Optical Measurement of Pavement Deflection Due to Vehicle Wheel Loads

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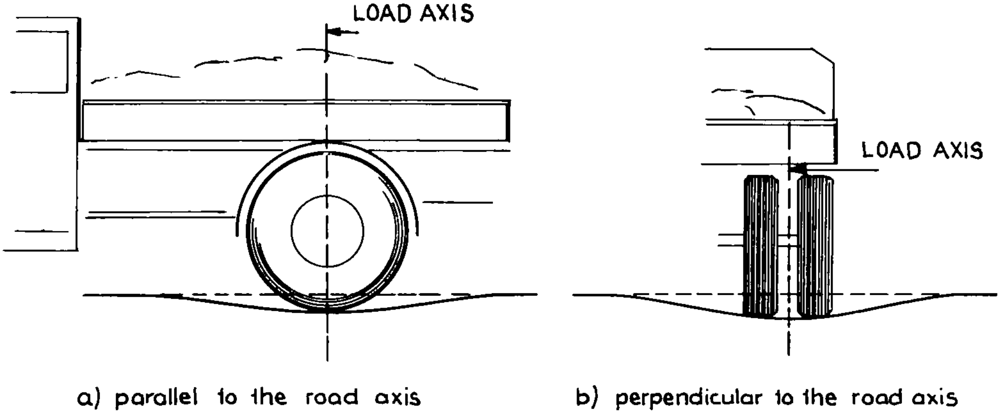
• IN CONNECTION with the problem of designing the multi-layer structure of road bodies, a number of methods have been evolved to characterize the service stresses acting on a particular structure or on individual layers thereof. One of these methods—the determination of the deflection of the pavement subject to a wheel load—has the advantage of disclosing the behavior of the entire structure and not only that of individual layers.

This paper describes the method of optical deflection measurement applied by the Laboratories for Hydraulic Research and Soil Mechanics (VAWE) at the Swiss Federal Institute of Technology, Zurich, and illustrates the method with reference to an application comparing several road structure variants in the planning of a heavy-duty road. As the measuring method was only recently introduced, the empirical data available are not yet sufficient to permit criteria to be formulated. The empirical data so far gained in various countries, especially in the United States, are not freely applicable to the different climatic and subsoil conditions prevailing in Switzerland. Moreover, the Swiss heavy-duty vehicles differ from those with which the previously mentioned empirical data were gained in several features of design, such as number of axles, axle load, and wheel distance of the twin wheels.

For the present, the method is being applied to test road structure variants, with a view to finding, by empirical means, a design criterion so urgently required for the construction of the Swiss National Road System.

GENERAL

The term "deflection" as used herein denotes the bending that can be meas-



a) parallel to the road axis b) perpendicular to the road axis

Figure 1. Bending (influence) lines.

ured on the surface of a road pavement as the result of the wheel load of a heavy vehicle. The following notations are used: the total deflection *W* in the center of the load; the permanent deflection *U* measured after removal of the load; and the resilient deflection *T*, expressed as the difference between total and permanent deflection. Any particular case of deflection is fully characterized by the bending lines parallel and perpendicular to the road axis (Fig. 1).

TABLE 1
SEASONAL EFFECT ON FLEXIBLE PAVEMENT DEFLECTION FACTORS

Season	Pavt. Temp.	*E*-Mod. of Pavt.	Load-Carrying Cap. of Subbase	Deflection
Spring	Low	Large	Possibly reduced	Large
Summer	High	Small	Large	Large
Fall and winter	Low	Large	Large	Small

It is necessary to know the bending lines because the stresses induced in the pavement by the same magnitude of deflection can be different. With constant deflection under the load center, the elongations arising in the pavement decrease with increasing range of the load influence zone. The deflection measured on a multi-layer structure and the form of the bending lines depend on the following:

1. The bulk of the individual layers.
2. The material and strength properties thereof, which in turn vary with climatic conditions; the modulus of elasticity of flexible pavements decreases with rising pavement temperature, and the quality of the base and the subbase vary according to water content and during the frost period.
3. The loaded surface (contact surface) and the wheel load applied.

Owing to climatic influences, a distinction must be drawn between the states of a given structure with flexible pavements as given in Table 1 by season of the year.

Where the controlling factors can be determined separately, deflection measurement becomes a valuable means for the theoretical design of road structures. As the problem of determining the material properties of the individual layers of a multi-layer structure has not yet been solved, an attempt is first made to approach the design problem empirically. When the permissible deflection for a particular pavement is known, it is possible, by testing several structure variants on test road sections, to determine which layer arrangement of the available materials will insure that the permissible deflection is not exceeded.

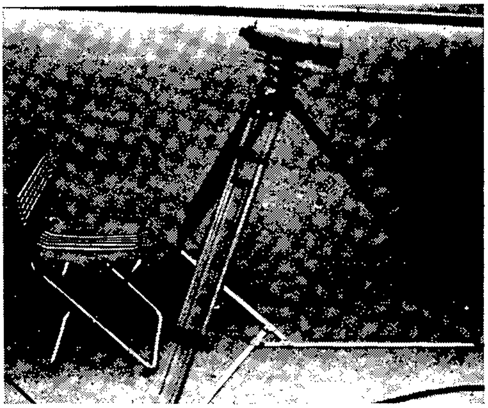


Figure 2. N III precision level set up for taking pavement deflection readings.

MEASURING INSTRUMENTS

Benkelman Beam

The first deflection measurements performed by the VAWE were carried out with the Benkelman beam, a mechanical measuring instrument, which has been described elsewhere (*1*). The bearing points of the instrument are only 2.8 m from the point to be measured. Accordingly, when measurements are made on structures of high load-distributing character, the bearing points are obviously located within the load influence zone, rendering the result unreliable. Elimination of this source of error requires an alteration of design which would make the

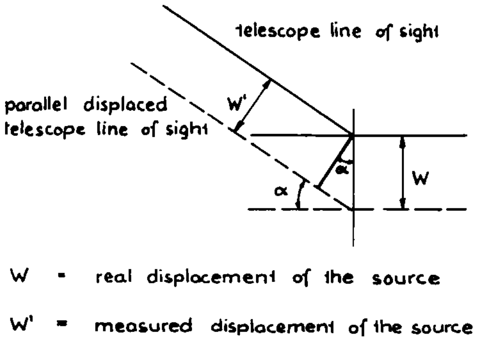


Figure 3. Error of measurement.

instrument more difficult to operate and move from one location to another. A further drawback of the Benkelman beam is that the bending line perpendicular to the road axis cannot be measured efficiently.

Déflectomètre Optique D2

The D2 *déflectomètre optique* (optical deflectometer) was evolved in France specifically for measuring deflections of road pavements. The optical system permits the instrument to be located at a neutral spot outside the load-affected zone. The instrument and its application have been described elsewhere (*2*).

Precision Level N III

Prompted by the French optical measuring method, the VAWE looked for an optical measuring instrument which would be simple in design while still meeting the requirements specified for the purpose. It was found that the Type N III precision level (Fig. 2), made in Switzerland by Wild Heerbrugg, Ltd., was eminently suitable for deflection measurement, without involving any alteration of design. The instrument can also be used as a level and as a measuring instrument for plate bearing tests.

DEFLECTION MEASUREMENTS WITH THE N III

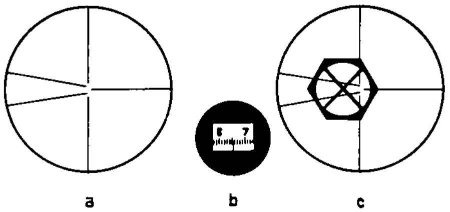
Instrument, Source and Load

The N III is a high-precision level with which an accuracy of ±0.25 mm in one kilometer of single-run leveling can be attained. Despite the 42-power telescopic magnification and the robust, weatherproof construction, the instrument weighs only 3.5 kg.

The use of the N III for deflection measuring is made possible by the following feature of design: With the instrument fixed in position and the telescope axis set, the line of sight can be displaced parallel to itself in a vertical plane by tilting a plane-parallel-faced glass plate. This displacement, effected by turning a micrometer screw, is indicated on a micrometer scale. The range of the measurable parallel displacement is 1 cm, which is adequate for measurement of road pavement deflections. Tenths of millimeters can be read directly from the micrometer scale, while hundredths of a millimeter can be reliably estimated.

The instrument is set up on a tripod at a convenient reading level. The line of sight is thus inclined by the angle α, so that the quantity measured is not the total vertical displacement W of the source, but only $W/\cos\alpha$ (Fig. 3). With the usual position adopted for the instrument (approximately 5 m from the source and 1 m above the ground) the angle α approximates 11°; that is, the values measured are approximately 2 percent too small.

The light source used is a robust prismatic body of brass, 5 cm long and 2 cm in diameter. Fitted into this body is a reticle with lighting system. The



a) N III - telescope reticle with wedge lines

b) Micrometer scale

c) Splitting graduation with wedge lines and source reticle

Figure 4. N III telescope reticle and source.

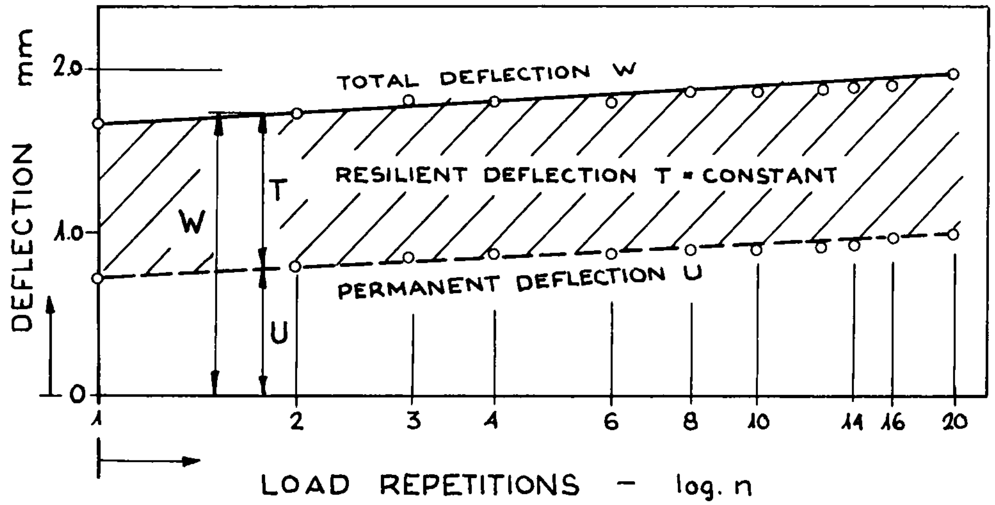


Figure 5. Example of measurement of *W*, *U*, and *T* on same point, 20 load repetitions.

latter is fed by a battery, to which any number of sources can be connected.

Figure 4 shows the reading image as seen through the eyepiece of the instrument. A skilled viewer will attain a reading accuracy of ±0.02 mm, as will be seen from the measuring examples later given.

Besides instrument, sources, and battery, the operator requires a measuring tape, a sunshade for the instrument, and a resistance thermometer for measuring the pavement temperature. The complete equipment can be easily transported in a station wagon, so that moving from one location to another can be done rapidly.

For the load, the 2-axle motortruck type with twin-wheeled rear axle common in Switzerland is used. In accordance with Swiss traffic regulations concerning maximum axle loads, the measurements are usually performed with an axle load of 10 tons, which, with a tire pressure of 5 atm/g (about 75 psi), gives a contact surface of 1,000 cm^2.

Measuring Procedure

The source with the illuminated reticle is laid on the point to be measured and sighted at a distance of approximately 5 m with the N III. For no-load condition, the truck must be at least 5 m from the measuring point, so that the latter is outside the load-affected zone. For load, the truck is backed toward the source until the latter lies between the two tires of one of the twin wheels of the rear axle and, accordingly, is at the load center.

Total, permanent, and resilient deflection are determined in a single loading cycle: 1st (zero) reading, measuring point before loading; 2nd reading, source at load center; and 3rd reading, after unloading.

The difference between the first and second readings gives the total deflection *W*, that between the first and third readings the permanent deflection *U*, and that between the second and third readings the resilient deflection *T*.

In the course of several load repetitions, the resilient deflection remains nearly constant, whereas the total and permanent deflections gradually increase. This increase characterizes the plastic deformation of the entire structure. Figure 5 gives an example carried out with 20 measured load repetitions.

The time required for measuring a single loading cycle is about one-half minute. To characterize a particular

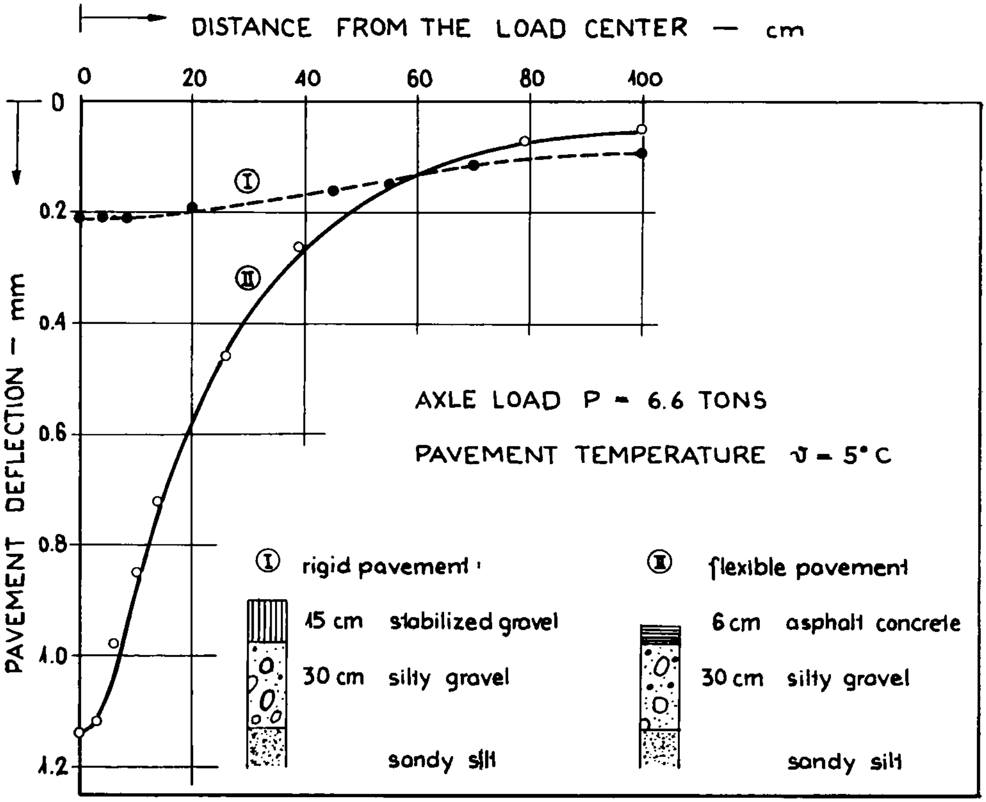


Figure 6. Characteristic influence lines parallel to road axis.

structure by its resilient deflection, it is sufficient to determine the latter as the average obtained from 3 to 5 load repetitions, so that about 8 measuring points can be tested per hour.

Influence lines parallel to road axis are measured by moving the truck toward the measuring point in short increments. For each position of the load, the deflection is determined and the distance from load to measuring point is recorded. When the deflection is plotted against the load distance, the influence line is obtained. Figure 6 shows two characteristic influence lines, one measured on a rigid pavement (15-cm stabilized gravel), the other on a flexible pavement (6-cm asphalt concrete). The base and subbase are the same in both cases.

The curves clearly show the different load-distributing character of the two pavements. At a distance of 1 m from the load center, the rigid pavement still showed 50 percent of its maximum deflection, whereas the flexible pave-

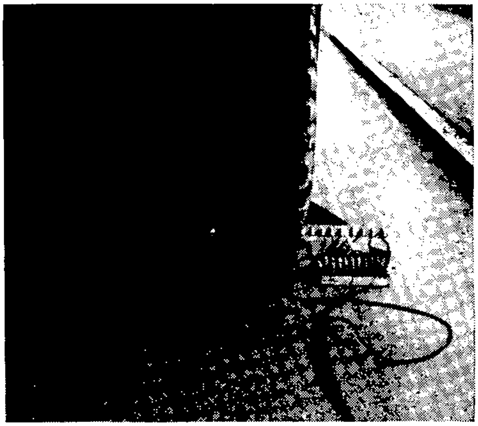


Figure 7. Position of 10 sources for measurement of bending lines perpendicular to road axis.

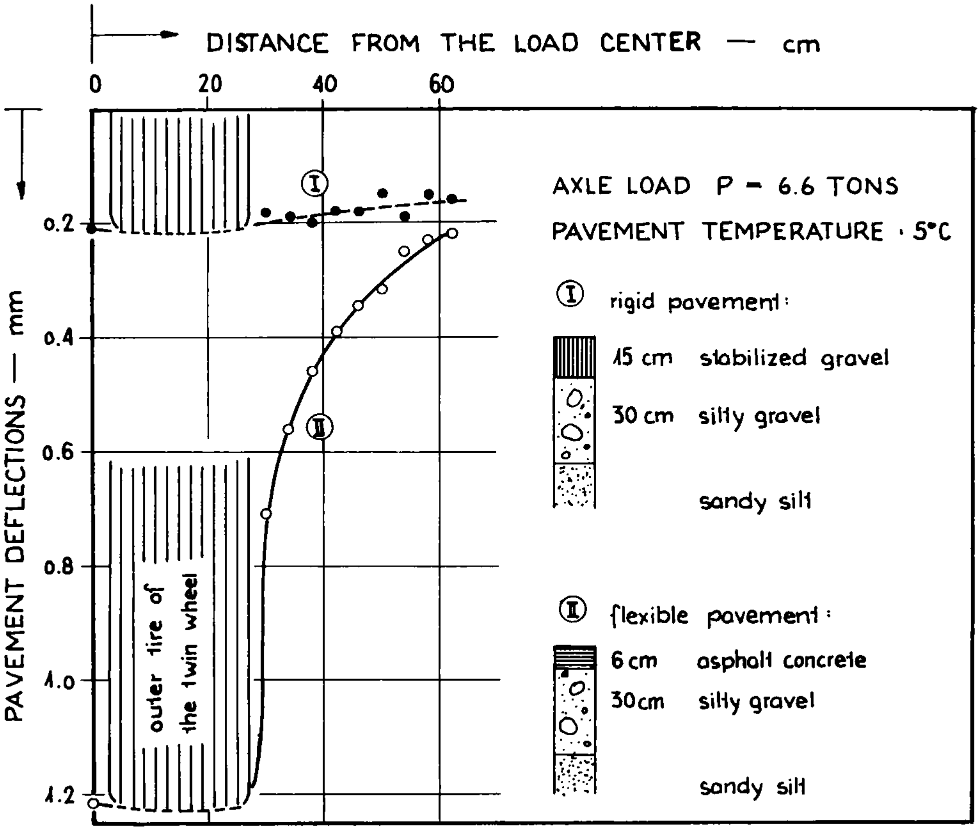


Figure 8. Characteristic bending lines perpendicular to road axis.

ment only showed 5 percent of its maximum. A good picture of the curve is obtained by determining points on the curve at 4-, 3-, 2- and 1-m distance, thence every 20 cm, and, close to the measuring point, every 5 cm. This procedure takes about 2 min.

Bending lines perpendicular to the road axis are determined by placing, before loading, 10 sources on the measuring spot in such a manner that, under load, one of the sources is positioned between the tires of one of the twin wheels of the rear axle, while the other 9 are positioned at right angles to the direction of travel of the truck and outside the outer tired wheel (see Fig. 7). Each source corresponds to a point of the curve, so it is not the influence line which is determined, but the bending line itself. In one loading cycle, the total, permanent, and resilient portions of the bending line are obtained, in analogy to the measuring procedure previously described.

The measurements showed that the critical part of the bending line is near the wheel, so the sources are positioned at 4-cm distance from each other. By increasing the distances or by placing more than 10 sources, however, it is also possible to cover a wider part or even the entire range of the bending line.

With the N III, it is possible to read all the sources from a fixed instrument location, as follows: The reticles of the sources positioned side by side are arranged in a vertical plane. When the telescope of the instrument is rotated about its pivot, the rays of all possible

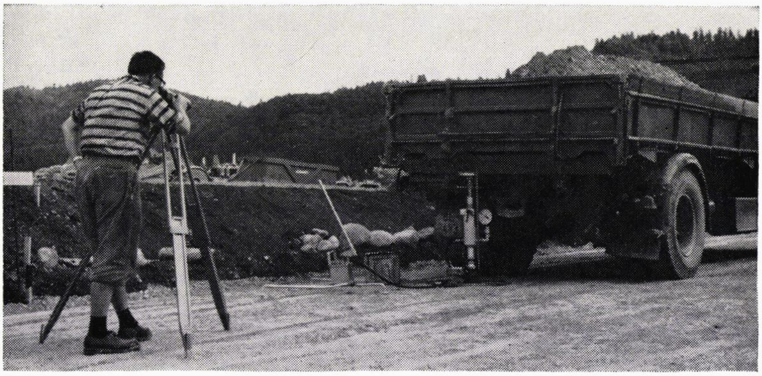


Figure 9. N III precision level set up for making plate bearing test measurements.

sighting lines describe a second plane. This plane must intersect the vertical plane containing the reticles in such a manner that the straight line of intersection contains all the reticles. As the 10 reticles of the sources are not exactly on a straight line, each source receives its own zero reading. The range of the micrometer scale is sufficient to embrace the movement of all the sources. Figure 8 shows the measurements of two characteristic bending lines perpendicular to the road axis. The two curves were determined on the same measuring points as those on which the influence lines in Figure 6 were measured.

The less effective load distribution of the flexible pavement is clearly shown in the sharp drop increase in the deflection immediately beside the wheel, as compared with the gradually increasing deflection of the rigid pavement.

It is possible to combine measurement of the influence line parallel to the road axis with that perpendicular to the road axis by reading all the sources for each load position, thus covering the entire influence zone of the load. Generally, however, only the bending line, which represents the maximum deflection, is determined.

Use for Plate Bearing Test

The load test with the circular plate always involves the difficulty of placing the reference system with the gages in such a manner that the latter is supported outside the load influence zone. This source of error can be eliminated

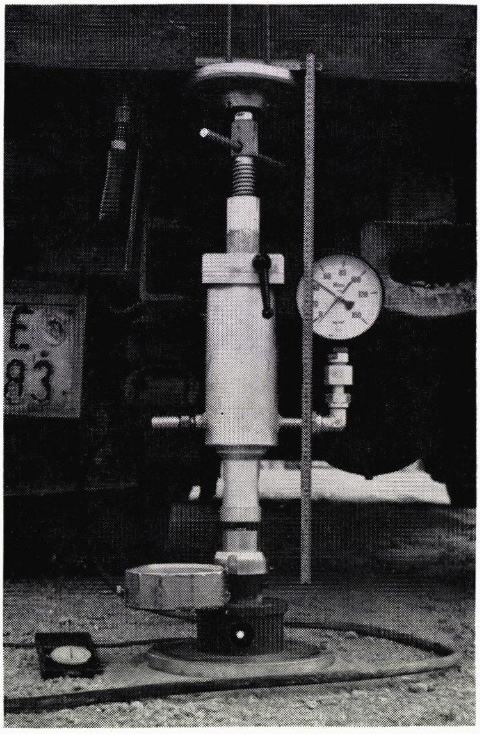


Figure 10. Light source in base of plate bearing test apparatus adapted for optical measurement.

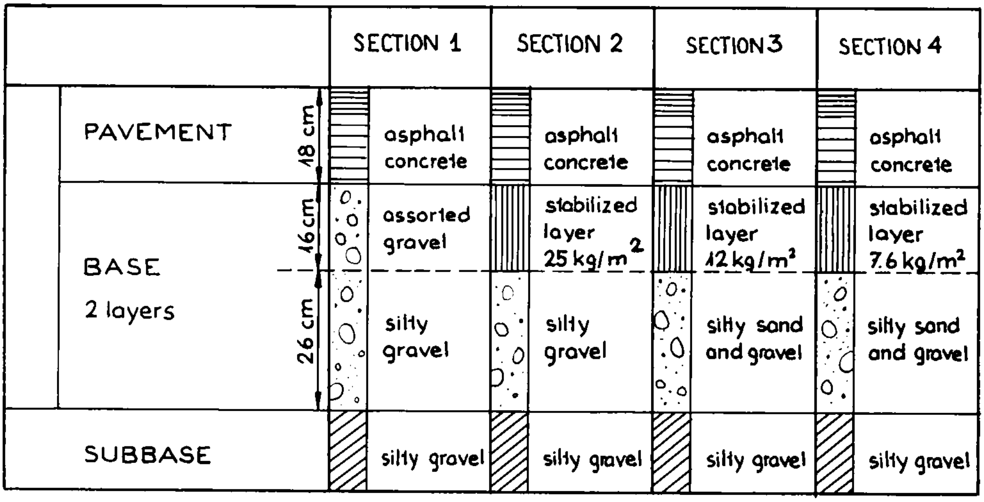


Figure 11. Structural components of the test sections.

by optically measuring the movement of the plate by means of the N III. For this purpose, the instrument is set up several meters from the plate (Fig. 9), or, for tests on rigid pavements, outside the range of the plate influence. Serving as the reference point is a source of light with a reticle, which is centered on the plate and held in position magnetically (Fig. 10).

EXAMPLE OF TESTING AND COMPARING TEST SECTIONS OF DIFFERING STRUCTURE

Problem

The occasion for the tests arose during the planning of a highway section in Switzerland. A dam made chiefly of compacted silty gravel provided a subbase of adequate load-carrying capacity. The question which arose, however, was whether the available very sandy base material would provide a suitable base for a road subject to heavy traffic, or what methods of grading or treating (stabilizing) this material would be suitable.

First, the following general comments might be inserted: In Switzerland, the structure of a road body must comply with certain standard specifications. In particular, these specifications relate to the quality of the base materials and to the load capacity of the base that can be attained by compacting those materials. A well-graded sandy gravel is specified. The coefficient of load-carrying capacity used is the so-called M_E-value obtained in the plate bearing test with the circular 700-cm² plate; that is,

$$M_E = \frac{\Delta\sigma}{\Delta y} \Big/ D$$

in which

$\Delta\sigma$ = difference of the contact stress of two load stages, in kg/cm²;
Δy = settlement of the plate during a load interval, in mm; and
D = plate diameter, in cm.

A completed base must attain a specific M_E-value; that is, within a specified load interval the settlement of the standard plate must not exceed a certain permissible value. The M_E-criterion becomes invalid if the base material, on which the value is determined, fails to satisfy the quality specifications for which the standard values were set up. Nor is the M_E-value acceptable as a criterion for load capacity if the test is performed on a system having small layer thicknesses (for example, base with stabilized layer), for

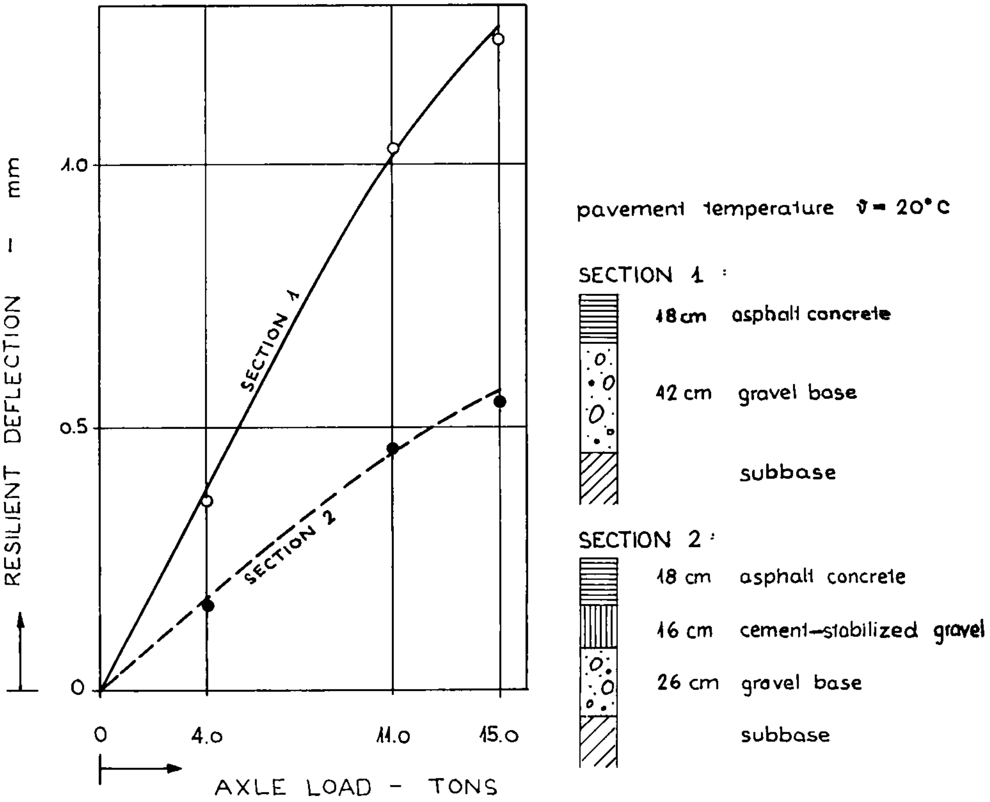
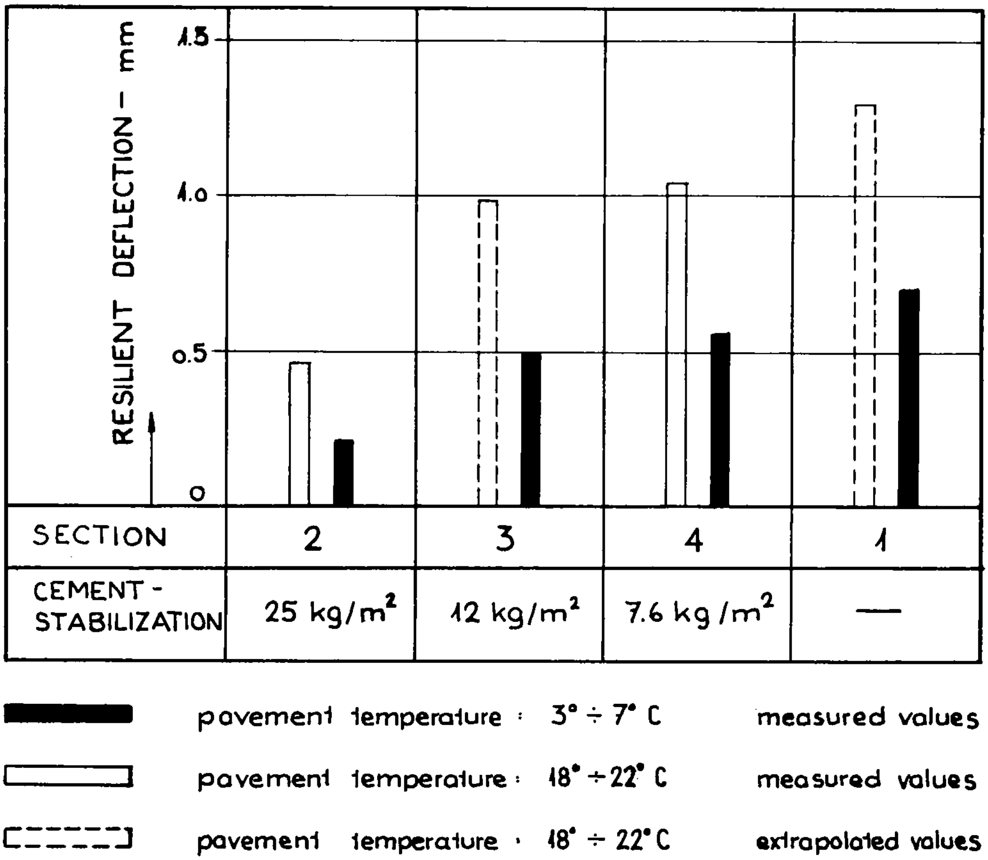


Figure 12. Effect of axle load on pavement deflection.

then the value measured is dependent on the plate size, the material properties, and the bulk of the individual layers. The stresses induced in the individual layers by the standard test differ from those arising from the traffic load acting on the entire structure, as neither the load interval nor the plate size can represent the load-distributing effect corresponding to the particular pavement. This is why the VAWE holds the opinion that the entire structure of a road should be tested, and not the individual components thereof. Moreover, the type and magnitude of the stress applied in the test should not be arbitrary, such as that produced by a circular rigid plate, but should instead resemble the actual service conditions of a road, as is the case in deflection measuring.

Structure of Test Sections

For the purpose of comparing several structure variants of the previously mentioned highway section, four test sections were constructed with the structural components shown in Fig. 11. For all sections the compacted subbase, the pavement, and the layer thicknesses are the same, the only variable feature being the construction of the upper portion of the two-layer base. Test sections 1 and 2 were constructed with a view to comparing the two variants (a) washing and grading, and (b) cement-stabilization without previous washing or grading. Sections 3 and 4 subsequently served the purpose of establishing the suitable cement dosage.



SECTION	2	3	4	1
CEMENT - STABILIZATION	25 kg/m²	12 kg/m²	7.6 kg/m²	—

Figure 13. Effect of structure and pavement temperature on pavement deflection.

Deflection Measurements

The completed test sections were preloaded with 40 repetitions of a 15-ton axle load.

The deflection measurement work was carried out in two stages: The tests on sections 1 and 2 were performed in summer, those on sections 3 and 4 in late fall. To permit the tests on the latter two sections to be compared with those on sections 1 and 2, it was necessary, owing to the then lower pavement temperatures, to retest sections 1 and 2 at the same temperature. Efforts were focused on determination of the resilient deflection; first, because the minimized scatter seems to suggest that this method characterizes the load-carrying capacity of the entire structure, irrespective of subsidiary effects, such as the plastic deformation of the pavement, and second, because the resilient deflections represent the main part of the stresses induced in a road structure, as shown in Figure 5. In the following, the magnitude of resilient deflection is given as the average taken from four measuring points per section, the average at each measuring point having been taken from 20 load repetitions. The mean error in the average of a measuring point was ±0.06 mm maximum, that in the average from 4 measuring points ±0.10 mm. This scatter, however, is due not so much to inaccuracies of measurement as it is to the inhomogeneity of the structures.

Figure 12 shows the resilient deflec-

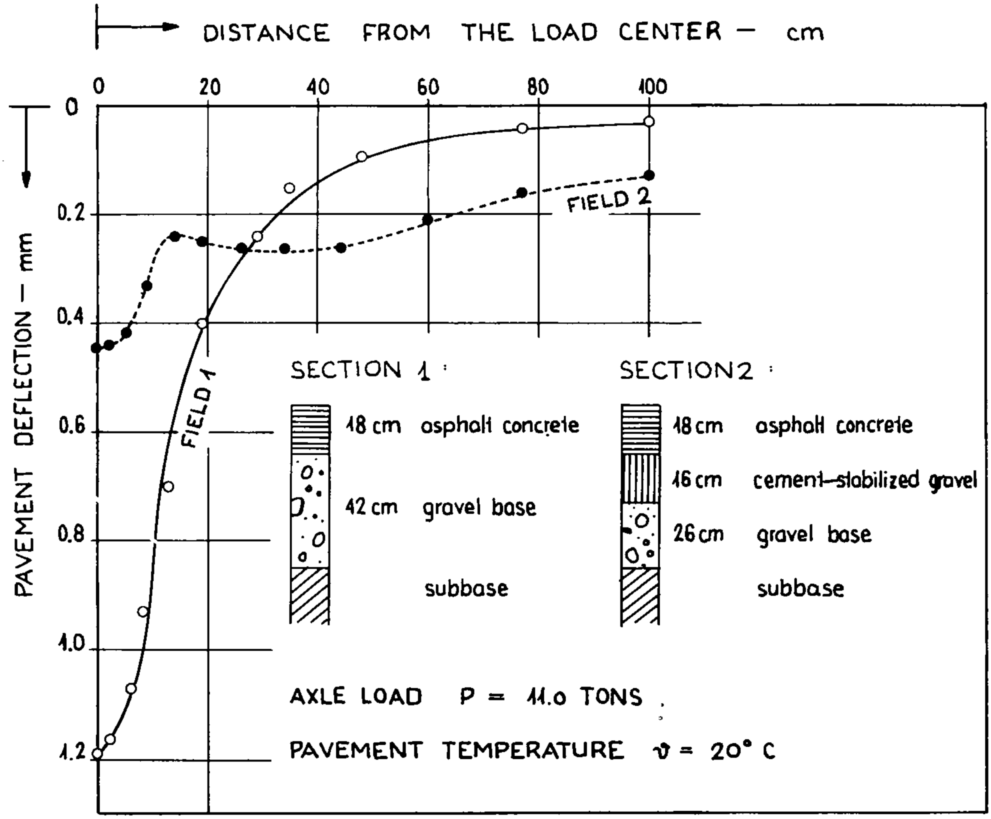


Figure 14. Influence lines parallel to road axis.

tions T plotted against the axle load P. The tests made with three different axle loads (4, 11 and 15 tons) show the same trend for both the section with stabilized layer and that without stabilized layer; that is, an approximately linear dependence with a slight flattening of the curve with increasing load. The values measured on section 2, with stabilized layer, are 2.25 times smaller than those taken on section 1, without stabilized layer.

The dependence of resilient deflection on structure and on pavement temperature is shown in Figure 13. The resilient deflection shows only a slight improvement in the structures with a stabilized layer of 7.6 and 12 kg PC/m^2, respectively, with respect to the structure without stabilized layer.

On the other hand, the values measured on the section whose stabilized layer was made with a dosage of 25 kg PC/m^2 are less than one-half those measured on the other three variants. The difference between the resilient deflection measured in summer and that measured in late fall is due to the dependence of the modulus of elasticity of flexible pavements on temperature. The load-carrying capacity of the subbase remained the same in both measuring periods. With a 15 C difference in temperature, the values measured differ by a factor of 2.

Finally, it is instructive to examine the load-distributing effect of the stabilized layer by comparing two typical measured influence lines parallel to the road axis (Fig. 14) and bending lines perpendicular to the road axis (Fig. 15).

The character of the curves is the

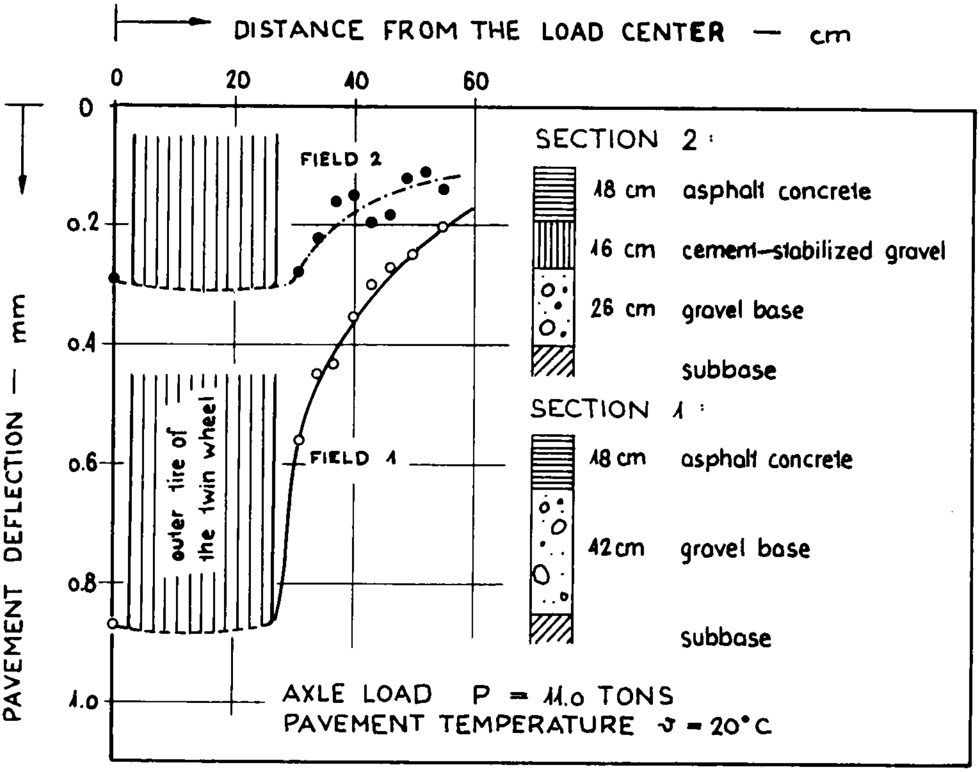


Figure 15. Bending lines perpendicular to road axis.

same as those of Figures 6 and 8, where the curve measured on a flexible pavement is compared with one determined on a rigid pavement. A curious feature, however, is the bump at 15 cm from the load center in the influence line parallel to the road axis, measured on the structure with stabilized layer. So far, the only measurements carried out on structures having a thick flexible pavement superimposed on a rigid stabilized layer are those performed on the test sections described herein. Moreover, those are the only influence lines measured whose curvature shows such an irregularity. No definite reason can yet be given for this phenomenon. Nevertheless, judging by the general trend of the curve, it appears to be a superficial effect which is probably caused by a displacement of the flexible pavement on the unyielding stabilized layer. It remains to be seen whether the same effect still arises after the flexible pavement has been run in by the traffic.

CONCLUSION

The results obtained substantiate the fact that optical deflection determination by means of the N III precise level constitutes a rapid and accurate measuring method. The next step is to apply the method systematically and attempt empirically to arrive at a criterion for design purposes. Although a relative judgment of the load-carrying capacity of the different structures of the example is permissible, inasmuch as all the sections were constructed and tested under the same conditions, it must be said that the empirical data so far available are not yet sufficient to enable reaching an absolute conclusion as to which structure is the correctly designed one. It will take a comprehensive measuring program to disclose what type and magnitude of deflection results in damage to a particular pavement, dependent on its material properties, its layer thicknesses, the temperature, and the number of load repetitions applied.

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