OVERLAY DESIGN USING DEFLECTIONS

George B. Sherman and Joseph B. Hannon, California Division of Highways

This paper presents a summary of the pavement deflection measuring experience of the California Division of Highways. These measurements provide a means of determining in-place roadway strength under existing conditions. The California traveling deflectometer with a 15-kip test load is described as the standard deflection measuring device. Measurements obtained with this device are compared to those produced by the procedure of the Canadian Good Roads Association or the Benkelman beam rebound procedure using an 18-kip load. Correlation data are presented for follow-up to deflection results obtained on projects reconstructed based on deflection studies. The various factors that influence a particular design selection are described and shown in a schematic chart. As a result of a recent study, a relationship between Benkelman beam deflection under a 15-kip loading and subgrade modulus, K-value, is presented. A procedure is suggested, based on these criteria, to determine PCC overlay thickness design.

The design of roadway structural sections is frequently based on the most severe environmental conditions that a particular pavement might possibly encounter during its design life. Environmental conditions are not consistently predictable for all geographic areas or for all portions of any one individual project. As a result some structural sections never experience as severe a condition as they were designed for. On the other hand some experience conditions that are more severe.

Because of the variation of conditions throughout a given stretch of road, the evaluation of an existing bituminous pavement for purposes of determining structural upgrading is best accomplished by an in situ type of measurement of the pavement structural strength under actual field conditions. The California Division of Highways and many other agencies have found that transient pavement deflection measurements are a reliable means to obtain such evaluation strength.

Pavement deflections can be used to determine the nature and extent of reconstruction for an existing distressed roadway. However, we have not as yet found a reliable method for using deflections to determine when maintenance will be required. Many roadways continue to provide satisfactory service with only minor losses in riding quality even though the surfacing is cracked or exhibits distress. A pavement rating system based on riding quality is therefore necessary to determine when a particular roadway requires major maintenance or complete reconstruction. The Maintenance Department of the California Division of Highways is presently developing such a rating system. This program, if incorporated with pavement deflection measurements, could assist in planning and budgeting future reconstruction of existing facilities.

Sponsored by Committee on Design of Composite Pavements and Structural Overlays.

PAVEMENT DEFLECTION MEASUREMENTS IN CALIFORNIA

Pavement deflection measuring experience by the California Division of Highways dates back to 1938 (1). The earliest device used for measuring pavement deflection was the General Electric travel gage. These instruments were installed on various California highways as early as 1938 and on the Brighton test track in 1940 and later during World War II on the Stockton test track. The installation of these units required the drilling of 5-in. diameter holes through the pavement surface and the insertion of rods to depths of up to 18 ft into the pavement section. Through installations at various depths it was possible to measure not only the total deflection but also the compression contributed by each element of the structural section. It was found that pavement deflection could be measured up to depths of about 21 ft. However, most of the deflection occurred in the top 3 ft of the structural section. This type of gage installation was rather expensive because of the time consumed in installation.

Because the use of General Electric travel gage units were expensive from an installation standpoint and relatively few measurements could be made per day, a more sophisticated device was needed. During the WASHO Road Test an improved version of this device, the linear variable deferential transformer (LVDT), was used but difficulties were encountered in maintaining calibration. As a result, a new instrument was developed by A. C. Benkelman during the WASHO study. This device, known as the Benkelman beam, is manually operated and works on a simple lever-arm principle.

In 1954 the California Division of Highways began using the Benkelman beam, which greatly simplified the task of measuring pavement deflections under wheel loadings. An automatic deflection measuring device known as the California traveling deflectometer was later developed by the Materials and Research Department and put into operation in 1960. A newer version was introduced in 1967 and is shown in Figure 1.

The deflectometer is based on the Benkelman beam principle. It combines a truck-trailer unit that carries a 15,000-lb single-axle load on the rear tires and a carriage to support probes for measuring pavement deflection under both wheels simultaneously.

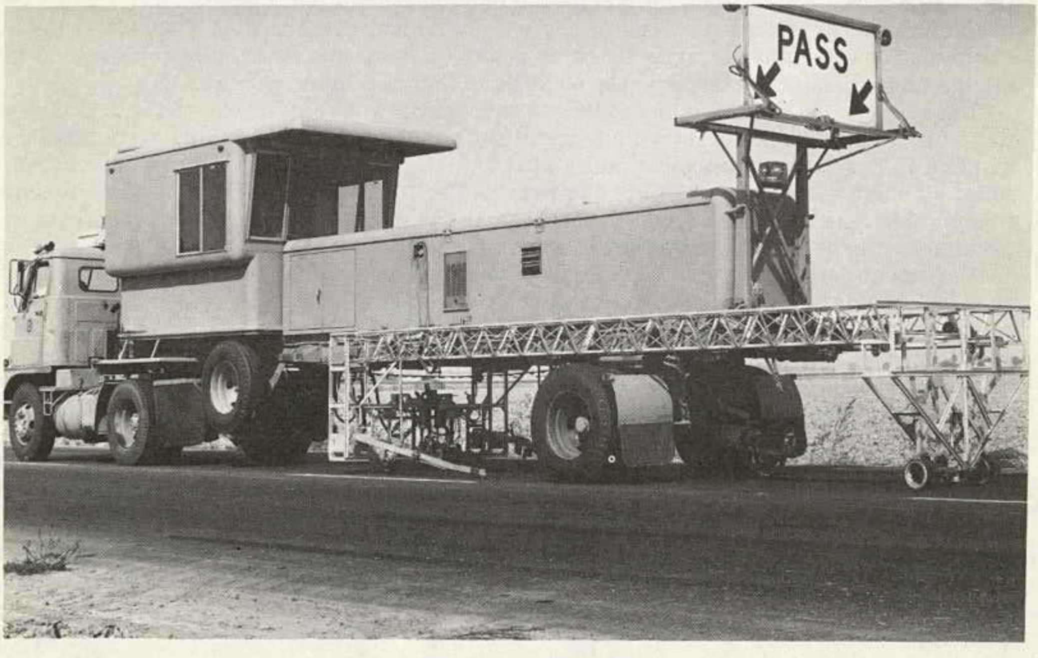

Figure 1. California traveling deflectometer.

It is an electromechanical instrument that measures pavement deflections at 20-ft intervals while the vehicle moves steadily along the road at ½ mph. The deflections are measured to the nearest 0.001 in. by means of a probe arm resting on the pavement and are permanently recorded on chart paper. Between 1,500 and 2,000 individual deflection measurements are possible per day as opposed to about 300 measurements using the manually operated Benkelman beam.

Another device that is presently used by California is of commercial manufacture and is known as the Dynaflect. It is an electromechanical system for measuring the dynamic deflection of a roadway surface produced by an oscillatory load. The device consists of a dynamic force generator together with a motion-measuring instrument, a calibration unit, and 5 motion-sensing geophones mounted on a small trailer. The trailer in a stopped position exerts a 1,000-lb, peak-to-peak, 8-cps oscillatory load onto the pavement surface through 2 rigid test wheels. The resulting amplitude of pavement deflection is picked up by the geophones and read as a deflection measurement on a meter located in the tow vehicle. Approximately 600 individual deflection measurements are possible per day with this unit using 1 sensor.

This device has been used in California on deflection research and special investigation work during the past few years. An evaluation of the Dynaflect, which was reported in 1968 (2), presented a correlation between this device and the traveling deflectometer.

Another deflection measuring system of recent commercial manufacture, which is known as the Road Rater, has been subjected to a limited amount of evaluation by the California Division of Highways. Although of limited scope, this evaluation tends to indicate that this system has much promise. It operates on a principle similar to that of the Dynaflect but its operation is somewhat more flexible because the frequency of load application can be varied from 10 to 60 cps. There is a basic difference in the method of load application between the 2 devices. The Road Rater loading is applied through 2 pads attached to a steel plate, whereas the Dynaflect utilizes 2 steel test wheels.

The traveling deflectometer measurement produced by a 15,000-lb single-axle, dual wheel load has been adopted as a standard for use by the California Division of Highways. All other measuring systems have been related to this device. Many other states and agencies utilize the Benkelman beam rebound or Canadian Good Roads Association (CGRA) procedure using an 18,000-lb single-axle, dual wheel load. However, we feel that the dynamic type of measurement provided by the traveling deflectometer is more representative of the detrimental effects of repetitive wheel loading. It was found during early studies (3) that a static or standing type of load deflection was generally of higher magnitude than that produced by dynamic transient type of traffic loading.

From deflection data collected in 1969 in the San Diego Experimental Base Project on Sweetwater Road in San Diego County, Kingham presents a correlation between the California traveling deflectometer and the CGRA-Benkelman beam rebound procedure (4). This produced a line of best fit, $Y = 0.004 + 0.52X$, where Y = traveling deflectometer deflection (in.) under a 15-kip load, and X = CGRA rebound deflection (in.) under an 18-kip load. This formula is based on the first model of the deflectometer, which has since been replaced. The latest model of the deflectometer (Fig. 1) was used in a similar correlation with slight modification and is shown in Figure 2. This relationship produced a line of best fit, $Y = -0.002 + 0.52X$. The coefficient of correlation, R, was 0.905. The relationship of this correlation to the correlation work done by Kingham in terms of data obtained by our first deflectometer model can be explained by the equation $X_1 = 1.1Y - 0.0035$, where X_1 = deflection in terms of the first deflectometer (in.), and Y = deflection in terms of the new deflectometer (in.). The slight variation in the 2 systems is the result of different tire sizes and pressures.

DEVELOPMENT OF OVERLAY DESIGN METHOD

To effectively utilize deflection measurements, it was found necessary to relate the magnitude of pavement deflection to pavement performance. This is not possible

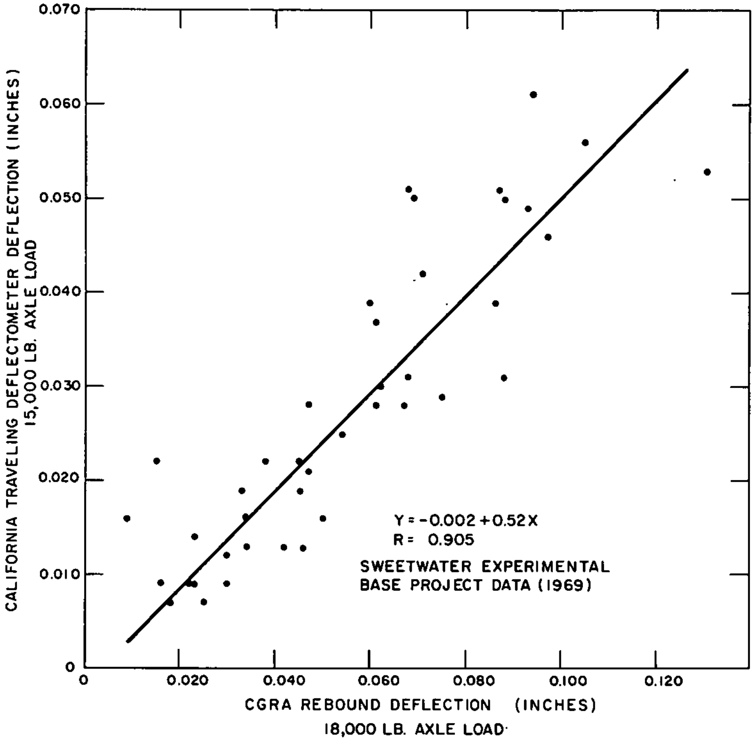

Figure 2. Comparison of deflections of deflectometer and CGRA rebound.

through accelerated test track wheel loading because relatively short-duration testing does not permit the average asphalt concrete (AC) surfacing to weather and harden. A reasonable tie between fatigue failure of AC surfacing and magnitude of transient deflection required the obtaining of deflection measurements over roadways that had been in operation for several years. This allowed the AC surfacing to reach a realistic or near critical state of hardness. In 1951 a comprehensive deflection research program was initiated by the Materials and Research Department to evaluate these relationships as a primary objective.

For this study General Electric travel gage units were installed on 43 projects throughout California. The test roadways included a wide variety of pavement structural sections because it was found earlier that thickness of AC surfacing was a prime variable. Installations were made on both cracked and uncracked pavements. The results of this study were reported in 1955 (3).

As a result of this study, a 15,000-lb single-axle loading was later established as a standard loading for use by the Materials and Research Department. Although the allowable maximum single-axle loading in California is 18,000 lb, the 15,000-lb loading more closely represents an average for the loaded axle portion of all trucks. Evaluation of data from this study also suggested maximum tolerable deflection levels for various pavement thicknesses. These values represented the highest levels of transient pavement deflection that a particular pavement thickness could be subjected to during its design life without developing fatigue cracking. The deflection criteria that were reported in 1955 provided the basis for further study because the roads that were investigated were main-line pavements with relatively high traffic volumes. To be more representative of lower traffic situations, these criteria had to be adjusted for variations in traffic volume. This was accomplished with fatigue tests on specimens

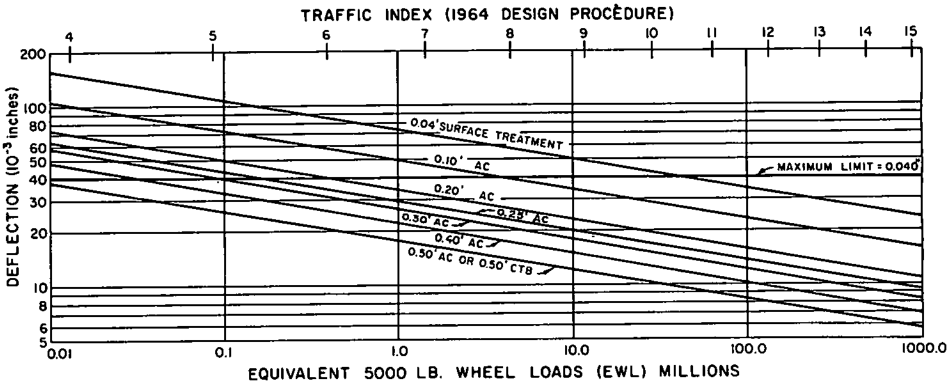

Figure 3. Variation in tolerable deflection based on fatigue tests on AC pavements.

cut from various AC pavements and was reported by Zube and Forsyth (5). The present criteria for tolerable deflection adjustment are shown in Figure 3. However, these criteria are considered tentative because the slope lines are based solely on laboratory surface fatigue data and have not yet been correlated with field performance. Our deflection experience is also limited for lightly traveled roadways; therefore, a maximum level of tolerable deflection of 0.040 in. is suggested. Also the California Division of Highways changed its asphalt specifications in 1960 in the hope of producing more durable AC pavements. This may change the tolerable limits.

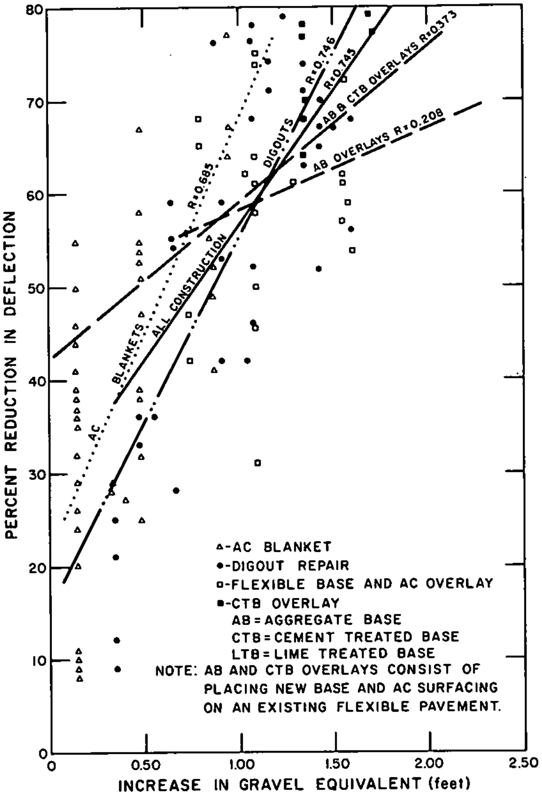

Figure 4. Reduction in deflection resulting from pavement reconstruction for various types of construction.

Currently under way in California is a research project to evaluate present deflection criteria (Fig. 3) by relating pavement performance to tolerable deflection level, structural section, asphalt hardness properties, and traffic loading. Deflection attenuation properties of various roadway materials are also being investigated on highway projects reconstructed based on California's present overlay design method utilizing pavement deflection measurements (5). During the past 10 years more than 400 different roadways have been investigated to determine in-place strength by using deflection measurements. The total follow-up deflection results on projects reconstructed subsequent to deflection investigation studies are shown in Figure 4. Here, the basis for California's overlay design is illustrated for various types of reconstruction. The deflection attenuation is presented in terms of reduction in deflection, percent, versus increase in gravel equivalent, ft. A line of best fit by regression analysis is shown for each type of construction. A poor correlation, R = 0.208, was produced for flexible-cushion construction, AC over aggregate base (AB), and was somewhat improved, R = 0.373, with the addition of cement-treated base overlay data. However, few data points were available for this relationship. For dig-out types of repairs and AC contact blankets, somewhat better correlations were determined. For example, a coefficient of correlation of 0.685 was produced for AC contact blankets and 0.746 was determined for dig-out type of construction. Except for thin AC construction, the bulk of these data were obtained at an age of 6 months or more. This allowed for initial traffic compaction to develop.

For design purposes, a single curve is shown in Figure 5 that encompasses all types of reconstruction and provides a correlation coefficient of 0.745. This is the present overlay design curve used by the California Division of Highways. Because experience includes only a few AC contact blankets thicker than 0.35 ft, the dashed line is used for AC blanket repairs on a tentative basis until additional data on thick AC overlay construction are obtained. The slope of this line is the same as that shown for AC blankets in Figure 4. With only minor exceptions, the performance of our overlays have thus far been very good. On a few roadways, some reflection type of cracking has appeared in thin AC blankets. However, we are not aware of any fatigue type of failures such as chicken-wire or alligator cracking on overlay projects constructed according to our deflection method. The age of these projects ranges from 1 to 10 years.

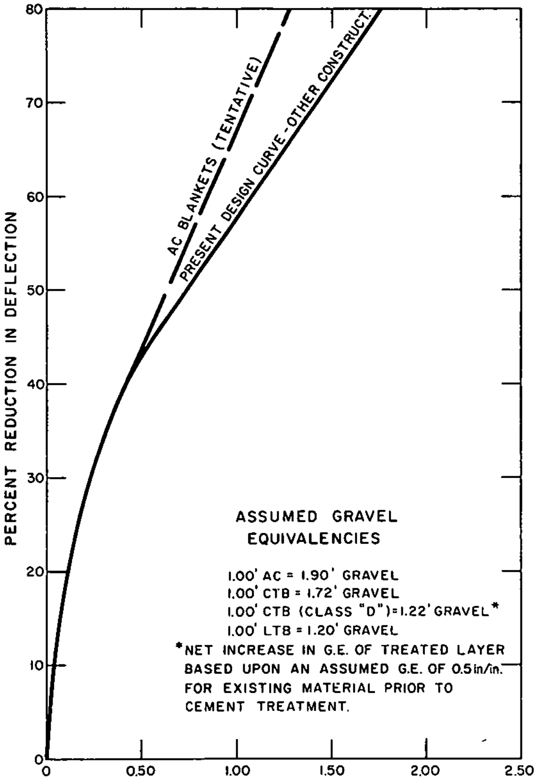

Figure 5. Reduction in deflection resulting from pavement reconstruction for all types of construction.

PAVEMENT EVALUATION PROCEDURE

For corrective treatment or overlay design of a particular roadway, several factors must be considered in addition to deflection measurements. A schematic chart that illustrates these factors and their relationship to other variables is shown in Figure 6. A satisfactory design is arrived at by considering the following factors: cause of pavement failure, existing structural section materials, deflection magnitude of existing section, reflection cracking potential, traffic index, and tolerable deflection level. (In the California method, traffic index, TI, is determined from equivalent wheel loads. It is also directly related to gravel equivalent. For example, an increase in traffic from 10 TI to 11 TI will cause a 10 percent increase in required gravel equivalent.)

The first step in the evaluation process is to collect pertinent data concerning existing structural sections, unusual drainage and foundation conditions, and anticipated traffic volume. Preliminary field work then consists of selecting test sections that are representative of the various levels of pavement condition and

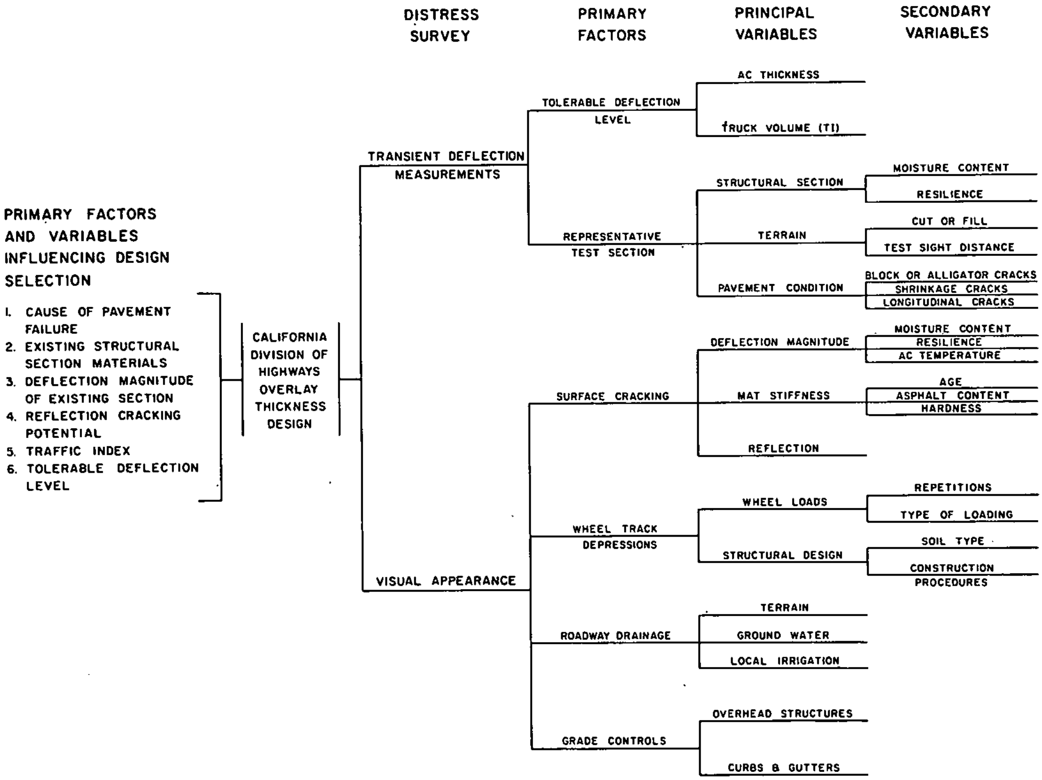

Figure 6. Overlay design.

changes in structural section. Test sections normally vary from 800 to 1,000 ft in length, and 1 or 2 test areas may represent a centerline mile of roadway.

Visual observations are recorded concerning type and extent of pavement distress and any vertical control features. Photographs are obtained for each test section and for all localized areas of major distress. These aid in the overlay design and the determination of the cause of pavement failure. Transient pavement deflections are then obtained and the mean, $\bar{X}$, and evaluated 80th percentile deflection levels are determined for each test section. These measurements are usually made in the spring or when the subgrade soils are in their most critical moisture condition. For the design based on deflections, the evaluated 80th percentile deflection is used. Most areas of extreme deflection are delineated by areas of severe distress. It is normally recommended that these areas be repaired, possibly by dig-outs, prior to placing the overlay.

The existence of vertical control features such as curbs and gutters may restrict overlay construction. In these situations, dig-out types of repairs may be necessary, and the nature of the reconstruction is governed by the existing structural section materials. Where no vertical controls exist, full utilization is made of the residual strength of the existing pavement, by the placing of a contact overlay.

The extent and nature of cracking affect the thickness required for a successful overlay. This is important in determining whether an AC blanket will add strength to the old surfacing by increasing the stiffness or whether the existing pavement is cracked to such a degree that its residual stiffness should not be considered in the design.

For some pavements, the magnitude of the existing deflection level is not a governing criterion for design. Frequently the need to eliminate potential reflection cracking from the underlying pavement establishes the AC blanket thickness. We have no set method to determine this thickness; however, a rule of thumb is generally used. This consists of recommending a new blanket thickness that is at least half the thickness o the existing AC pavement. For this case, the existing base must be untreated.

It should be pointed out that the deflection method for design of reconstruction is applicable only to fatigue-related distress associated with excessive compression and rebound of the structural section. Evidence of instability such as permanent wheel track depressions or rutting generally indicates a weakness or thickness deficiency of a structural layer or layers. Generally, design for this latter type of failure has been accomplished by testing of samples removed from the roadbed as required by th California R-value procedure. In our experience, however, we do not have seriously rutted roads when our design criteria for deflection are satisfied.

The development of the basic criteria used for our deflection method (Figs. 3 and 5 has previously been discussed. In order to illustrate the method of analysis and the procedure for determining corrective treatment, a typical example is provided for a roadway with an anticipated traffic index of 6.5. The existing structural section on this road consists of 0.17 ft of AC over 0.50 ft of AB. Distress consists of intermitte to-continuous small alligator cracking that has progressed to the point that the existin surfacing can be assumed to act as an unbonded flexible layer. There are no curbs an gutters and there is no evidence of rutting. Pavement deflection measurements produced a maximum evaluated 80th percentile level of 0.057 in.

If there is no loss in riding quality, a seal coat could possibly be used as an interi treatment. However, to restore riding quality and eliminate the high deflection condition, an AC contact blanket is the most economic repair.

A trial design begins by selecting a 0.10-ft AC blanket. For the 6.5 traffic index, Figure 3 shows 0.040 in. as the tolerable deflection. This deflection value is used because it is considered as the maximum deflection limit for lower trafficked roadways. The necessary deflection reduction is

$$\frac{0.057\text{ in.} - 0.040\text{ in.}}{0.057\text{ in.}} (100) = 30 \text{ percent}$$

It is then determined from data shown in Figure 5 that 0.25 ft of gravel equivalent is required to produce a 30 percent reduction in the existing deflection level. The 0.10-ft AC blanket is considered inadequate because 0.10 ft of AC is equal to only 0.19 ft of gravel equivalent.

A second trial design using 0.20 ft of AC is next selected. For this thickness, Figure 3 shows a tolerable deflection level of 0.035 in. The necessary deflection reduction is

$$\frac{0.057\text{ in.} - 0.035\text{ in.}}{0.057\text{ in.}} (100) = 39 \text{ percent}$$

Figure 5 shows that 0.40 ft of gravel equivalent is required to produce a 39 percent reduction in the existing deflection level. The 0.20-ft AC blanket provides 0.38 ft of gravel equivalent. This is considered to be sufficient.

PCC OVERLAYS BY DEFLECTION

California's most recent contribution to the field of deflection research consists of the development of a test method for predicting the subgrade modulus, K-value, of an existing AC pavement from Benkelman beam deflection measurements obtained on the pavement surface (6).

The criteria were developed from correlation work done by the Canadian Good Roads Association in which Benkelman beam deflection measurements under an 18,000-lb single-axle load were related to the load-carrying capacity of a 30-in. diameter steel bearing plate (7). This load was determined under a 0.5-in. plate settlement after 10 applications of load. From this relationship, a tentative correlation curve was established in terms of a Benkelman beam deflection under a 15,000-lb single-axle load (California's standard) and K-value in terms of lb/in^3. This relationship is shown in

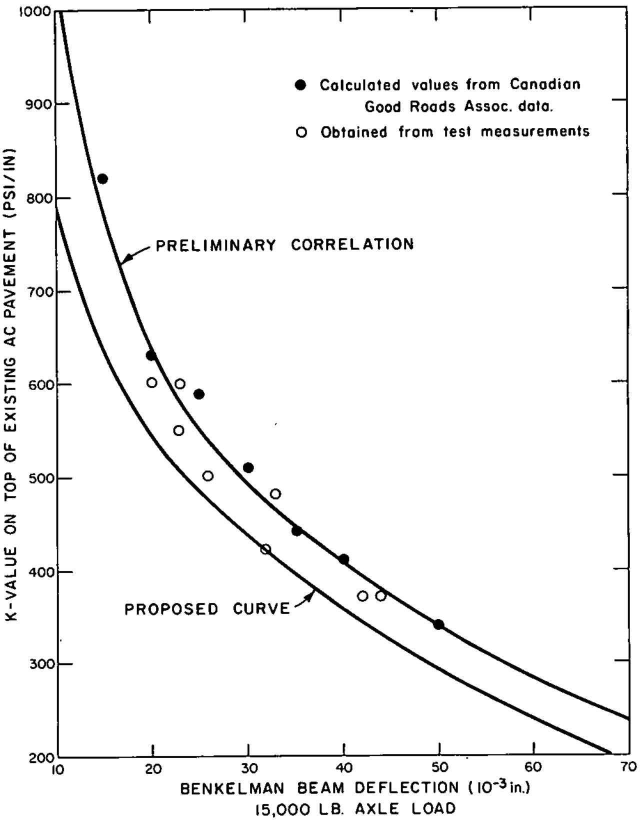

Figure 7. Correlation between K-value and pavement deflection.

Figure 7. The tentative correlation curve was established by first applying a factor of 0.83 to convert the loading to California's 15,000-lb standard. It was then necessary to convert the data to one application of load at 0.050 in. of plate settlement to determine the K-value. A factor of 0.25 was used for the settlement conversion and 1.2 was applied to change the data to one application of load. With the exception of the 0.83 factor for Benkelman loading, all other factors were obtained from work reported by McLeod (8, 9).

The tentative correlation curve was then verified by a minimal amount of plate bearing and Benkelman beam measurements. This was accomplished at various test locations on the AC hardstand areas of the Materials and Research Laboratory and the Service and Supply Warehouse Yard in Sacramento. A proposed design curve was then constructed parallel to the preliminary correlation curve and through the lowest data point. This research work enables the engineer to develop both flexible and rigid overlay design alternates for existing AC pavements.

Portland cement concrete (PCC) overlays for distressed AC pavements are presently selected in California on an arbitrary basis. These overlay thicknesses vary from a minimum of 0.55 ft to a maximum of 0.70 ft and in some cases may be quite conservative. Deflections now provide a basis for analysis.

The new test procedure (Test Method 359A) consists of first performing a deflection investigation on the existing AC roadway as previously discussed. The K-value is then determined based on the maximum 80th percentile deflection level using the proposed curve shown in Figure 7. The K-value is predicted by assuming that 600 pci is an upper limit. The selected K-value is then used in stress charts provided in our Planning Manual on Design to determine the required PCC overlay thickness. Design comparisons are now possible for AC and PCC overlays.

SUMMARY

1. The satisfactory results of designs for overlays, based on deflection measurements for approximately 400 roadways, indicate the value of pavement deflection as a tool for designing overlay thickness.
2. Experience shows that other factors such as drainage, traffic, and type of distress must also be evaluated in an overlay design.
3. A correlation was found between the California dynamic deflection and the Canadian Good Roads Association static deflection.
4. A method for determining the K-value of an existing bituminous roadway from deflection measurements has been developed. This allows for the design of a PCC overlay using existing design formulas.
5. A rating system based on riding quality is needed to determine which roadways require an overlay.

ACKNOWLEDGMENT

This paper is based on data collected during numerous research projects by various researchers including Raymond Forsyth, Ernest Zube, Donald Tueller, and Francis Hveem. The work has generally been accomplished in cooperation with the Federal Highway Administration. The opinions expressed in this report are those of the authors and not necessarily those of the Administration.

REFERENCES

1. Zube, E., and Forsyth, R. A. Pavement Deflection Research and Operations Since 1938. Materials and Research Dept., California Div. of Highways, Research Rept., April 1966.
2. Zube, E., Tueller, D. O., Forsyth, R. A., and Hannon, J. B. Evaluation of the Lane-Wells Dynaflect. Materials and Research Dept., California Div. of Highways, Research Rept. 633297, Oct. 1968.
3. Hveem, F. N. Pavement Deflection and Fatigue Failures. HRB Bull. 114, 1955, pp. 43-73.
4. Kingham, R. I. San Diego Experimental Base Project: A Correlation of California and Canadian Benkelman Beam Deflection Procedures. The Asphalt Institute, Research Rept. 70-1, Jan. 1970.
5. Zube, E., and Forsyth, R. A. Flexible Pavement Maintenance Requirements as Determined by Deflection Measurements. Highway Research Record 129, 1966, pp. 60-75.
6. Zube, E., Tueller, D. O., and Hannon, J. B. K-Value—Deflection Relationship for AC Pavements. Materials and Research Dept., California Div. of Highways, Research Rept. 643449, Nov. 1969.
7. Canadian Good Roads Association. Pavement Evaluation Studies in Canada. Proc., Internat. Conf. on the Structural Design of Asphalt Pavements, Univ. of Michigan, Ann Arbor, 1962, pp. 181-182.
8. McLeod, N. W. Airport Runway Evaluation in Canada. HRB Research Rept. 4-B, 1947, 133 pp.
9. McLeod, N. W. Airport Runway Evaluation in Canada, Part II. HRB Research Rept. 4B-1948 Supplement, 1948, 80 pp.