# Non-Destructive Testing of Pavements

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A vibratory-type machine was developed by the Royal Dutch Shell Company, Amsterdam, Holland, for non-destructive testing of pavements. This machine was made available to the Corps of Engineers for about six months, during which tests were made on pavements and unsurfaced soil areas. For the greater part of the time the tests were under the direct supervision of engineers from the Royal Dutch Shell Company. Evaluations of the pavements can be made based on two distinct principles. The machine can be made to serve as a source of vibrations from 10 to 2,000 cycles per second, and the wave velocity can be determined. The elastic modulus of the pavement can then be established based on accepted relationships between the velocity of the wave propagations and elastic constants. A second approach is a determination of the so-called stiffness factor, which is the relationship between a dynamic load and the resulting deflection of the pavement surface under a circular loaded area. This paper presents typical results obtained with the machine.

●THE SHELL ROAD vibration machine was developed at the Shell Laboratories in Amsterdam, Holland. The U.S. Air Force made arrangements with Shell for the use of the machine, and it was brought to this country in April 1958. The machine has been used at the Corps of Engineers' Rigid Pavement Laboratory in Cincinnati, Ohio, the Flexible Pavement Laboratory in Vicksburg, Miss., and the Columbus Air Force Base, Miss. William Heukelom and Theodorus W. Niesman accompanied the machine. Niesman returned to Amsterdam as soon as an operator had been trained, but Heukelom remained throughout most of the test program. Thus, almost all the tests were made under the supervision of Heukelom. Tests were made on three occasions at Columbus AFB by Corps personnel after Heukelom's departure for Holland. After completion of the tests at Columbus AFB, the machine was transferred to the custody of the Transportation Corps for use on the AASHO Test Road.

## SHELL ROAD VIBRATION MACHINE

This paper presents the results of tests made with the Shell road vibration machine which furnish some measure of the accuracy of the method and some indications of its potential usefulness and limitations. The machine and the method of operation have been described fully in the papers in the list of references, and only the basic elements will be discussed in this paper.

Two quantities are measured with this machine, the "stiffness modulus" and the velocity of waves over a wide range of frequencies. The stiffness modulus is defined as the ratio of a dynamic load and the resulting deflection. It is expressed in kilograms per centimeter or tons per inch and is therefore similar to a spring constant.

The machine can be operated so as to induce vibration over a range of frequencies of about 5 to 2,000 cycles per second. Vibrations with frequencies of 5 to 60 cycles per second are produced by counter rotating eccentric weights powered by a gasoline engine. This vibrating mass is attached to a 30-cm-diameter circular plate and rests

n the pavement surface. Forces up to about 4 tons can be applied with this low fre-
uency unit. This unit is used to determine the stiffness modulus as well as a source
f low frequency waves which are required for other purposes.

Vibrations at frequencies of 40 to 2,000 cycles per second are induced by a high
equency electromagnetic vibrator. This unit is used solely as a wave source, as the
rces developed are too small to determine the stiffness modulus.

## VELOCITY MEASUREMENTS

In operation, a probe or pickup is placed on the ground or pavement surface at a nown distance from the source of vibrations. This pickup is wired through an oscillo-cope on which the wave form can be viewed. Further, a phase mark is superimposed n the wave so that the position of the pickup with respect to the crest and troughs of e wave at the point of generation is immediately apparent. The distance between the ickup and the source of vibration is changed a little at a time until the phase mark ppears exactly at the crest or trough of a wave. The distance is recorded and is then ncreased until the phase mark appears at the next trough (one-half the wave length) or rest (one wave length). Thus, the wave length is determined directly. Knowing the equency of vibration and the wave length, the velocity is given by the relation

$$V = Ln$$

n which

$V$ = velocity in meters per second,
$L$ = length in meters, and
$n$ = frequency.

Jsually, the probe is operated over a distance of several wave lengths, and distance rom the source is plotted against number of wave lengths. The slope of the line de-ned by these points is the wave length. This method gives greater accuracy than the neasurement of a single wave length.

Questions have been raised by several investigators as to the type of waves generated. They are generally thought to be shear waves, although the occurrence of Rayleigh or ther type waves is possible. The difference in velocity of shear and Rayleigh waves s only a few percent and is not considered significant in this type of work. The veloc-ty of propagation of shear waves in a medium is related to the modulus of elasticity nd Poisson's ratio of the medium in accordance with the following classic equation:

$$V = \sqrt{\frac{Eg}{\gamma\,(1+\mu)}}$$

n which

$V$ = velocity,
$E$ = Young's modulus,
$g$ = acceleration of gravity,
$\gamma$ = unit weight, and
$\mu$ = Poisson's ratio.

Taking $\mu$ as 0.5, squaring, and transposing gives

$$E = \frac{3\gamma}{g} V^2$$

The shear modulus G can be computed from the relation

$$E = 2(1+\mu)G$$

From the foregoing, it is apparent that the wave velocity V, the unit weight of the soil $\gamma$, and Poisson's ratio must be known in order to compute the modulus of elasticity E. The wave velocity is measured. The unit weight can be measured or in most cases

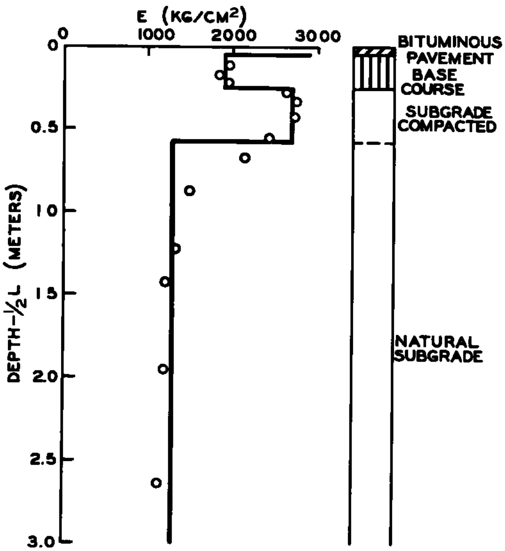


Figure 1.

estimated as a small variation has little effect on E. Poisson's ratio μ is probably more nearly 0.40 to 0.45, but, as wi unit weight, small differences do not grea affect the results.

In practice, the elastic moduli determined as outlined here are plotted agains depth. It is known that waves induced by low frequency vibrations (long wave lengt travel at relatively great depths, while waves induced by higher frequency vibrations (shorter wave length) travel at relatively shallow depths. Results of tests by the Royal Dutch Shell Company engine with the road vibration machine have shown that if the depth of travel is taken as one-half the wave length, the results agree remarkably well with known depths to the various layers in a pavement structure.

Figure 1 illustrates typical test results. It is a plot of E versus depth where the depth is taken as one-half the wave length. Each test point shown is based on a wave velocity measurement at a different frequency of vibration. The test point at the greatest depth was determined at a frequency of 60 cycles per second. The frequency was increased by steps up to 2,000 cycles per second.

The evaluation of a pavement structure is greatly facilitated if the subsurface materials can be separated into layers and specific properties assigned to these layers. It can be noted that lines have been drawn through the test points on Figure 1 with this end in view. It is necessary to determine the E-value of bituminous surface layers by laboratory methods. This determination was not made and no values are shown. A value of 1,900 is shown for the layer beneath the pavement to a depth of about 0.25 m. At this depth, the E-value increases to 2,700 and then shows with increasing depth a gradual decrease to about 1,300.

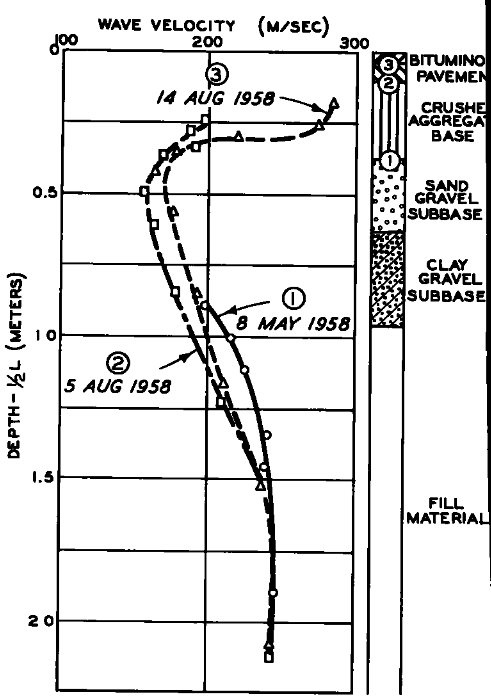


Figure 2.

The data shown in Figure 1 are the results of measurements taken at a small munic pal airport by Shell Oil Company personnel who had no knowledge of the subsurface con ditions at the time the test was conducted. Figure 1 also shows a section showing the actual construction at this site. The bituminous pavement surface consists of 1½ in. of sand asphalt with about a ¼-in. surface treatment. Below this is a 9 in. base of plastic clay gravel. The surface of the natural ground, a sandy silt, was compacted

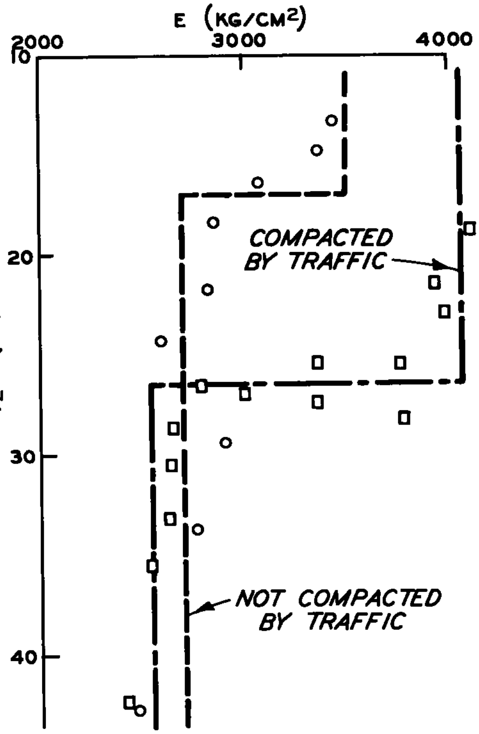


Figure 3.

prior to placement of the base course. The subsurface soils were not tested by conventional methods at the time of the vibration tests; however, it is known from pavement performance and from several series of earlier tests that the plastic clay gravel now has a high water content and a relatively low strength. It is considered that in this particular case, the results of the vibration tests agree satisfactorily with known relative strengths and depths to the subsurface layers.

Some idea of the capability of this method of exploration to resolve the subsurface properties adequately can be gained by an examination of Figure 2. Wave velocities are plotted against depth. Curve 1 was obtained from a test made May 8, 1958, at which time the surface was at point No. 1 on the log. The other curves were obtained from tests made after the addition of 11 in. of base course material and after construction of a 2 ½ - in. bituminous binder course. Obviously the curves are not coincident, but it should be remembered that the data were taken over a period from May 8 to August 27 as noted in Figure 2. It is suspected, and some supporting evidence is available, that a wetting and drying took place between May and August which may account for the differences occurring at the 40- to 60-in. depth interval. Even with no attempt to correct for such a possibility, the velocity values in the deeper layers before and after the addition of other layers at the surface are in good agreement.

Figure 3 shows that it is sometimes possible to detect changes in properties of the subsoil by means of velocity measurements. In this case, a portion of silty clay subgrade constructed under controlled conditions was subjected to traffic and other portions were not. These data show the increase in E-value caused by the effects of traffic. Data were also obtained from conventional soil tests made at depths of 2, 8, and 14 in. in trafficked and untrafficked areas and are given in Table 1 together with the E-value determined from vibration measurements.

TABLE 1

| | Before Traffic | | | | After Traffic | | | |
|---|---|---|---|---|---|---|---|---|
| Depth (in.) | γ | Water Content (%) | CBR | E | γ | Water Content (%) | CBR | E |
| 2 | 108.7 | 13.8 | 41 | - | 110.2 | 10.6 | 70 | - |
| 8 | 107.6 | 13.2 | 44 | 2,600 | 108.5 | 11.8 | 68 | 4,100 |
| 14 | 105.5 | 12.1 | 36 | 2,600 | 106.3 | 12.3 | 38 | 2,500 |

At a depth of 8 in., traffic caused the CBR value to increase from 44 to 68, an increase of 55 percent. Referring to Figure 3, it can be seen that the E-value at the 8-in. depth, determined from vibration measurements, increased from about 2,600 to about 4,100, an increase of 58 percent. It should also be noted that at a depth of 14 in., both CBR and E-values indicate that little or no change occurred.

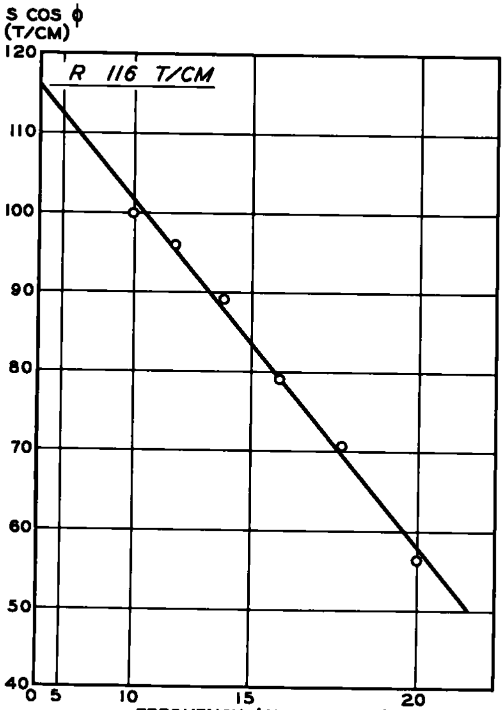


Figure 4.

## STIFFNESS MODULUS

Data presented thus far have shown ty cal results that have been obtained from velocity measurements only and have ind cated that such measurements can provid information on conditions throughout the depth of the construction except for the to several inches. As stated previously, a stiffness modulus for the whole system c be determined directly. This stiffness modulus was defined as the ratio of a dyn ic load to the resulting deflection. The l frequency vibrator is used in this test be cause the forces developed are great eno to result in measurable deflections.

The force on the pavement is depende on the frequency and the machine constan Machine constants take into account the mass of the machine, eccentricity and ma of the rotating weights, and phase angle. The deflection is measured by electronic means. Further details are beyond the scope of this paper but are available in th references listed.

It is obvious that the higher the freque at which the machine is operated the grea will be the force generated. Thus, a stiff ness modulus as previously defined can b determined for each frequency used. Oth investigators have found the stiffness mod lus to vary with the frequency and that the variation is generally not linear. Heukelom showed that the value of the stiffness mod lus depended on the mass of the soil in motion. In a system consisting of mass M, a spring R, and a dashpot, it can be shown that

$$S \cos \phi = R - W^2 M$$

in which

$S$ = dynamic stiffness (stiffness modulus as previously defined)
$\phi$ = phase lag of the deflection with respect to the applied force
$W$ = angular frequency ($2\pi n$ where $n$ = frequency in cycles per second)

When $S \cos \phi$ is plotted against a function of the square of the frequency, a straight line through the experimental points intersects the $S \cos \phi$ axis at a value R which is called the elastic stiffness. Figure 4 shows such a plot. The data shown in this figure were obtained from tests made at the same location as the velocity measurements show in Figure 1.

Returning now to Figure 1, it will be recalled that E-moduli of 1,900, 2,700, and 1,300 kg/cm$^2$ were found for the 9-in. base course, the compacted subgrade, and the deep soil, respectively, but that the E-modulus of the bituminous pavement was not determined. If this value was known, the elastic stiffness R of the entire system could be computed and this would permit a check on the R value determined as shown in Figure 4. The E-modulus of a bituminous pavement depends on the bitumen content, penetration value of the bitumen, temperature at the time of test, and rate of loading. Nijboer and others have developed theoretical methods whereby the E-modulus can be estimated, but a direct determination in the laboratory is much to be preferred. Folowing Nijboer's method, the E-modulus was estimated to be 7,000 kg/cm². Using this alue, and values for the underlying layers determined experimentally, R was computed o be 113 t/cm as compared with 116 t/cm determined from direct measurements. Too nuch significance cannot be given to the close check obtained in this particular case as t was necessary to estimate one of the one of the values used. The example was preented to illustrate that when all data are available, the determination of R by two diferent methods is possible which provides a check on the work. It is also evident that f the E-modulus of the surface layer is not known and cannot be accurately estimated, t can be treated as the "unknown" and determined, knowing the E-modulus of the underying layers and the elastic stiffness of the whole system.

Several values of elastic stiffness in tons per centimeter, together with a brief decription of the materials (to illustrate the range of values encountered) are given, as ollows:

115-130 — unsurfaced, well-compacted, silty clay; CBR 40-60 percent.
160-170 — 5- to 10-in. crushed gravel over 24-in. clay gravel.
170-180 — 10- to 12-in. crushed gravel and slag over 10-in. sand gravel over clay-gravel subgrade.
200-210 — ½-in. bituminous surface over 10- to 12-in. crushed gravel and slag over 10-in. sand gravel over clay-gravel subgrade.
250-400 — Heavy-duty airfield flexible pavement.

## POTENTIAL USES

The material in this paper has been restricted to essentially a presentation of exmples of the type of data obtained directly with the Shell road vibration machine and he initial treatment of these data. A study of the references will show that many uses an be made of these data. For example, actual deflections measured under given oads can be related to deflections to be expected under vehicles or aircraft of similar oadings. Also, with measured deflections, strains can be computed which can in turn e compared with strength available. Such uses involve assumptions and theories beond the scope of this paper.

It appears highly probable that useful relations can be developed between the values etermined from vibratory measurements and the conventional values used in design nd evaluations, such as unconfined compressive strength, subgrade modulus (K, from late bearing tests), density, CBR, and others. To establish such relationships, it is ecessary to make the vibration measurements at locations where complete information n the subsurface conditions at the time of test is available.

The Shell road vibration machine has been used for sometime in Europe with considrable success. The Waterways Experiment Station had the use of the machine for bout six months and based on the observations during that period, it is believed the nachine has immediate application in the evaluation of airfield pavements. The machine s usually operated by a crew of three men; however, a fourth man is desirable when he test data are to be reduced in the field for immediate use. In a normal working day, a four-man crew can determine the stiffness moduli of the pavement at four locations. These determinations will show relative over-all strength and will permit definition of 'weak" and "strong" areas. After stiffness moduli have been determined, velocity neasurements can be made at selected locations dependent on the particular problem nd information on the strengths of individual subsurface layers obtained to supplement he stiffness measurements. While proven methods are not presently available to relate esults obtained with this machine directly to bearing capacity or performance, data btained from satisfactory and unsatisfactory areas would permit an estimate of performnce. It also appears highly probable that periodic measurements would provide useul information on the seasonal changes taking place in a pavement structure such as vetting and drying or feezing or thawing.

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