
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THE EFFECT OF RESILIENCE-DEFLECTION RELATIONSHIP ON THE STRUCTURAL DESIGN OF ASPHALTIC PAVEMENTS

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SYNOPSIS

This report presents the results of a study conducted by the California Division of Highways, Materials and Research Department to determine the relationship between laboratory measurements of resilience of soils comprising the pavement structural section and the transient pavement deflection under a 7500 lb. wheel load.

Data from ten different roadways throughout California are presented as part of the correlation study. The program involved the determination of deflection for a section of roadway, the sampling of all soils and aggregates to a depth of 30 inches and the resiliometer testing of the soils and aggregates at test pressures. These pressures were determined from a theoretical depth pressure relationship for the configuration and loading of the wheel of the deflection truck used.

Presented also in the report is a procedure which can be used to predict the probable deflection of a proposed roadway based upon resilience tests of preliminary soils and aggregate samples. The predicted deflection can be compared with limiting deflection criteria to determine whether the proposed structural section is satisfactory to preclude fatigue cracking.

Presented also are some tentative resiliometer results from a study of thixotropic gain of strength of remolded specimens as compared to undisturbed specimens.

I ANALYSIS OF THE PROBLEM

The problem of fatigue cracking in bituminous pavements has long been recognized and has been studied and extensively reported during the past 6-10 years. The magnitude of repeatedly applied transient deflections which will cause fatigue failures in a bituminous surfacing during its design life has been suggested by various agencies from the results of actual roadway performance or test track data. Mr. T. A. Middlebrooks[1], in 1943, stated that, "Experience to date indicates that critical deflection will vary from 0.05" to 0.15" depending upon the type of subgrade, type of base material, wheel load, and probably other factors."

The development of the Benkelman Beam during the operation of the WASHO Test in 1953 greatly simplified the measurement of transient pavement deflections. Utilizing this apparatus, approximately 60,000 individual deflection measurements were made on the WASHO Test Road. Analysis of these data revealed that this particular test pavement could withstand transient deflections of 0.045" in warm weather and 0.030" in cold weather[2] for a period of 2 years. It was emphasized in the report, that these values may not be applicable to older pavements, or to those containing different types of asphalt or aggregate.

In 1955, the California Division of Highways reported on the results of a comprehensive deflection study which had been made throughout the State of California beginning in 1951[3]. The data in this investigation represented readings from nearly 400 electronic gauge units on 43 different projects. The report of this work presented the following safe limits (Table I) for maximum deflection for several types of pavement and base construction necessary to preclude cracking after several millions of repetitions using a 15,000 lb. single axle load.

The values shown by Table I have been applied as guide criteria by the Division of Highways since 1955 for planning the reconstruction of existing roadways. To date no additional evidence has been found which would seriously invalidate these criteria insofar as California pavements are

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TABLE I

Thickness Pavement	Type of Pavement	Maximum Deflection for Design Purposes (Tentative)
8 in.	Portland Cement Concrete	0.012"
6 in.	Cement Treated Base (Surfaced with Bit. Pavement)	0.012"
4 in.	Asphalt Concrete	0.017"
3 in.	Plant Mix on Gravel Base	0.020"
2 in.	" " " " "	0.025"
1 in.	Road Mix on Gravel Base	0.036"
1/2 in.	Surface Treatment	0.050"

concerned. Future adjustments may be warranted from experience to be gained from present day construction resulting from modifications of California Standard Specifications in 1960. The modifications applied to asphalt specifications and compaction requirements for asphalt surfaces. The objectives were to obtain more durable asphalts and denser, more compact surfaces which were better able to combat the deterioration and hardening due to weather. The final result hoped for was a more flexible, fatigue crack resistant surfacing.

Preliminary perusal of deflection data from the AASHO Test Road in Illinois indicate that these pavements tolerate deflections somewhat greater than those shown by Table I. However, differences in asphalt quality, design and control of the mixes, and duration of the test may have greatly influenced these values.

The results of a pavement deflection study of three years duration in the State of North Carolina were reported by Mr. L. D. Hicks, Chief Soils Engineer of the State Highway Commission[4]. In the course of this study, periodic deflection measurements were made over 4 projects with a Benkelman Beam and a dump truck loaded to provide 7500 lbs. on each rear dual wheel assembly (15,000 pound load axle), the same arrangement as that employed by the California Division of Highways.

Analysis of these data by Mr. Hicks resulted in a tentative desirable limit for deflection at 0.030 inches for 2, 3 and 4 inch surfacings of asphaltic concrete pavements in North Carolina.

Undoubtedly, the results of future deflection investigations over a variety of pavement structural sections throughout the United States will enable highway engineers to assign safe levels of deflection to pavements with reasonable certainty that they will not be overly fatigued during their design life. These deflection levels will of necessity take into account local materials, weather, mixture design and construction practices.

Measurement of pavement deflection, as now done, is an "in situ" test. There is, at present, no rational basis for the designer to predict the probable deflection of a proposed pavement structural section or to adjust the sections so as to reduce an anticipated high deflection to within permissible limits.

A laboratory testing device has been developed by the Materials and Research Department of the California Division of Highways which it is hoped, will enable the designer to incorporate the deflection factor into pavement design by providing a definite measure of the compression and rebound of a soil specimen under dynamic loading. Since, for a given load and specimen size this measurement is directly related to the recoverable stress energy of a deformed body when the load causing stress is removed, the instrument has been designated the "Resiliometer".

The test will supplement existing tests since it measures a separate and distinct soil property (resilience) not measured by other test methods commonly in use.

The apparatus, test method and procedure are described in detail in the appendix.

The Resiliometer, shown by Figure 1, is an apparatus which measures the volumetric displacement resulting from repetitions of a cyclic dynamic load applied to 4 inch diameter soil specimens ranging from 2-1/2" to 4" in height. The load is applied through a rubber diaphragm associated with a pressure system containing ethylene glycol solution, the fluid being acted upon by air pressures of from 0 to 60 psi. Volumetric displacement is measured by a manometer tube. Lateral pressures are applied and measured by a Hveem Stabilometer.

Although the original resiliometer was designed and constructed by this laboratory in 1946, the press of other work plus the destruction of an earlier model in a laboratory fire in 1954 delayed development. From 1954 until 1959, several modifications in equipment and technique were instituted which improved the sensitivity and reproducibility of the instrument. This period was also devoted to studies of the effect on resilience of specimen height, density, gradation, moisture content, and number of load repetitions. Qualitative resilience appraisals were made on roadway materials from locations throughout the State of California in addition to samples from Idaho, Washington as well as the WASHO and AASHO Test Roads.

The data assembled from these tests seem to warrant certain general conclusions concerning the resilient behavior of soils. Within the ranges of pressure used in the test, the following general observations may be made.

1. Resilience (internal compression and rebound) increases rapidly with increasing moisture content and, to a lesser extent, with increasing void ratio.

2. Although individual clay specimens have been found to be extremely resilient at elevated moisture contents, the greatest sensitivity to moisture, i.e., the largest variations in resilience for a given increase in moisture content are consistently found in the soils classed as silts or silty.

3. Sands and gravels are consistently low in resilience. The resilience-moisture content plots shown by Figure 2 illustrate fairly typical behavior of several distinct types of soil. The general descriptive ratings on the right side of the chart are based upon the evaluation of results from hundreds of individual tests.

4. As a general rule, the greatest soil "sensitivity" begins slightly on the wet side of optimum moisture content.

The accumulation of these resilience data and the assignment of general resilience classifications proved beneficial for the qualitative appraisal of roadway materials for special projects and distress investigations. However, in order to introduce the resilience factor into the California pavement structural design procedure on a rational basis, it was apparent that a tie was required between laboratory measurements in the resiliometer and field performance as measured by pavement deflections.

The attempt to develop a correlation was initiated in the Spring of 1959 at the Franklin Airport, an inactive airstrip 22 miles southeast of Sacramento by taking undisturbed samples and performing deflection measurements. Subsequent samplings were made at the California State Fair Grounds and in the Division of Highways Service and Supply Yard in Sacramento. The results of these early correlation samplings were beneficial primarily for development of technique in deflection measurements, sampling, and testing specifically for the resilience-deflection correlation study. In addition, several basic changes in the method of analysis of data were made. The samplings which will be discussed in this report were made on roadways throughout California and on the AASHO Test Road in 1960-61.

II RESILIENCE-DEFLECTION CORRELATION STUDY

The sampling procedure used for the resilience-deflection correlation study since 1959 is as follows:

A. Deflection Testing

1. Device - Benkelman Beam

2. Load - Ford F-800 Dump Truck with rear axle load of 15,000 lbs., dual wheels, 10:00 x 20 tires inflated to 70 psi.

3. Deflection Test Interval - 15 to 25 feet in each wheel track of a selected lane throughout a generalized area of 500 lineal feet.

B. Method of Selecting Sampling Location

1. Select the spot from within an area where relatively uniform deflections were obtained so that the deflection measurement reflects the general state of the roadway rather than a localized condition.

2. Do not consider areas with cracked surfacing since rocking of the individual blocks will result in abnormally high deflection measurements.

3. Record the surfacing temperature when the deflection measurement is made.

C. Sampling

1. Size of Hole - Cut a 2'x3' hole to a depth of 30 to 36 inches.

2. Samples - In addition to thickness measurements, obtain at least 3 undisturbed 4" high by 4" diameter samples of each element of the structural section. Those materials from which (due to lack of cohesion) undisturbed samples cannot be taken are tested for inplace density utilizing the sand volume method (Calif. Test No. 216 E). Finally, take moisture samples and a 40-50 lb. disturbed sample from each different material to a depth of 30 inches from the surface.

A typical deflection pattern and sampling diagram used for the sample taken on Road IV-SCr-FAS 1270 is shown by Figure 3.

D. Evolution of a Testing Procedure

1. Lateral Confining Pressure

For purposes of correlation of field deflection with laboratory resilience data it was considered desirable to test specimens with the stabilometer with a lateral confining pressure comparable to that exerted on an element of soil inplace resulting from dynamic loading representative of the traffic using the highway. The inplace passive-active pressure state in soils covered with different pavements, however, cannot be duplicated with any known laboratory device. Therefore, a uniform lateral confining pressure of 3 psi was used for all tests. This value was selected as a result of a series of resilience tests in which several confining pressures were used with a variety of soils. The results indicated that the least lateral distortion occurred in the test specimen at 3 psi for the range of vertical pressures utilized.

2. Vertical Dynamic Load

Probably the most important single variable in the correlation of field deflection and laboratory resilience is the application of a vertical dynamic pressure with the resiliometer which corresponds to that absorbed by the soil as the result of a transient wheel loading. The more important variables which must be considered include:

(a) Depth of cover

(b) Stiffness of cover material

(c) Stratification of overlying material

(d) Wheel loading and spacing

(e) Rate of application

A review of the literature on the subject of depth-vertical pressure relationships in soils must inevitably begin with the work of Boussinesq[5] who, in 1885, introduced a well known mathematical expression for calculating the vertical pressure distribution pattern in a homogeneous, elastic, level, and infinite medium.

Much productive research in recent years has been devoted to modifying the theory so that it may closely parallel experience with actual soil conditions.

In 1936 a modification of the Boussinesq equation was proposed by A. E. Cummings[6] which involved the application of a concentration factor "n" as a parameter which could be adjusted to fit materials other than isotropic elastic solids. The concentration factor concept was empirical by nature and thus required verification by field data. The accelerated traffic test (No. 2)[8] at Stockton Airfield in 1942 was partially devoted to the comparison of recorded vertical pressures with theoretical values obtained using concentration factors ranging from 2 to 8 with varying wheel loads, temperatures and structural sections.

Examination of the resulting plots indicates that for the range of variables included in the test, the concentration factor (n) fell generally between 2 and 4 (n = 3 for the theoretical equation). There appears to be a tendency toward larger concentration factors with heavier structural sections. The magnitude of the wheel loading, however, had no noticeable effect upon the parameter.

In 1938 Westergaard[7] introduced a further modification of the Boussinesq equation, with the inclusion of Poisson's Ratio. This change was based on the non isotropic conditions found in sedimentary soils. These equations express relationships that are undoubtedly closer to conditions in sedimentary soils and are generally thought preferable for settlement predictions.

A comparatively recent and comprehensive physical pressure-depth investigation was conducted by the Civil Aeronautics Administration Technical Development and Evaluation Center under the direction of Mr. Raymond C. Herner[9]. Herner utilized a "Mechanical subgrade" with which it was possible to measure, on a plane, the vertical pressures induced by a variety of static aircraft and truck wheel loadings through asphaltic concrete surfacing and flexible bases of differing thickness and quality. Herner's study provided a great deal of useful physical data. The tests indicated wide variations in maximum vertical pressure with varying pavement and base thickness and quality, wheel load and subgrade reaction. Although the tests were primarily concerned with aircraft tire loadings, a number of readings were made utilizing 8.25 x 20 and 10:00 x 20 dual truck tire loadings over a "weak subgrade" (modulus of subgrade reaction = 82). These data for the 7 and 8 kip loadings and 70 psi inflation pressure are shown plotted on Figure 4 along with the theoretical Boussinesq curve utilizing the loading and configuration most representative of our Benkelman Beam truck tire print (twin circular discs at a uniform pressure of 70 psi with 5-1/2" between inside edges). Since our beam truck wheel load is 7.5 kips and utilizes 10:00 x 20 tires, the data from the load transmission test is approximately applicable. It is interesting to note that these points are in comparatively good agreement with the theoretical curve.

In 1943, Donald M. Burmeister[10] introduced a rigorous mathematical development of the elastic theory for the general case of a "two layer system" for the determination of stresses in layered soil deposits. Burmeister developed his original analysis further to a "three layer system" in 1945.

In 1951 W. E. A. Acum and L. Fox [11] published a series of tables in which stresses were numerically presented for a series of specific conditions for the three layer system. These computations were based upon the following assumptions.

(a) All materials involved behave elastically

(b) Perfect continuity (or friction) exists at each interface

(d) Poisson's Ratio equals 0.5 for all elements of the structural section

Whether these assumptions are valid for highway design will have to be determined by further physical measurements.

The evolution of influence diagrams or equations for application of the elastic theory for the more complex structural sections is continuing through efforts of Mr. Burmeister and others.

At the present time, however, the material available for its convenient application to the present day multi-layered sections is still inadequate. The results of the accelerated traffic test at Stockton and the work of the CAA with the "mechanical subgrade" agree well enough to the theoretical Boussinesq equation for flexible pavement systems so that its use for assumed variation of pressure with depth was adopted with reasonable confidence.

3. Limiting Depth

The electronic gauge units installed throughout California in the years 1951-1955 provided not only the data on total pavement deflection but also some idea of the amounts contributed by individual layers or strata. Examination of these data indicated that compression and rebound is developed in measurable amounts to depths of 21 feet. However, computations assigning the contribution to total deflection made by each of the various strata under flexible sections revealed that approximately 86% of the deflection caused by compression of the upper 8' of material occurred in the upper 2' layer and that 82% of that due to the top 18' depth was in the top 3 feet. A typical example of this phenomena is shown by Figure 5.

It was apparent that sampling or taking into account the effects of depths below 2-3 feet would be unrealistic. In addition, pressures occurring at depths below 2 feet are so low that experimental errors begin to mask out the significance of the resulting resilience data. Accordingly, the limiting depth for sampling and consideration in computations was set at 30 inches.

For purposes of computation, the test resilience value for any strata is obtained by determining the average pressure at the depth the material exists. This can be conveniently done using the depth-vertical pressure curve shown by Figure 4. The pressure so determined is corrected by adding 10 psi and the test resilience value is determined at the corrected pressure reading. The addition of the 10 psi is a deviation from the theoretical curve and is utilized for the following reasons:

(a) It distorts the depth-pressure curve in favor of those materials appearing at lower depths and, therefore, tends to compensate for the 30 inch cutoff.

(b) It results in a greater range of values and thus increased sensitivity to the test results.

(c) It reduces the significance of specimen variations when tested at low pressures.

4. Vertical Surcharge

A continuous vertical surcharge is applied to all specimens commensurate with the depth of the material sampled. This is accomplished by a spring loaded pop off valve on the air exhaust line which expels air at the end of each loading cycle until the pressure is reduced to a value equal to the weight of the overlying material in place. This residual surcharge pressure is then maintained until the beginning of the next cycle. Each sample is tested twice, once at each of the two continuous vertical surcharges appropriate to the top and bottom of the layer from which the specimen is taken.

5. Rate of Application

The rate of application of load has been held to a constant 8 cycles per minute, the minimum period found necessary for full rebound of the specimen, the 7.5 second cycle divided so that pressure is applied to the specimen for 0.75 seconds, the minimum period of time needed to secure an accurate reading of the manometer tube. A typical Benkelman Beam deflection vs. time plot is shown by Figure 6 superimposed upon a Brush analyzer record chart of the resiliometer test in which the dynamic load is plotted against time. The deflection trace corresponds to the rate of load application at a given point at the approximate operating speed of the Benkelman Beam truck.

The number of load repetitions applied at each increment of pressure is dependent upon the nature and state of the material being tested. The volumetric displacement is recorded only when the rebound reading is within 0.02 cubic in. of the initial reading, so that the data reflects, almost entirely, resilient deformation of the specimen.

Thus with sands and silts,

readings can be taken almost immediately while clays require several repetitions at each increment of pressure in order to reduce the plastic deformation to an acceptable minimum. Although plastic deformation is cumulative throughout the test, resilient deformation remains virtually constant for each applied pressure after the initial period of preliminary consolidation. This behavior is illustrated graphically by the compression and rebound history of an undisturbed clay specimen shown by Figure 7.

6. Typical Computation

The mechanics of sampling, testing, and analysis of data for the resilience-deflection correlation study can best be illustrated by a typical example, in this case, from project IV-SCr-FAS 1270 near Watsonville, California. A series of 4 deflection measurements taken on December 1, 1960 on the westbound outer wheel track from Sta. 14+87 to Sta. 15+28 were found to range from 0.036" to 0.044". Sta. 15+13 with a deflection of 0.040" was selected for sampling. The structural section and deflection pattern are shown by Figure 3. Disturbed samples and moisture samples of all elements of the structural section were taken. Inplace density determinations of the base and subbase were made using Test Method Calif. No. 216-C (Sand Volume). Chunks of the selected material layer were sprayed with paraffin wax and weighed in air and water for density determinations. Three 4" diameter by 4" high undisturbed samples were obtained from the basement soil at from 20-1/2" to 24-1/2".

Samples of base, subbase and selected material were compacted in the laboratory at field moisture and density and tested in the resiliometer under pressures ranging from 10 to 50 psi in 10 pound increments.

Samples taken by driving a brass sleeve into the basement soil were trimmed to proper length and tested in a like manner. Each specimen was tested under a vertical surcharge equivalent to the load on the top and bottom of the layer from which the specimen was taken.

The plotted results are shown by Figures 8 through 11. The aggregate base results, plotted on Figure 8, indicate no tangible effect due to vertical surcharge. Therefore, the computation for the base was made using a single resilience-pressure curve. Consulting Figure 4, it can be observed that the first 4 inch increment of depth (2.2 to 6.2 inches) was found to have an average pressure of 46.2 psi. Adding 10 psi, the resilience at 56 psi is observed to be 0.21 cu. in. from Figure 8. The average pressure for the remainder of the base (6.2 to 9.0 inches) is 19.1 + 10 = 29.1 psi from Figure 4. The resilience at this pressure is 0.14 cu. in. However, since the resilience data applies only to tests on specimens 4 inches in height, a correction is made on the last increment by multiplying the resilience value by a ratio of the actual thickness of the increment to 4 inches, in this case $0.14 \times \frac{2.8}{4.0} = 0.10$ cu. in. The total contribution to resilience by the layer of base material is, therefore, 0.21 + 0.10 = 0.31 cu. in.

The resilience plots for aggregate subbase, shown by Figure 9, show a definite effect of the vertical surcharge. The vertical pressure for the first 4 inch increment (9.0 to 13.0 inches) was found to average 14.9 psi + 10 psi = 24.9 psi. From the resilience-pressure plot, for a vertical surcharge of 0.7 psi and pressure of 24.9 psi the resilience was found to be 0.115. A similar computation was made for the 13.0 to 16.2 inch increment. The resilience value was determined using an interpolated resilience curve (dotted) for 1.0 psi vertical surcharge and again making a height correction. The resilience for the increment of subbase from 13.0 to 16.2 inches corrected for height was found to be 0.07 $in.^3$ and the total subbase resilience equal to 0.185 in^3.

This procedure was repeated for the selected material (Figure 10) and basement soil (Figure 11) to a depth of 30 inches. The total resilience for a depth of 30 inches totaled 0.84 cu. in. This was plotted against the field deflection at that point (0.040") on Fig. 12.

E. Discussion of Correlation Plot

The results of 24 samplings from 10 projects are plotted on Figure 12 with a regression line of correlation. Although there is considerable scatter, a fairly well defined pattern emerges. It is interesting to note that samples from the same project usually check each other, i.e., the lower deflections result in the lower summations of resilience. The average deflections and resilience summations of individual projects are plotted on Figure 13. Considering the variables which were not controlled in the study, the trend toward correlation is gratifying. In the writers' opinions the primary reasons for this scatter are:

1. Variations in density and moisture content in the materials as they exist in the field.

2. Deviation from the assumed depth-pressure distribution due primarily to varying states of hardness of the asphalt surfacing and to a lesser extent, its temperature.

3. The inability to reproduce in the testing apparatus the inplace lateral pressures of the soil.

III CONCLUSION

A. Adaption of Correlation to Design

The correlation shown by Figure 12 provides a relationship between field deflection and laboratory resilience measurement for flexible pavement systems and as such can be used in the design of a roadway structural section by applying the same analysis used in the correlation study. Based upon the summation of resilience for the proposed structural section, when a predicted deflection exceeds the tentative criteria shown by Table 1, adjustment of the structural section is required to reduce the summation of resilience and thus, bring the predicted field deflection within tolerable limits. Examination of resilience data will indicate which element of the structural section is critical or may be adjusted most economically to reduce field deflection to a tolerable limit. Alternative solutions would also include:

1. Reduction of thickness of surface and therefore increase the allowable deflection.

2. Utilizing a composite, i.e., semi-rigid structural section to reduce deflection by increasing the stiffness of the structure.

3. Increasing the thickness of subbase, base or surface layers.

The design application described above is illustrated by the following example:

A roadway pavement design is proposed with a structural section consisting of 3 inches of A.C. surfacing, 8 inches of aggregate base and 10 inches of aggregate subbase.

Resilience tests on preliminary samples compacted at design moisture content* at vertical surcharges appropriate to the depths the material will appear are shown by Figure 14.

The test values used in the illustration are considered generally representative for these materials.

The calculation of the summation of individual layer resilience is shown by Figure 14. The average pressure in the base layer (3" to 11") is found from Figure 3 to be $\frac{58.6 + 14.2}{2} = 36.4$ psi plus 10 = 46.4 psi. The average vertical surcharge through this layer is found to be 0.5 psi. Since the tests were made at 0.8 and 0 psi vertical surcharges, a 0.5 psi surcharge test curve is interpolated. The resilience from this curve at 46.4 psi equals 0.115 cu. in. per 4 inch specimen. The resilience contribution for the base layer will equal $0.115 \times \frac{8}{4} = 0.23$ cu. in.

Similar computations for subbase and basement soil (to a depth of 30 inches) result in resilience increments of 0.325 and 0.305 cu. in. respectively for a total of 0.86 cu. in. for the proposed section. From Figure 12 the predicted equivalent transient deflection for this section equals 0.026". Tentative criteria indicate that the pavement would not tolerate deflections in excess of 0.20" (Table 1). Therefore, a redesign is required.

*The moisture condition at which a soil specimen will be saturated under a static load of 300 psi. This represents the worst condition the roadway attains in its design life[12].

For a second trial, shown by Figure 15, the thickness of surfacing was decreased to 2" which increased the allowable deflection to 0.025". In addition the thickness of the least resilient material, aggregate base, was increased from 8 to 12 inches and the aggregate subbase increased from 10 to 12 inches.

As shown by Figure 15, this manipulation reduced the resilience summation to 0.80 cu. in. with a new predicted deflection of 0.024", slightly below the tolerable limit. The redesign therefore, meets the requirements for both stability and resilience. The required adjustment, in this case would ordinarily result in little increase in cost. An alternate solution would involve the utilization of a cement treated base with a 3 inch AC surfacing.

Studies by the Materials and Research Department on the deflection damping characteristics of various roadway materials indicate that reductions of from 0.002" to 0.0035" of deflection per inch of thickness are possible with CTB over and above that resulting from an equivalent layer of gravel base. Thus, utilizing the original design with an 8 inch cement treated base instead of the gravel base, we could reasonably expect the predicted deflection of this roadway to be reduced from 0.026" to 0.010", well below the tolerable limit for a cement treated base section (0.012").

The decision as to whether a 2 inch surfacing or a composite section should be used would depend primarily upon the predicted traffic volume.

The preceding example illustrates how the resilience factor could be incorporated into the procedure for design of the roadway structural section. Several important considerations should be borne in mind, however. The most important of these is the assumption of a design moisture content. Sensitivity to moisture particularly in the silt sizes, has been observed as a major factor in the resilience test. The choice of moisture content for the test specimen could, therefore, influence considerably the predicted deflection and consequently the design of the structural section. The criteria presently employed for determination of design moisture content for the R-value test (300 psi exudation pressure) could be utilized. Moisture data from the correlation samplings as well as those from recent distress investigations indicate that the 300 psi exudation criteria is a reasonable representative of the highest moisture conditions eventually attained in the field by fine grained soils in California. Bases and subbases, however, tend to remain on the dry side of this hypothetical highest moisture content except for extreme conditions. This circumstance should present no serious difficulty, however, since these materials are not, as a general rule, particularly sensitive to moisture.

The specimens to be utilized for the proposed procedure will be compacted in the California Kneading Compactor which generally produces specimens with densities slightly below the maximum attained by the California Impact Compaction method and presumably about the same relation to the Modified AASHO Method.

All specimens will be compacted to 95% relative compaction based upon the California Impact Method which is the compaction specified for all materials within 2.5 feet of finished grade by the 1960 California Division of Highways Standard Specifications*.

B. Future Studies

Undisturbed samplings were used for correlation between the resilience test and field deflection measurements insofar as the "sensitive" soils were concerned. These samples were either carved from chunks or taken by pneumatically driven 4 inch dia. brass sleeves. Thus, at the appropriate dynamic pressures and vertical surcharges, we could be reasonably confident that compression and rebound reaction of the soil test specimen approximated that of the material "in place".

It was apparent, however, that for purposes of incorporating resilience data into design, it would be necessary to test remolded specimens of basement soil prepared with varying degrees of sensitivity. It has long been recognized that remolded clays are subject to drastic reductions in strength, even

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*Section 19-5.02, Page 93.
Section 19-6.02, Page 96.

at the same moisture content and density as compared to an "undisturbed" specimen. The ratio of the strength of undisturbed material to recompacted clay varies from 2 to 4 for ordinary clays, 4 to 8 for sensitive clays and over 8 for extra sensitive clays. This phenomena has also been observed in varying degrees in resilience tests on clay soils.

As shown by Figure 16, the resiliometer value for a remolded specimen of AASHO test road embankment soil is approximately 3 times that of the undisturbed material. The utilization of data from remolded clay specimens for design, based upon undisturbed samplings could, therefore, introduce sizeable errors in the design of the structural section.

In order to take this property of clay soils into proper consideration, a study is in progress to determine the rate of the "thixotropic" regain of strength of the more sensitive clay soils encountered in California highway construction. It is hoped that the results of this investigation will indicate the minimum curing period required for a reasonably accurate determination of the "in situ" resilience characteristics of common California clays. The results of a comprehensive study of this subject by Prof. H. B. Seed and Mr. C. K. Chan[13] leads the writers to believe that significant strength gains are possible in from 7 to 12 days even at the relatively low inplace moisture contents thus far encountered. This trend is evident in the results of tests on silty clay from Road III-Sut-232-A (Fig. 17) with a field moisture content slightly above the plastic limit. Current studies on more sensitive clays should provide useful information as to the feasibility and duration of a curing period for recompacted clay specimens.

The mechanics of pavement deflection and soil resilience are complex and will be the subject of a great deal of research in the coming years. The problems involved in introducing these new factors into these design equations have, therefore, been approached in a very direct and admittedly empirical manner. The primary objective of this investigation has been to evaluate each element of the structural section with respect to its relative importance as a contributing factor in transient deflection and to relate this data to field performance. Because the results of earlier investigations have made it clear that the top two or three feet of flexible pavement structural section contributes over 80 percent of the measured transient deflection, a great deal of emphasis must necessarily be placed on the resilient characteristics of the base and subbase although granular materials have not heretofore been the subject of investigations involving dynamic loading. Certainly, if we can assume that the theoretical equations of distribution of vertical pressure with depth are valid, the importance of these materials is undeniable. If, at a given pressure the resilient displacement of the gravel base is 1/6 that of a clay basement soil, certainly, it is equal in importance considering that it is subject to at least six times the vertical pressure of the basement material.

In arriving at a relationship between field deflection and laboratory resilience, certain compromises with theory have been necessary. The utilization of the theoretical pressure depth relationship though not entirely applicable in stratified soils has been shown by field performance, to be of sufficient accuracy, so that its application could be made conveniently with reasonable confidence.

In utilizing the deflection resilience relationship for design, however, other factors are involved which may make greater refinement of the pressure depth relationship unproductive. For example, it is necessary to establish a "design" moisture content and density. The choice of these variables, of course, will clearly influence the predicted deflection since the laboratory resilience test is particularly sensitive with respect to these factors.

The writers would like to point out that the resilience or compression rebound characteristics of a given soil at the range of pressures employed reflect a state rather than an inherent characteristic of the soil. Certainly, the elastic property of the individual soil particle remains constant, however, the percentage of voids, air permeability and water content are subject to wide variations. For this reason, it is believed that the resilience test as it is now employed is more an indicator of the degree to which void spaces may be compressed and relaxed rather than a measure of the elastic property of the given soil particles. With this in mind the results or predicted deflection for a proposed structural section should be viewed as an indication of the highest deflection a roadway would undergo in its design life. Deflections would tend to diminish as the roadway aged due to the increased slab strength of the surfacing as the bituminous binder hardened and the gradual gain of strength of embankment soils under repeated light loadings. This would assume, of course, that the surface remains uncracked so that surface runoff water would not be introduced into the structural section in large quantities.

Briefly Summarizing:

A program in which field deflection has been related to a laboratory measurement of soil resilience has been completed.

The results have established a sufficiently definable trend between these variables so that the relationship can be utilized for design purposes. An example is given.

The procedure set forth places primary emphasis upon the evaluation of each element with respect to its relative importance as a contributor to the compression and rebound of the structural section as a whole.

At the present time a study is underway involving the use of remolded "sensitive" soils for design purposes. Of primary interest is the determination of the curing time interval required for the thixotropic gain of strength of the remolded specimens results in resilience characteristics approaching those of undisturbed specimens.

ACKNOWLEDGMENTS

The writers wish to acknowledge the contribution of the many individuals who have participated directly in the development of the Resiliometer or who have assisted by helpful advice and criticism, particularly, Joseph R. Santos, George Dick and Harold Munday.

The work of the Materials and Research Department librarian, Robert Anderson, in searching and organizing pertinent technical publications is also appreciated.

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(11) "Computation of Load Stresses in a Three-Layer Elastic System", W. E. A. Acum and L. Fox, Geo Technique, Vol. II, No. 4, December 1951, pp 293-300.

(12) State of California, Division of Highways Materials Manual, Testing and Control Procedures, Vol. I, Test Calif. No. 301 B.

(13) "Thixotropic Characteristics of Compacted Clays", H. B. Seed and C. K. Chan. Proceedings ASCE. Vol. 83, No. SM 4, November 1957, Paper 1427.

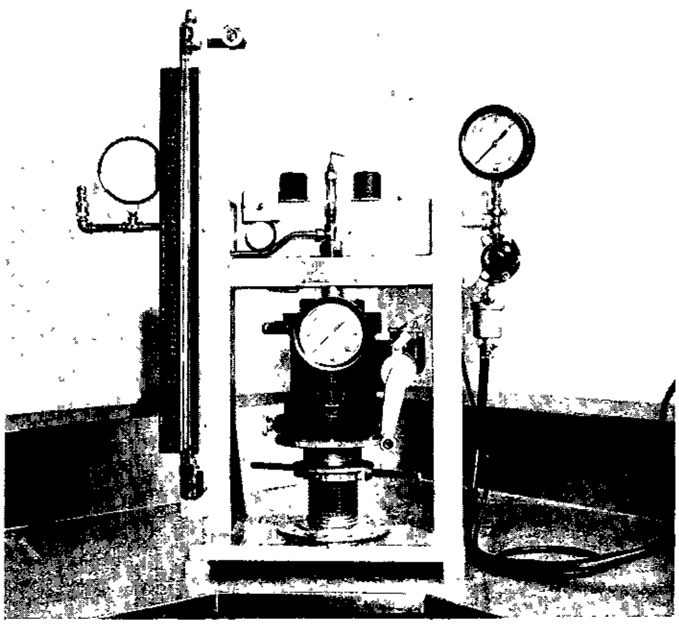


FIGURE 1

RESILIOMETER

Figure 2

TYPICAL RESILIENCE - PERCENT MOISTURE CURVES

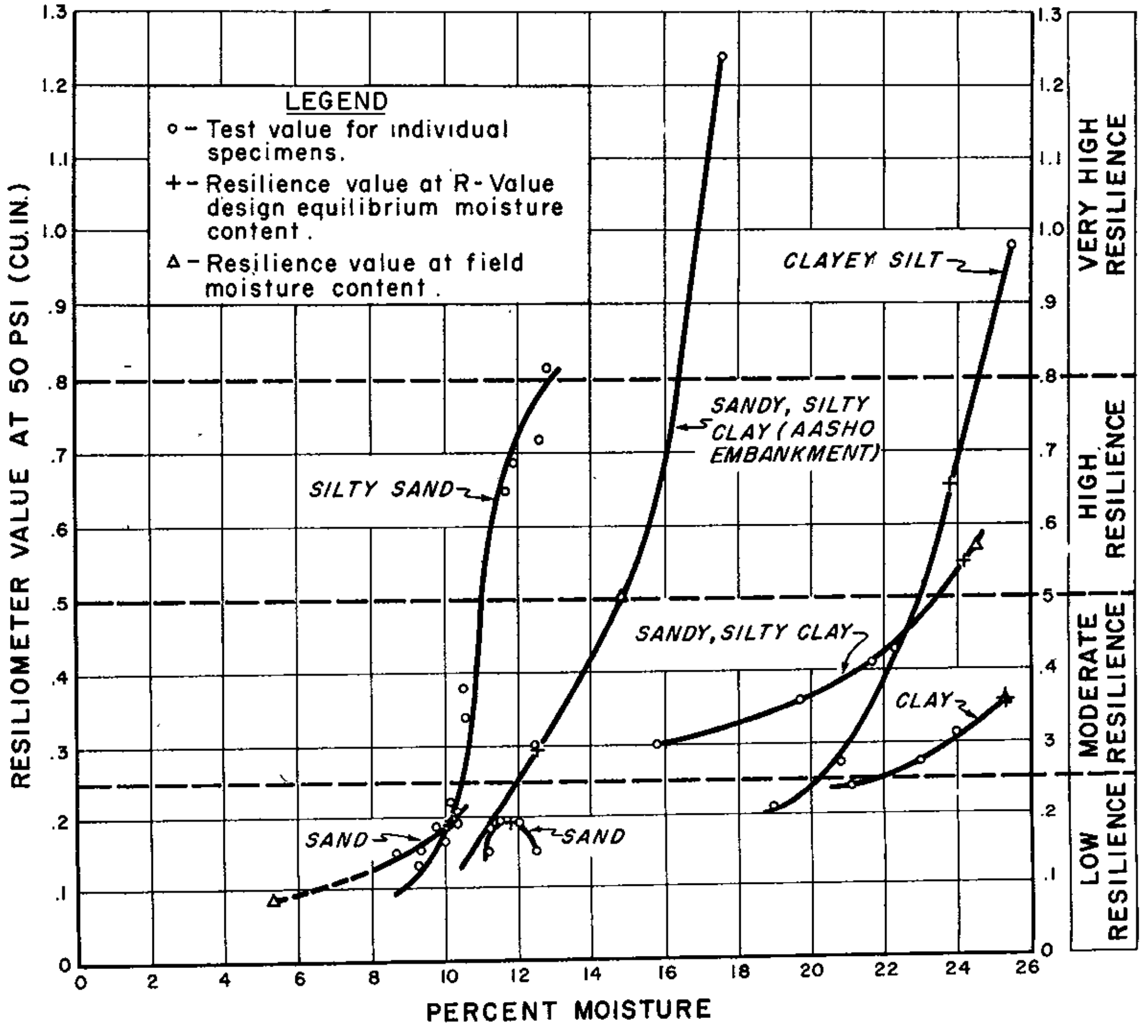
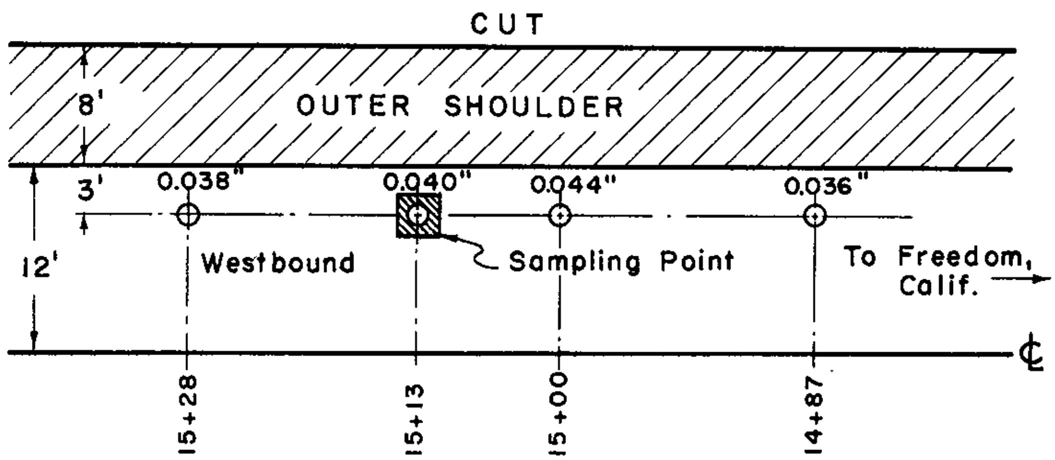


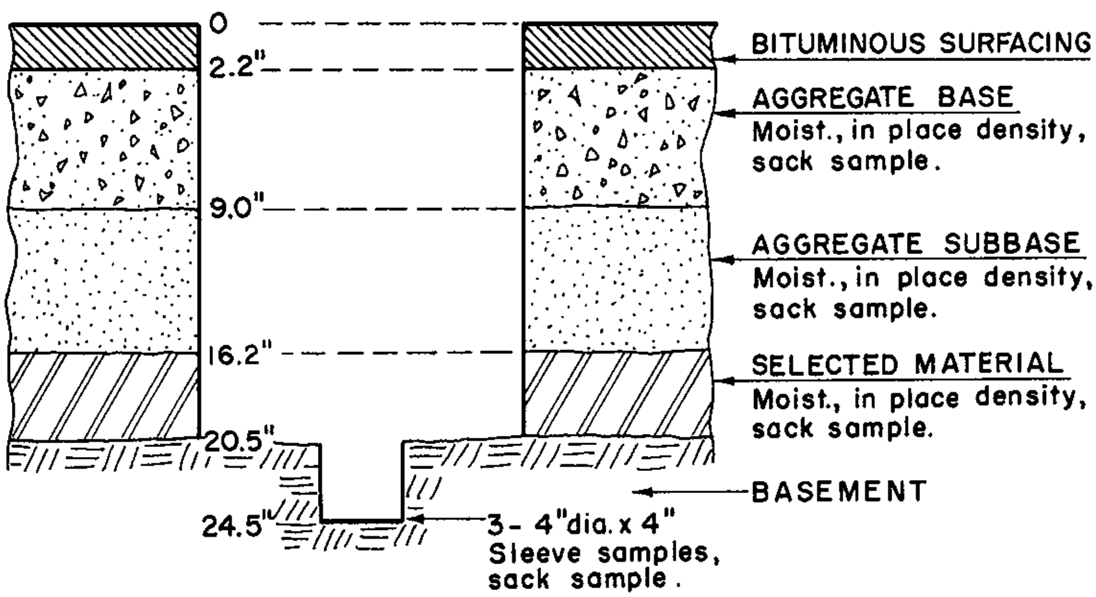
Figure 3

SAMPLE LOCATION AND DEFLECTION PATTERN

Road IV-SCR-FAS-1270



PLAN



SAMPLING DIAGRAM

Figure 4

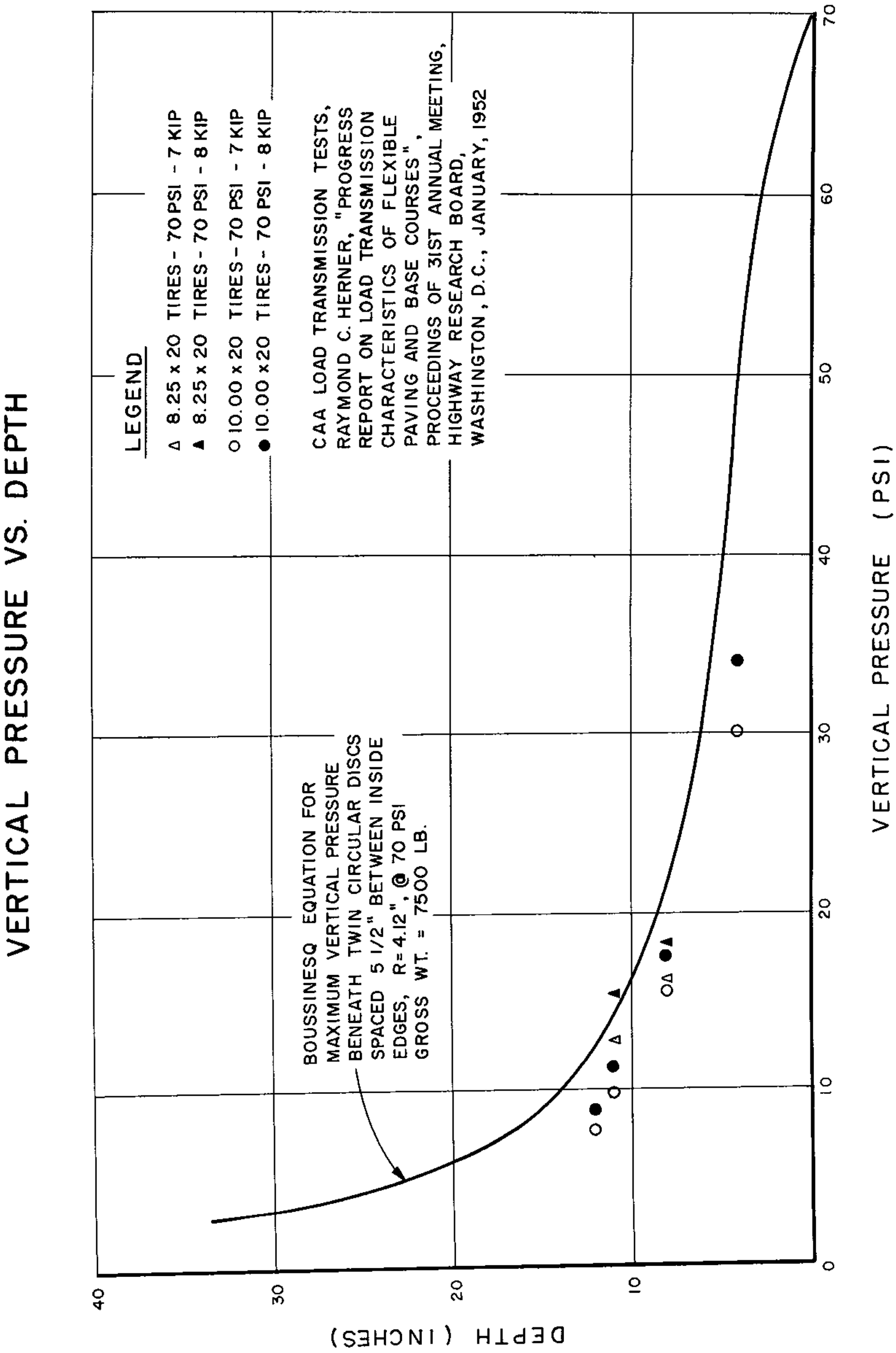

VERTICAL PRESSURE VS. DEPTH
LEGEND
△ 8.25 x 20 TIRES - 70 PSI - 7 KIP
▲ 8.25 x 20 TIRES - 70 PSI - 8 KIP
○ 10.00 x 20 TIRES - 70 PSI - 7 KIP
● 10.00 x 20 TIRES - 70 PSI - 8 KIP
CAA LOAD TRANSMISSION TESTS, RAYMOND C. HERNER, "PROGRESS REPORT ON LOAD TRANSMISSION CHARACTERISTICS OF FLEXIBLE PAVING AND BASE COURSES", PROCEEDINGS OF 31ST ANNUAL MEETING, HIGHWAY RESEARCH BOARD, WASHINGTON, D.C., JANUARY, 1952
BOUSSINESQ EQUATION FOR MAXIMUM VERTICAL PRESSURE BENEATH TWIN CIRCULAR DISCS SPACED 5 1/2" BETWEEN INSIDE EDGES, R= 4.12", @ 70 PSI GROSS WT. = 7500 LB.
0
10
20
30
40
50
60
70
VERTICAL PRESSURE (PSI)
10
20
30
40
DEPTH (INCHES)

Figure 4

VERTICAL PRESSURE VS. DEPTH

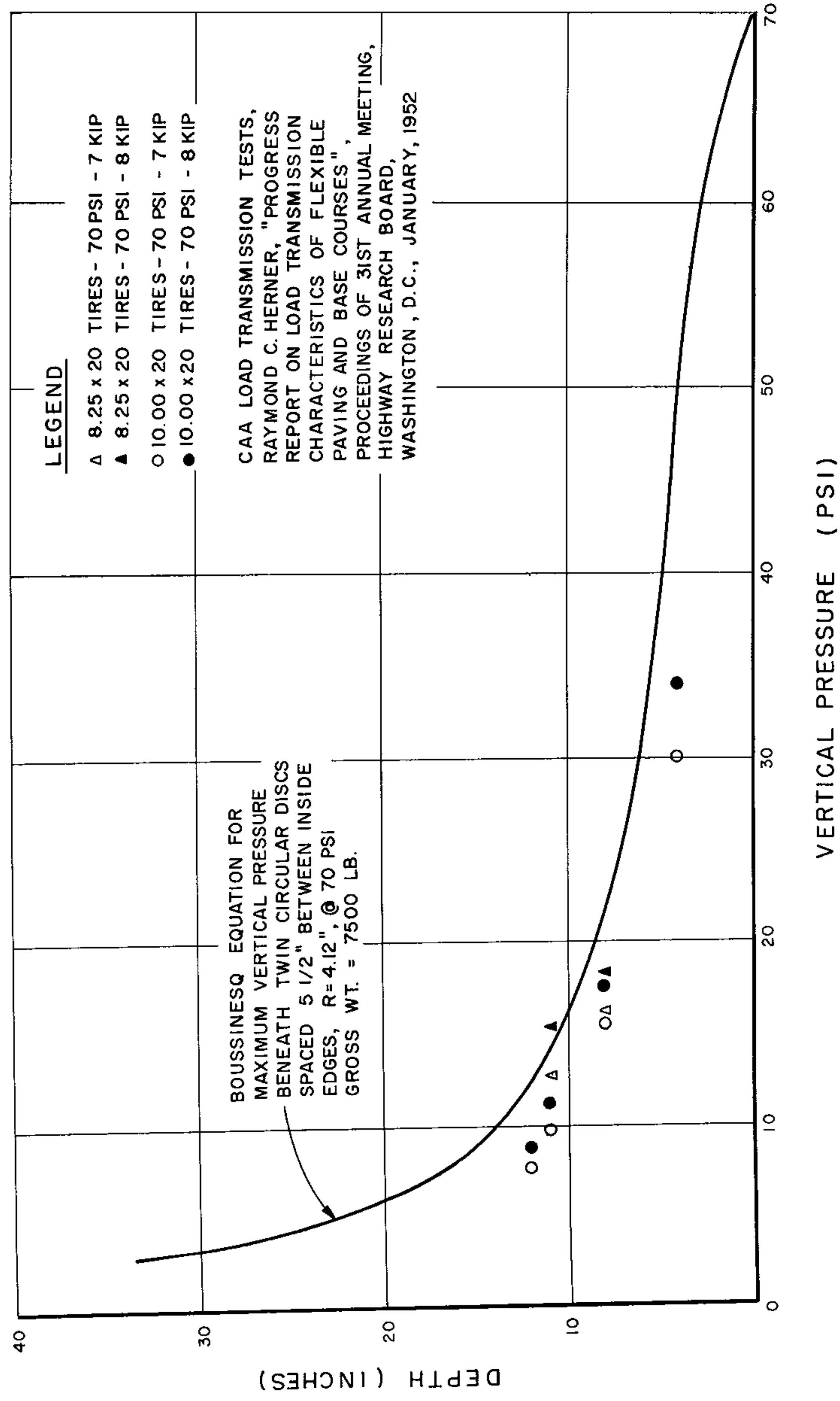


Figure 5

PAVEMENT DEFLECTION VS. AXLE LOAD
ROAD V-SLO-2-E

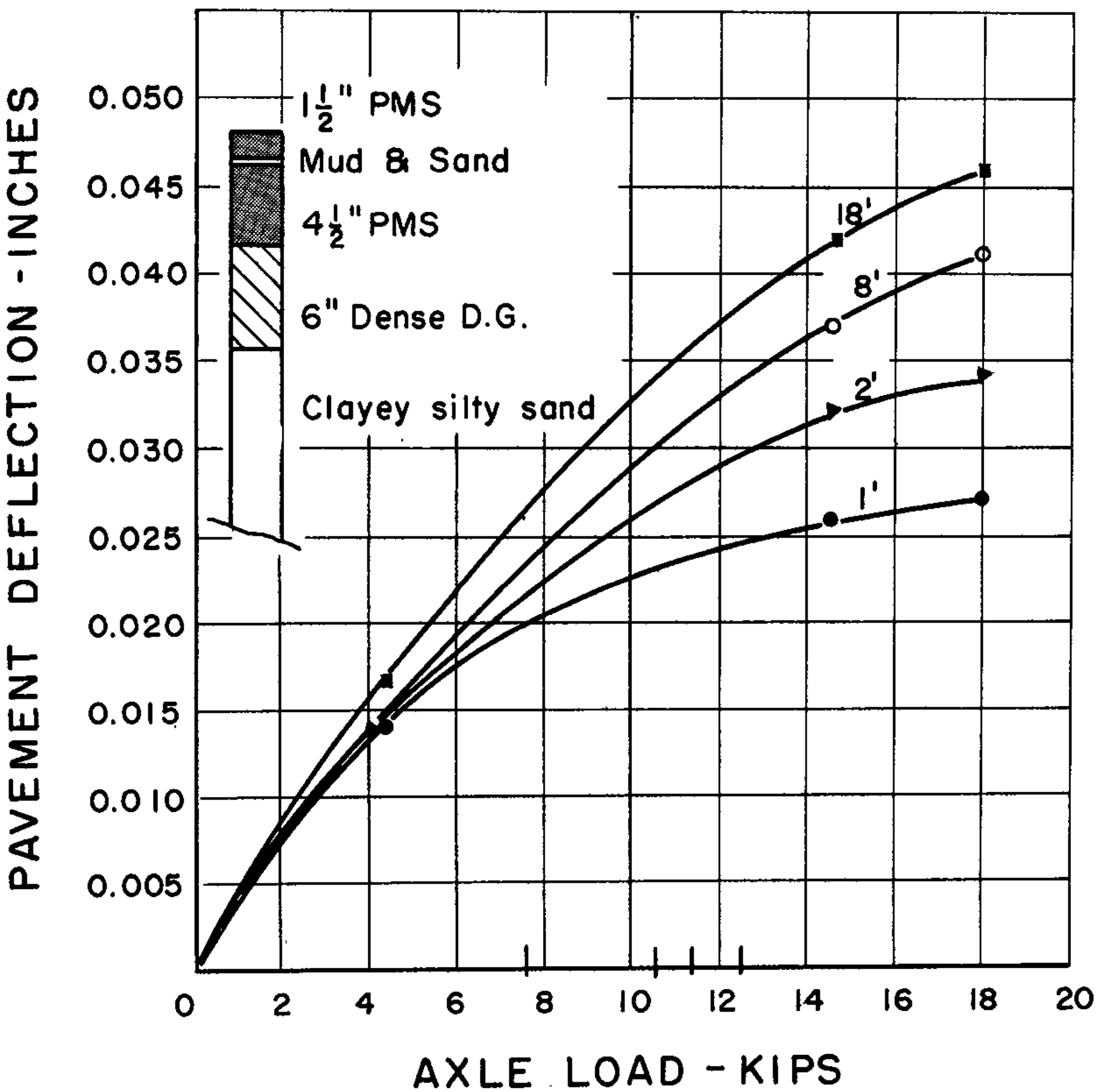


Figure 6

DEFLECTION - RESILIOMETER LOADING TRACE

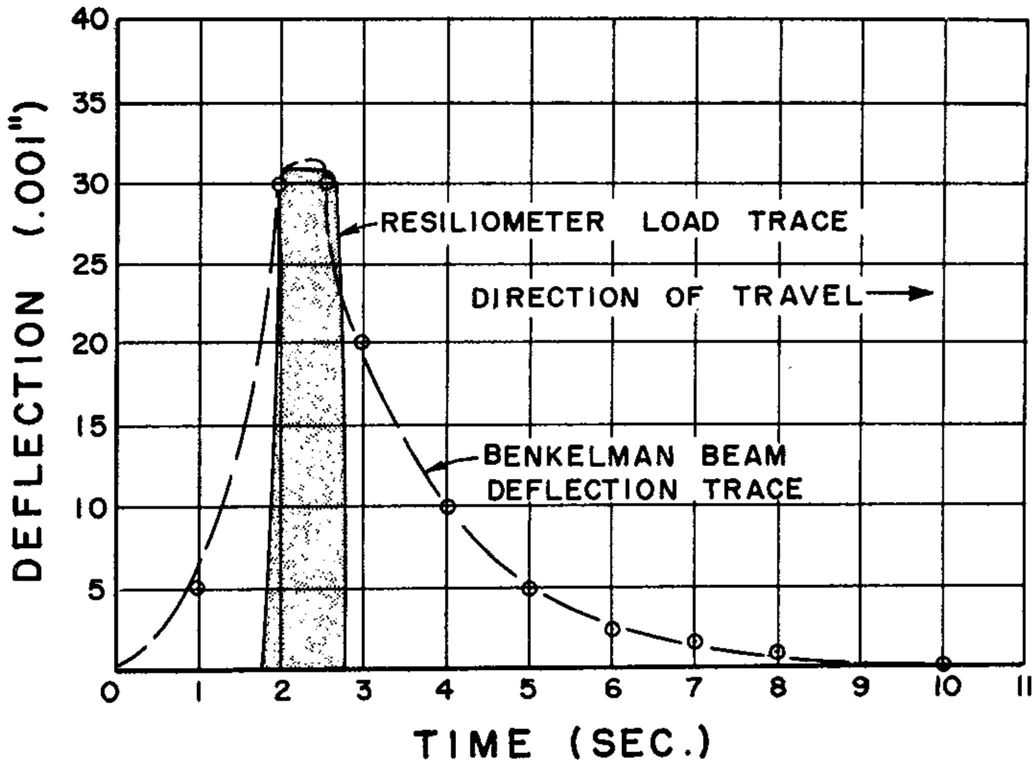


Figure 7

COMPRESSION AND REBOUND HISTORY
OF AN UNDISTURBED CLAY SPECIMEN

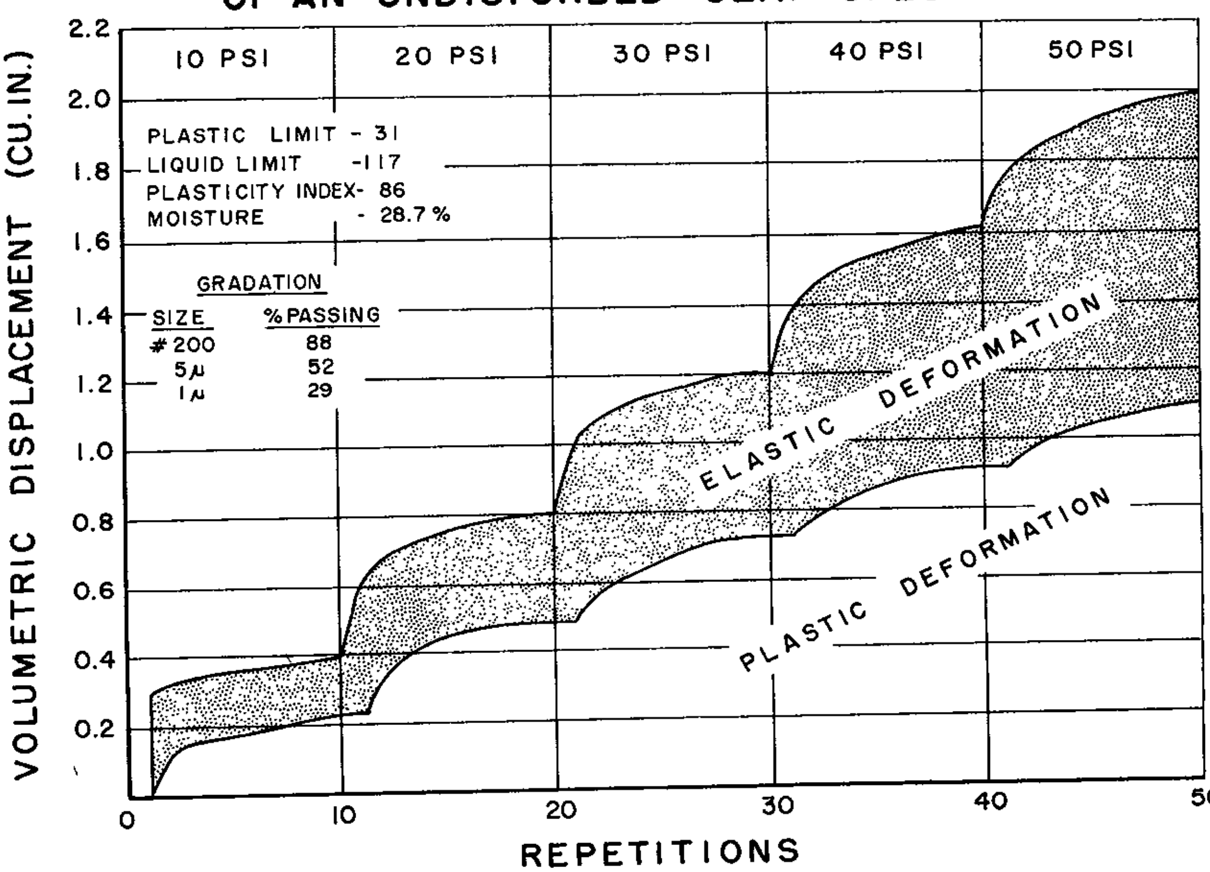
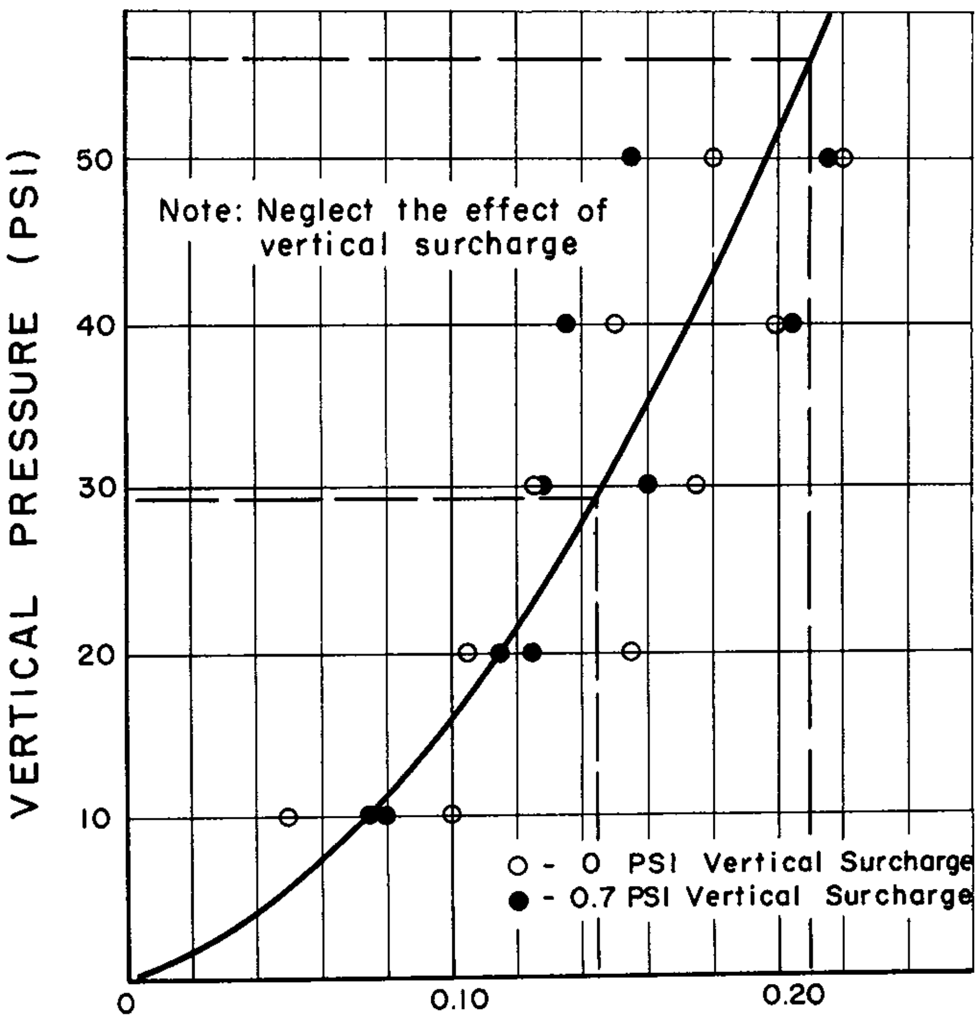


Figure 8

PRESSURE-RESILIENCE PLOT OF AGGREGATE BASE

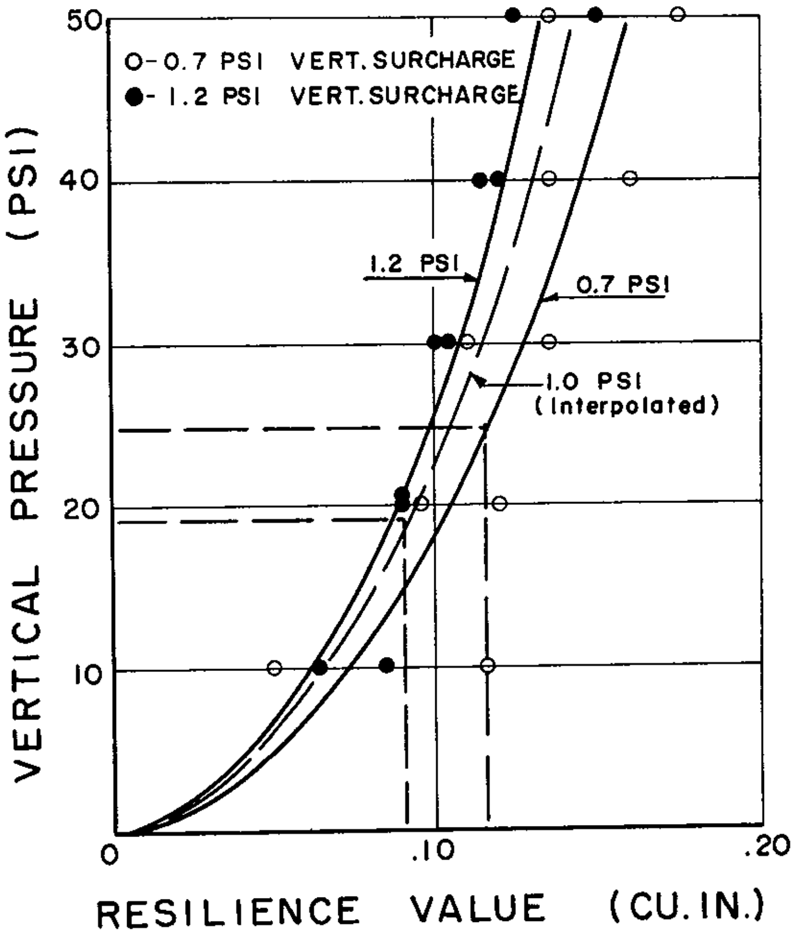
ROAD IV-SCR-FAS-1270



DEPTH (IN.)	AV. PRESSURE (PSI)	RESILIENCE VALUE (CU. IN.)
2.2 - 6.2	46.2 + 10	0.21
6.2 - 9.0	19.1 + 10	$0.14 \times \frac{2.8}{4} = 0.10$
	TOTAL	0.31 CU. IN.

Figure 9

PRESSURE-RESILIENCE PLOT OF AGGREGATE SUBBASE ROAD IV-SCR-FAS-1270



DEPTH (IN.)	AV. PRESSURE (PSI)	VERT. SURCHARGE (PSI)	RESILIENCE VALUE (CU. IN.)
9.0 - 13.0	14.9 + 10	0.7	0.115
13.0 - 16.2	9.6 + 10	1.0	$0.09 \times \frac{3.2}{4} = 0.07$
		TOTAL	0.185 CU. IN.

Figure 10

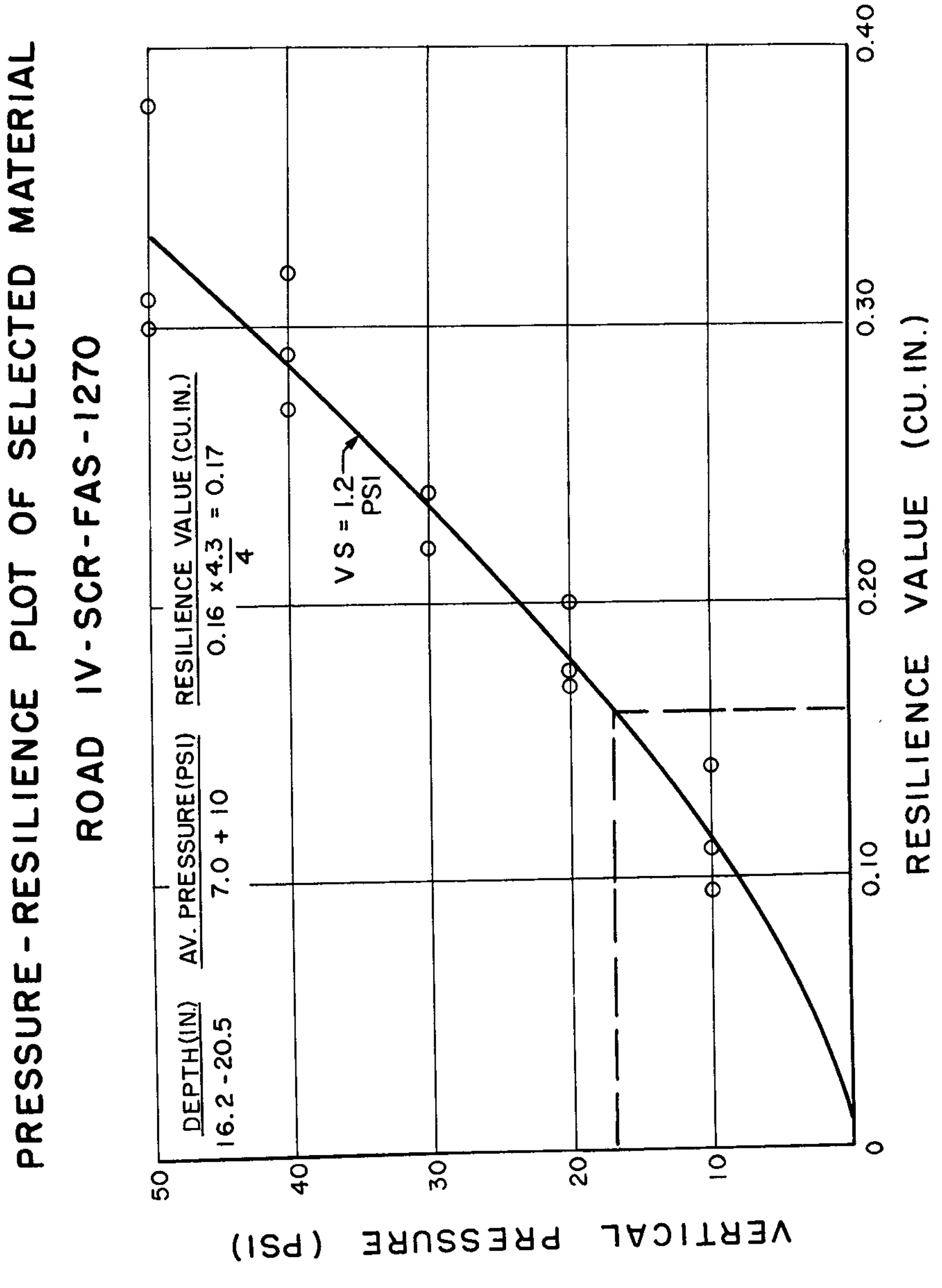
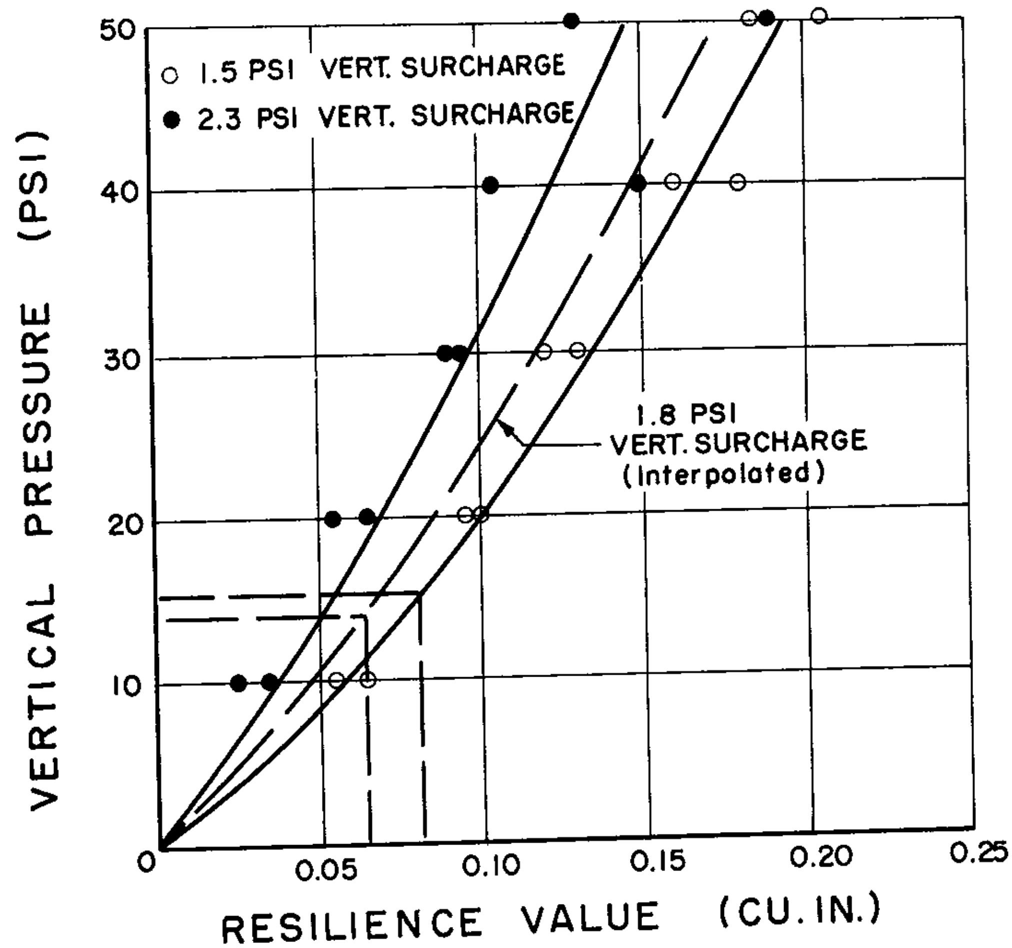

PRESSURE - RESILIENCE PLOT OF SELECTED MATERIAL
ROAD IV-SCR-FAS-1270
DEPTH (IN.)
16.2 - 20.5
AV. PRESSURE (PSI)
7.0 + 10
RESILIENCE VALUE (CU. IN.)
0.16 x 4.3 / 4 = 0.17
VS = 1.2 PSI
VERTICAL PRESSURE (PSI)
50
40
30
20
10
0
0.10
0.20
0.30
0.40
RESILIENCE VALUE (CU. IN.)

Figure 11

PRESSURE-RESILIENCE PLOT OF BASEMENT SOIL ROAD IV-SCR-FAS-1270



DEPTH - IN.	AV. PRESS.- PSI	VERT. SURCH.- PSI	RESIL. VALUE - CU. IN.
20.5 - 24.5	5.3 + 10	1.5	0.08
24.5 - 30	4.0 + 10	1.8	$0.65 \times \frac{5.5}{4} =$ 0.09
			TOTAL 0.17

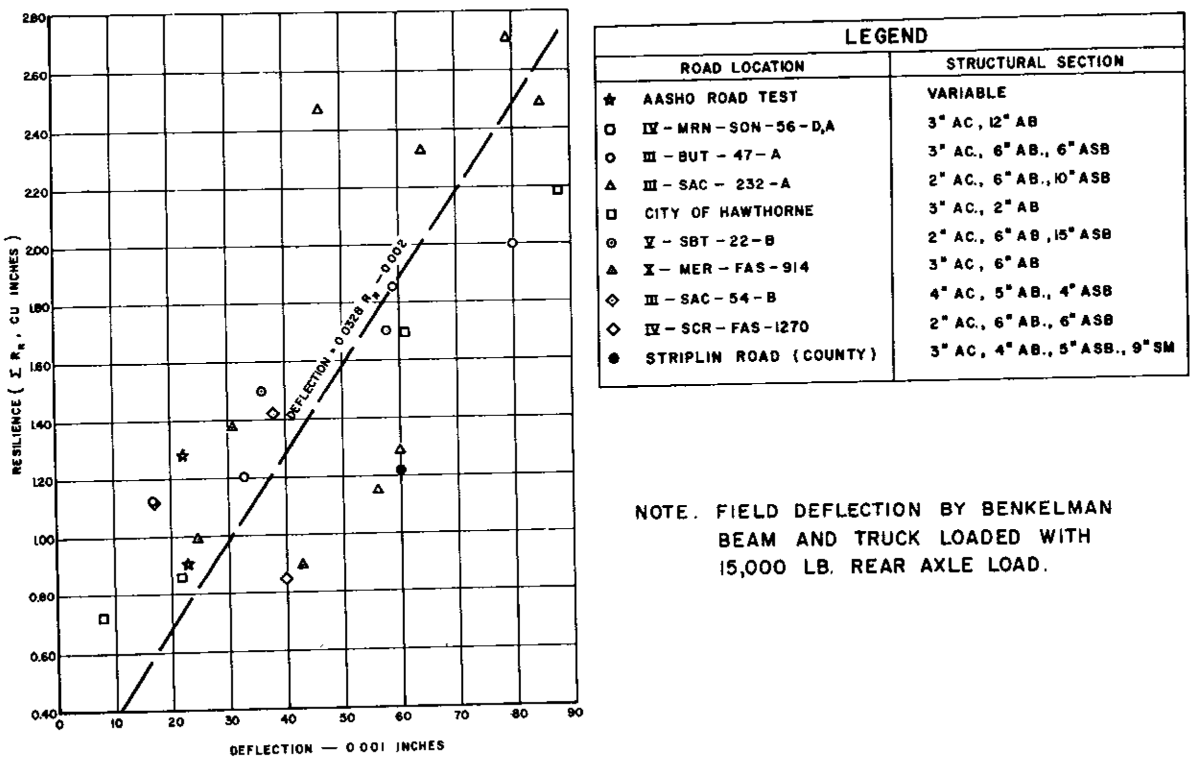
RECAPITULATION

MATERIAL	TOTAL RESILIENCE VALUE
AGGREGATE BASE	0.31
AGGREGATE SUBBASE	0.185
SELECTED MATERIAL	0.17
BASEMENT SOIL	0.17
GRAND TOTAL	0.84 CU. IN.

Figure 12

RESILIENCE SUMMARY VS FIELD DEFLECTION

25 INDIVIDUAL SAMPLES FROM 10 ROAD LOCATIONS

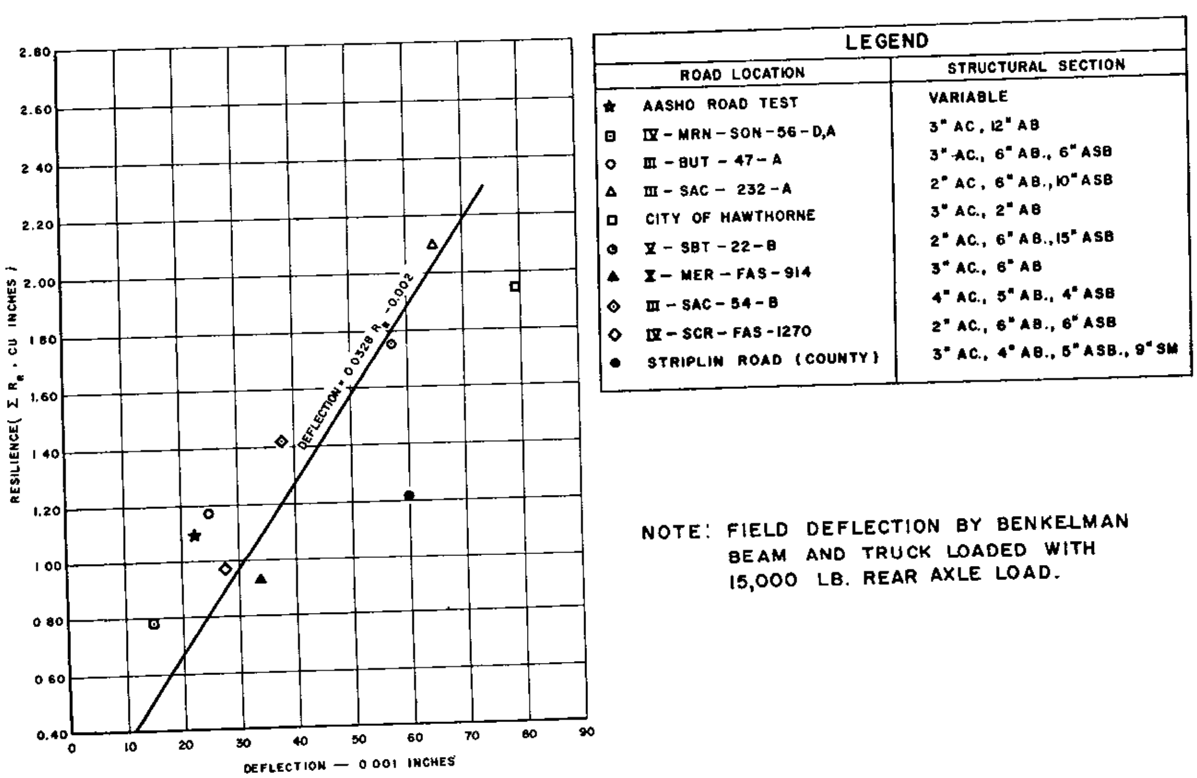


NOTE. FIELD DEFLECTION BY BENKELMAN BEAM AND TRUCK LOADED WITH 15,000 LB. REAR AXLE LOAD.

Figure 13

RESILIENCE SUMMARY VS FIELD DEFLECTION

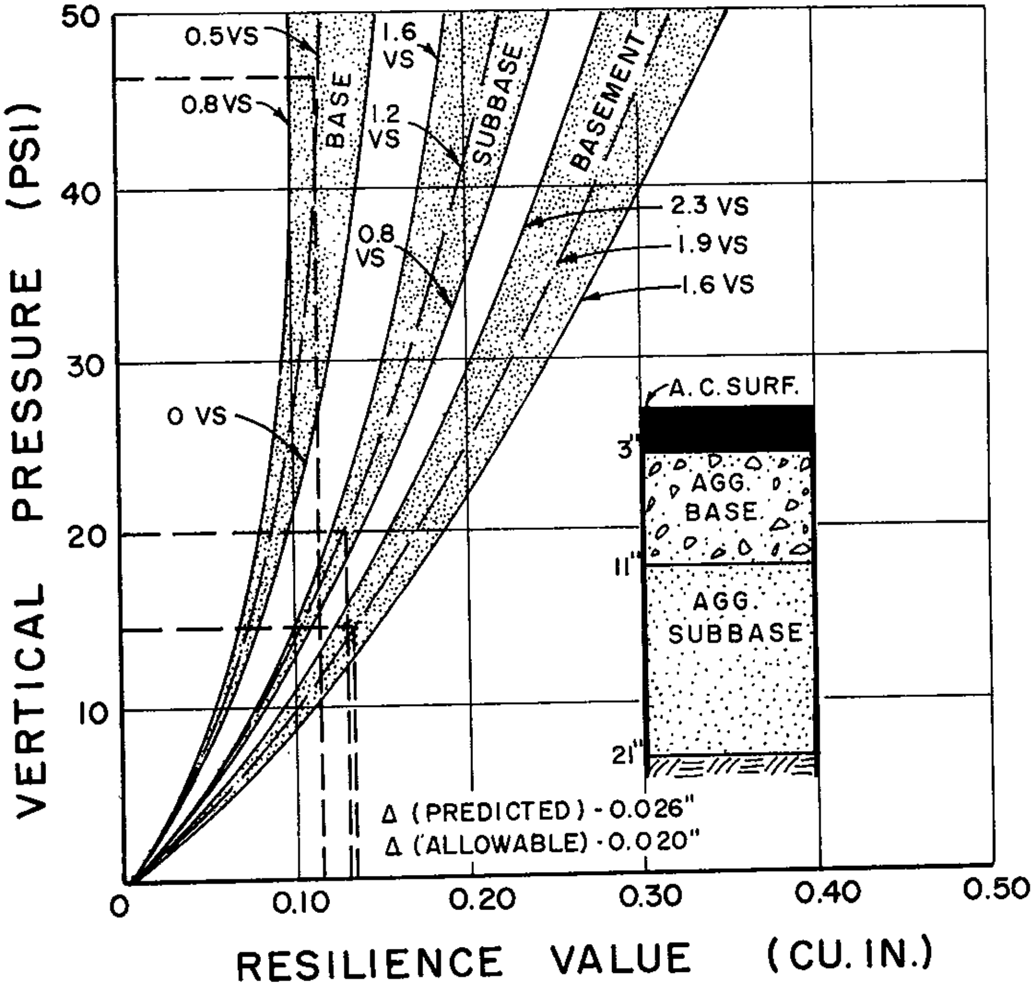
AVERAGE OF SAMPLES FROM 10 ROAD LOCATIONS



NOTE: FIELD DEFLECTION BY BENKELMAN BEAM AND TRUCK LOADED WITH 15,000 LB. REAR AXLE LOAD.

Figure 14

DESIGN TRIAL NO. 1

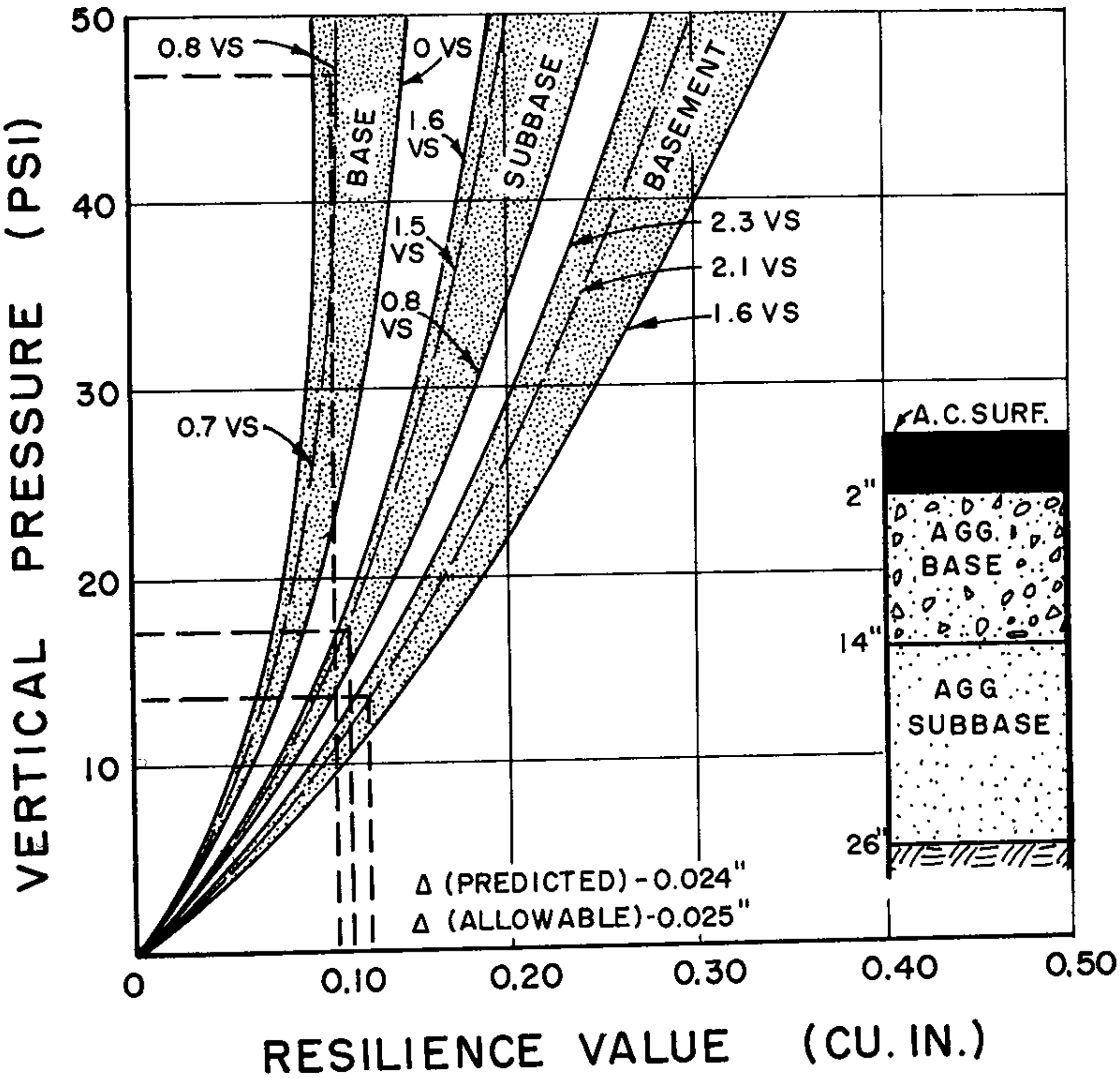


	DEPTH (IN.)	AV. PRESS. (PSI)	AV. V.S. (PSI)	RESIL. VALUE (CU. IN.)
BASE	3 - 11	36.4 + 10	0.5	0.115 x 8/4 = 0.23
SUBBASE	11 - 21	10 + 10	1.2	0.13 x 10/4 = 0.325
BASEMENT	21 - 30	4.6 + 10	1.9	0.135 x 9/4 = 0.305

TOTAL 0.86 CU. IN.

Figure 15

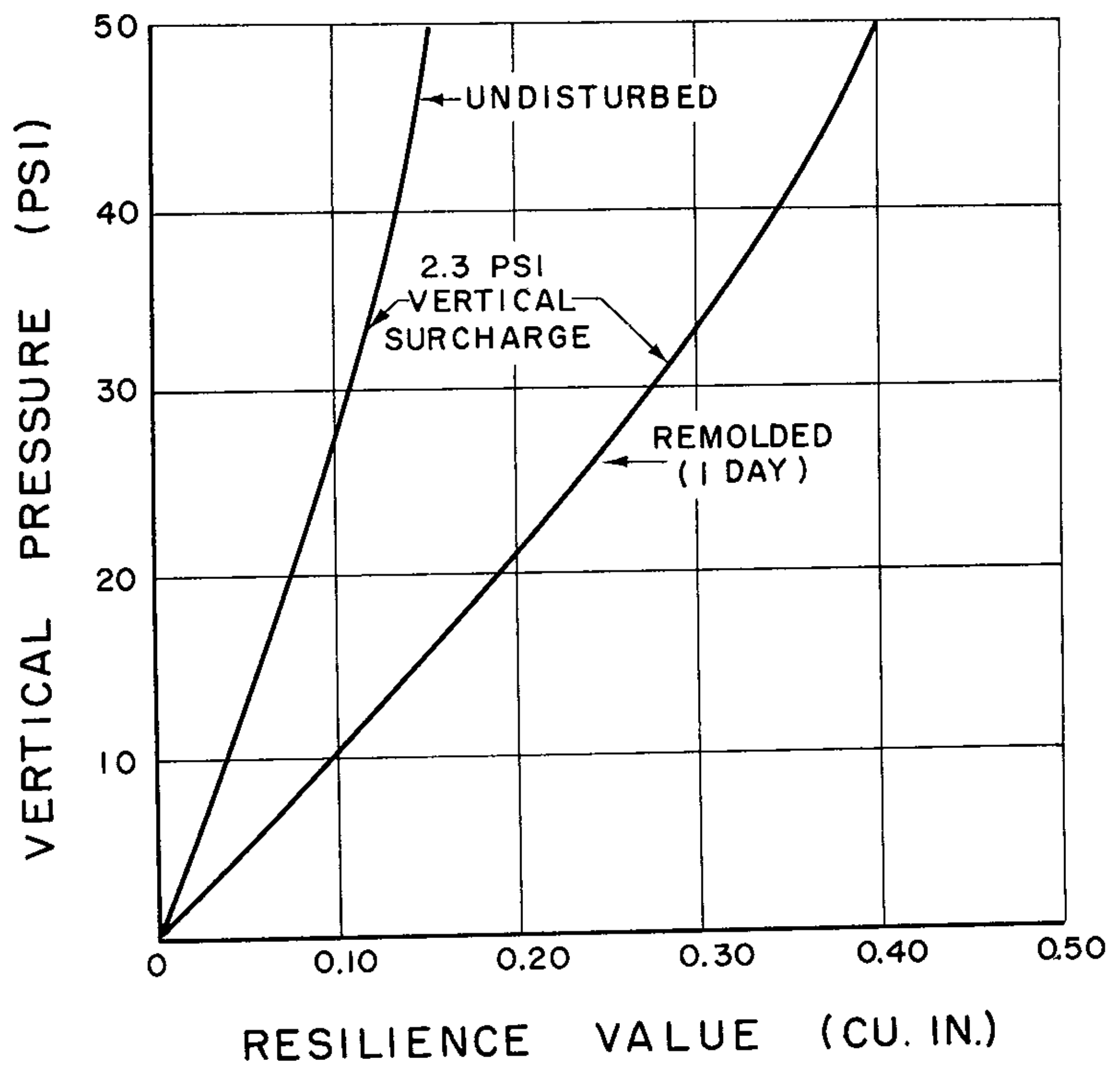
DESIGN TRIAL NO. 2



	DEPTH (IN.)	AV. PRESS (PSI)	AV. V.S. (PSI)	RESIL. VALUE (CU. IN.)
BASE	2 - 14	36.8 + 10	0.7	0.11 x 12/4 = 0.330
SUBBASE	14 - 26	7.1 + 10	1.5	0.115 x 12/4 = 0.345
BASEMENT	26 - 30	3.8 + 10	2.1	= 0.125
			TOTAL	0.800 CU. IN.

Figure 16

REMOLDED VS. UNDISTURBED RESILIENCE
AASHO EMBANKMENT MATERIAL



AASHO ROAD TEST

Sect. 828, Loop I

Moisture Content –

14.0 % Remolded

16.5 % Undisturbed

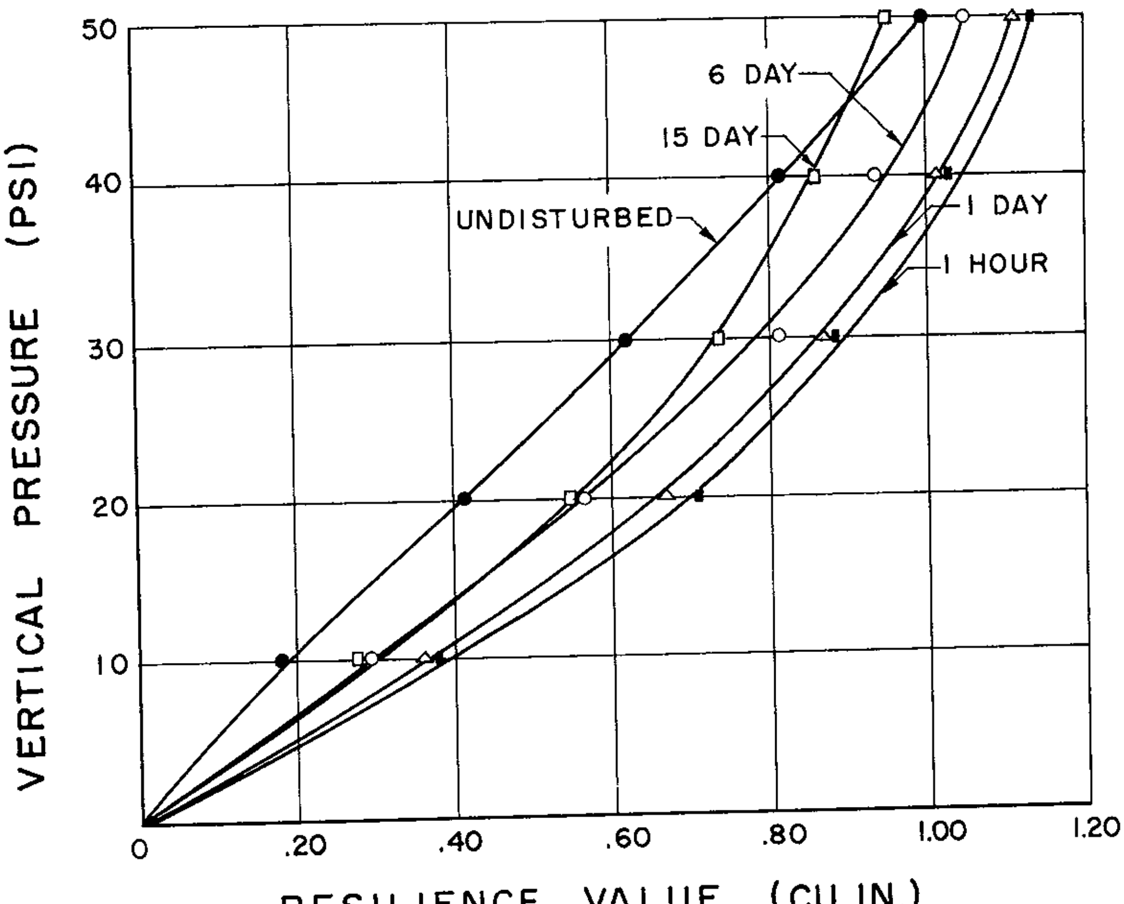
Liquid Limit - 31

Plastic Limit - 18

Plasticity Index - 13

Figure 17

EFFECT OF CURING ON THE RESILIENCE OF A REMOLDED SILTY CLAY



ROAD III - SUTT - 232 - A

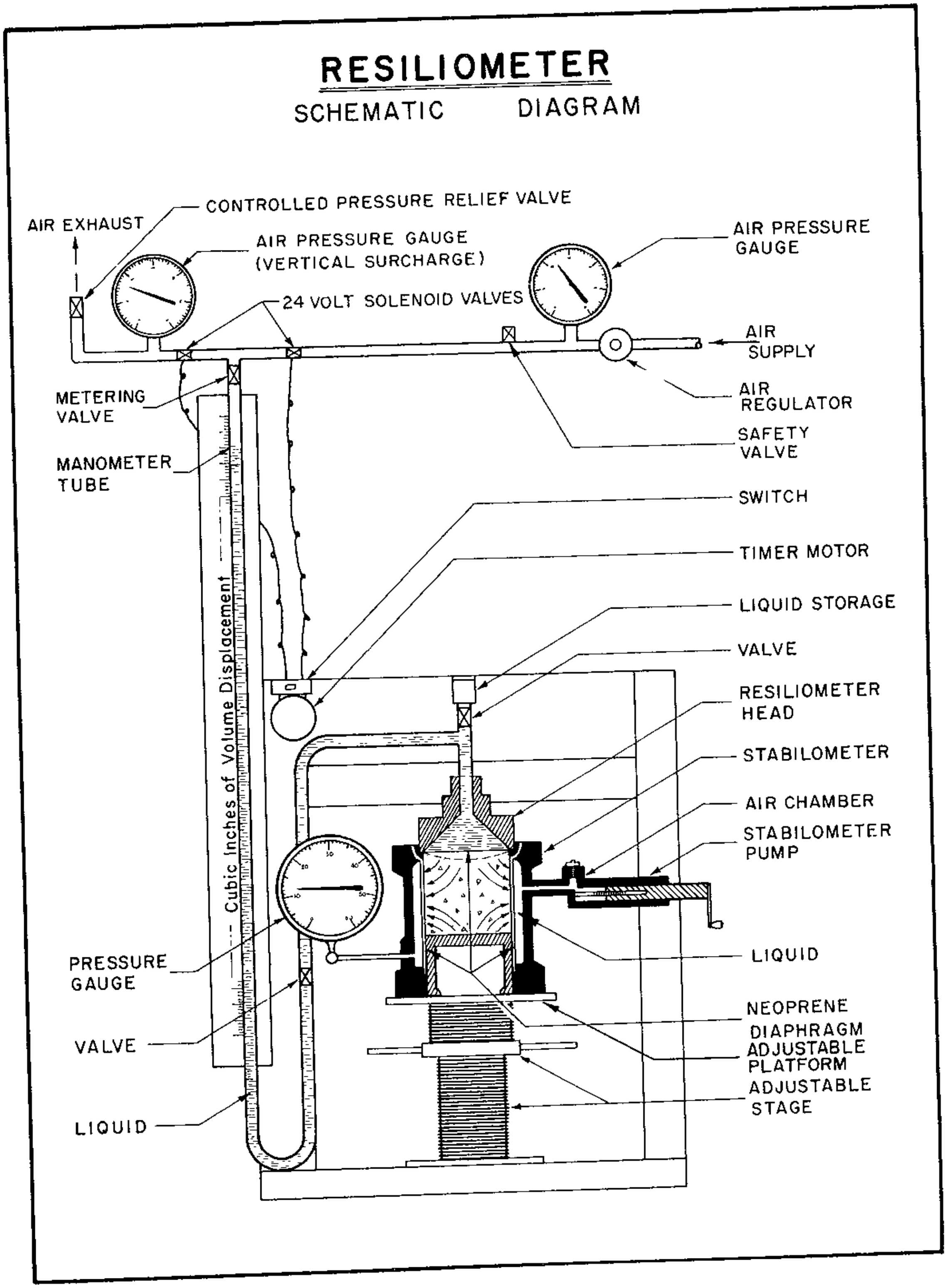
EMBANKMENT (CLAY)
VERTICAL SURCHARGE - 0
MOISTURE CONTENT - 20 %
DRY DENSITY - 103 P.C.F.

SAND EQUIVALENT - 11
LIQUID LIMIT - 32
PLASTIC LIMIT - 19
PLASTICITY INDEX - 13

GRADATION

PARTICLE SIZE	% PASSING
200	63
5 μ	34
1 μ	19

Figure 18


RESILIOMETER
SCHEMATIC DIAGRAM
AIR EXHAUST
CONTROLLED PRESSURE RELIEF VALVE
AIR PRESSURE GAUGE
(VERTICAL SURCHARGE)
24 VOLT SOLENOID VALVES
AIR PRESSURE
GAUGE
AIR
SUPPLY
AIR
REGULATOR
SAFETY
VALVE
METERING
VALVE
MANOMETER
TUBE
Cubic Inches of Volume Displacement
SWITCH
TIMER MOTOR
LIQUID STORAGE
VALVE
RESILIOMETER
HEAD
STABILOMETER
AIR CHAMBER
STABILOMETER
PUMP
LIQUID
PRESSURE
GAUGE
VALVE
NEOPRENE
DIAPHRAGM
ADJUSTABLE
PLATFORM
ADJUSTABLE
STAGE
LIQUID

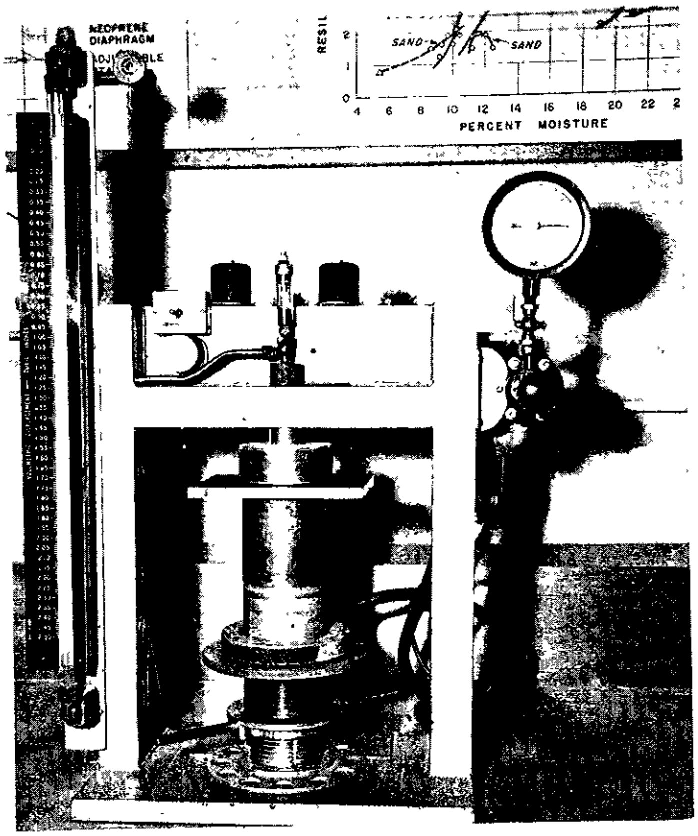


FIGURE 19

RESILIOMETER CALIBRATION

Figure 20

STATE OF CALIFORNIA
DEPARTMENT OF PUBLIC WORKS
DIVISION OF HIGHWAYS
MATERIALS & RESEARCH DEPARTMENT

Laboratory Record of
RESILIOMETER TESTS

Test No. 61-1441	Date Rec'd. 7-12-61		
Operator R. A. F.	Date Tested 7-14-61		
Cost Distribution: Class 35 R-	Category 3003	Auth.	
Contract 61-5TC21	Research No.		
Dist. V	Co. SLO	Rte 2	Sec. E
Limits of Work: Between 0.2 and 1.5 Mi. North of Shell Beach			

				5	6	7	8	9	10	11	12	
Specimen Number	Air Pressure P.S.I.	Tube Reading Upper cu. in	Tube Reading Lower cu in.	Corr. Factor cu. in.	Resiliometer Reading cu. in.	Horiz. Disp. cu. in.	Resiliometer Value cu. in.	Stab. Reading Lower P.S.I.	Stab. Reading Upper P.S.I.	Surf Corr Cubic in	Height Corr Cubic in	Remarks
A	10	0.04	0.12	.01	0.07	0.015	0.055	3.0	3.5	.0350	.035	Sandy Silt
	20	0.06	0.25	.02	0.17	0.045	0.125	3.0	4.5	.1050	.105	10.0% Moist at 300 PSI
	30	0.10	0.42	.03	0.29	0.06	0.23	3.0	5.0	.210	.205	Exudation Press.
	40	0.16	0.58	.04	0.41	0.085	0.325	3.0	6.0	.305	.300	0.02 cu. in, at 1.0#
	50	0.21	0.78	.05	0.52	0.110	0.41	3.0	7.0	.390	.38	(Surface Correction)
												Weight = 1650g
												Ht. = 4.10
A	10	0.22	0.30	.01	0.7	.015	.055	3.0	3.5	.025	.025	Dry Density = 101.5 P.C.F.
	20	0.23	0.41	.02	0.16	.045	.115	3.0	4.5	.085	.085	1.0 P.S.I. vert. Surcharge
	30	0.24	0.53	.03	.26	.06	.20	3.0	5.0	0.17	.165	
	40	0.25	0.66	.04	.37	0.10	.27	3.0	6.5	0.24	.235	
	50	0.25	0.75	.05	.45	0.12	.33	3.0	7.5	0.30	.295	
												Same
												2.0 PSI Vert. Surcharge
												0.03 cu. in. at 1#
												(Surface Correction)

FORM T-3036 (REV 7-61)

APPENDIX A

EQUIPMENT AND TEST METHOD

Description of Apparatus

The resiliometer is shown by Fig. 1 with a schematic representation of Fig. 18. During operation, air pressure is introduced to the surface of the manometer fluid (Ethylene Glycol Solution) in cycles of 7.5 seconds with full pressure applied to the fluid column for 0.75 sec. periods. Load cycles are automatically controlled by twin 24 volt solenoid valves.

The air surge acts through the manometer tube into the resiliometer head reservoir causing a volumetric penetration of the fluid, contained by a neoprene diaphragm into the soil specimen mounted in the stabilometer. The total volumetric displacement is obtained by subtracting the final from the initial manometer tube readings. The manometer tube is graduated in 1/100 cu. in. increments.

As vertical pressure is applied the soil specimen distorts laterally causing compression of the air in the stabilometer reservoir. The increase in horizontal pressure at this time is noted on the stabilometer pressure gage. This pressure can be converted to a lateral volumetric displacement by an application of Boyle's law. The difference between total displacement (from the manometer tube) and horizontal displacement is the net internal compression or resilience value.

The air exhaust is controlled by a spring loaded pop off valve, the adjustment of which permits the retention of a continuous vertical surcharge shown by an air pressure gage mounted above the valve.

Preparation of Test Specimens

Specimens 4 inches in dia. by 4 inches high are utilized in the test. Undisturbed samples are trimmed as closely as possible to plane surface at the ends and placed on the adjustable stage.

Laboratory compacted specimens to be utilized in design are compacted to 95% of maximum dry density at design (300 psi exudation) moisture content on the mechanical kneading compactor. Preliminary preparation of the material is the same as that shown in Test Method No. Calif. 301-B*. Design moisture content and maximum dry density are predetermined from R-value and compaction test (Test Method No. Calif. 216-C).

Test Procedure

Determination of Resiliometer Correction:

As shown by Figure 19, a steel plate on a 4 inch dia. steel specimen are placed on the adjustable stage and turned into position so that the steel plate bears snugly upon the resiliometer head. In this position, the top of the fluid column of the manometer tube should be opposite "0" on the graduated scale. Adjustment of the fluid column is made by introducing or removing fluid through the liquid storage reservoir.

Upon attainment of the proper fluid level in the manometer tube, the air regulating valve is turned to 10 psi indicated pressure on the air pressure gage and the electrical timing motor switch is turned on. The difference between the manometer tube reading at the beginning and end of the load cycle is entered in the appended data card under "correction factor". This procedure is repeated for 20, 30, 40 and 50 psi pressures.

The correction herein obtained reflects the compression and rebound inherent in the adjustable stage plus compression of any air trapped in the manometer tube. A correction greater than 0.05 cu. in. at 50 psi indicates an excess of trapped air which should be removed by opening the liquid storage chamber and manipulating the resiliometer diaphragm.

Refer to Method No. Calif. 902 for details on the mechanics of the Hveem Stabilometer including its operation, calibration, and installation of neoprene diaphragm.

With a 4 inch compacted specimen on the adjustable stage platform, carefully place the stabilometer into position. Care should be taken so as not to damage the edges of the specimen. Adjust the stage platform

*Materials Manual, Testing and Control Procedures, Vol. 1.

until the top of the specimen is level with shelf of the stabilometer joint ring.

Raise the adjustable stage until the stabilometer joint ring shelf makes firm contact with the resiliometer head. Raise the horizontal pressure reading on the stabilometer to 3 psi.

If the top of the manometer fluid column is not opposite "0", lower the stabilometer with the adjustable stage handle then raise or lower, as required, the stabilometer around the specimen with the adjustable platform. Again tighten the stabilometer against the resiliometer. Repeat this procedure until the top of the manometer fluid column is opposite "0" on the graduated scale.

Turn the air supply valve to 5 psi, turn switch to "on" position. As cyclic loads are applied to specimen, adjust the vertical surcharge pop off until the desired vertical surcharge is attained.

Set air pressure to 1.0 psi above vertical surcharge and note the volumetric displacement into the specimen. Enter this in the remarks column as shown by Figure 20. This is the surface correction which will be made in column 11 of the data card.

Set air pressure to 10 psi and note the upper and lower manometer tube readings. When the rebound reading is within 0.02 cu. in. of the initial reading record upper and lower tube readings for the succeeding cycle in columns 3 and 4. Record lower and upper stabilometer reading in columns 9 and 10.

Repeat this procedure for air pressures of 20, 30, 40 and 50 psi.

Test Data Reduction

A typical test data card is shown by Figure 20. The top and bottom groupings were run at 1.0 and 2.0 psi vertical surcharge respectively. The specimen height, weight, moisture content, dry density, and surface correction are entered in the "remarks" column.

In the first grouping (1.0 psi vertical surcharge) at 10 psi air pressure, the upper and lower tube readings were 0.04 and 0.12 cu. in. Subtracting the correction factor (0.01 cu. in. in column 5) the difference equals 0.07 cu. in (column 6). The horizontal displacement resulting from a horizontal pressure differential of 0.5 psi (columns 9 and 10) equals 0.015 cu. in. (column 7).

The difference between columns 6 and 7 equals the net internal compression and rebound, i.e., the "resiliometer value" in column 8 (0.055 cu. in.).

From the resiliometer value, the surface correction of 0.02 cu. in. is subtracted resulting in a corrected resiliometer value of 0.035 in column 11.

Since the specimen was 4.10 in. in height. a height correction of $\frac{4.0}{4.10}$ x the figure in colume 11 is placed in column 12.

This computation is repeated for the remaining pressure increments for both vertical surcharges.

A plot of the corrected resilience value from column 12 vs. vertical pressure is used for design or correlation computations, as shown on Figures 14 and 15.

As shown by the preceding examples on correlation and design, the resilience data for each element of the structural section is totaled and the final resilience summation is used in conjunction with the correlation plot (Figure 12) to predict a deflection for the proposed structural section.