Study of Pavements using Surface Wave Propagation Technique

by

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Introduction

A few years back, the Central Road Research Institute acquired, under ECAFE assistance, an apparatus for the study of pavement structures using surface wave propagation technique. Using this apparatus, a good number of typical pavements were studied. Presented in this paper are the various aspects of the study of pavement structures through surface wave propagation. The capabilities and limitations of this technique are brought out on the basis of the experience at the Institute and elsewhere. The data collected on typical locations are presented along with the related analyses. Further work and possible uses of the measurements are also indicated.

Historical Background

2.1 Vibrational technique for the study of sub-strata is known to have been first employed in Germany, a few years before the World War II (Hertwig et al 1933, Erlenbach 1936 and Ramspeok et al 1938). Using a mechanical vibrator (rotary, out-of-balance mass type), efforts were made to arrive at the mechanical properties of soil strata. This work brought out the limitations of evaluations/measurements with regards to: representing soil mass through a spring or a damped spring, and variations due to changes in the vibratory force, the inertia effects of soil, etc. By that time, the subject of wave propagation was not so well understood. This work in Germany was followed, upto World War II, by studies in Sweeden *(Bergstrom et al 1946) on a clayey stratum.* Notable work from the point of view of pavement application came from the Dutch Shell Laboratory (Vander Poel and Nijboer et al 1953). Their vibrator worked at forces 2 ± 2 tonnes (approximate.) In the frequency range of 5 to 60 c/s. The work inter-alia brought out the concept of dynamic stiffness which is defined as the peak force divided by the peak displacement. This stiffness is found to be dependent on both the frequency and the force of vibration. As the frequency range of the Shell Vibrator was too small for encompassing the top layer of the pavement, developmental work in U.K. led to another vibrator with frequency capability of 5000 c/s and more (Jones 1958, 1960). Since then, still improved versions capable of frequencies of upto 30000 c/s have been brought forth.

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Equipment Used

The equipment acquired by the Institute is of French make (Socie'te' Europe 'enne d' 'Etudes et d'Essais d'Environnment). The apparatus consists of a relatively low force vibrator (self weight 60 kgs., Goodman type) with frequency range of 5 to 20000 c/s. It may be considered to be having two sub-assemblies: one to generate vibrations, and the other to monitor wave propagation. The equipment is vehicle-mounted and thus mobile. There is a blower for the cooling of the vibrator. Shown in figure 1 is a general view of the equipment whereas Figure 2 shows an inside view of the van and the instrumentation for measurement. Shown in Figure 3 is the block diagram indicating the main components of the two sub-assemblies. The equipment has been described in more detail in another paper (Swaminathan et al 1979). The vibrations imparted by the vibrator lead to the generation of elastic waves which can be picked up at different radial distances through a pick-up. After the pre-amplifier, there is a selective amplifier which responds to the frequency in use. On the dual trace oscilloscope, two sinusoidal waves are indicated: one directly from the oscillator (feeding to the vibrator) and the other received from

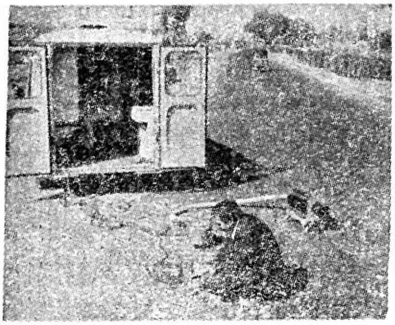


FIGURE 1 General view of the setup for wave Propagation measurement

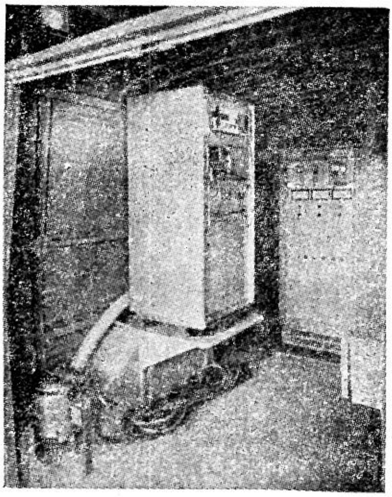


FIGURE 2 Inside view of the Van flowing instrumentation for measurement

the pick-up after amplification (Figure 4). The phase difference in these waves is measured with the 'Phase Meter'. The measurement of phase angle gives wave length and thus velocity of propagation. At the same location, a series of measurements are made with varying frequencies, higher frequencies being needed for studying top layers.

Wave Propagation

Wave propagation through semi-infinite media has been a subject of study for quite some time now. Shown in Figure 5 are the different common modes of propagation of waves generated by vibrator with circular base placed normal to the surface. We have the longitudinal, the

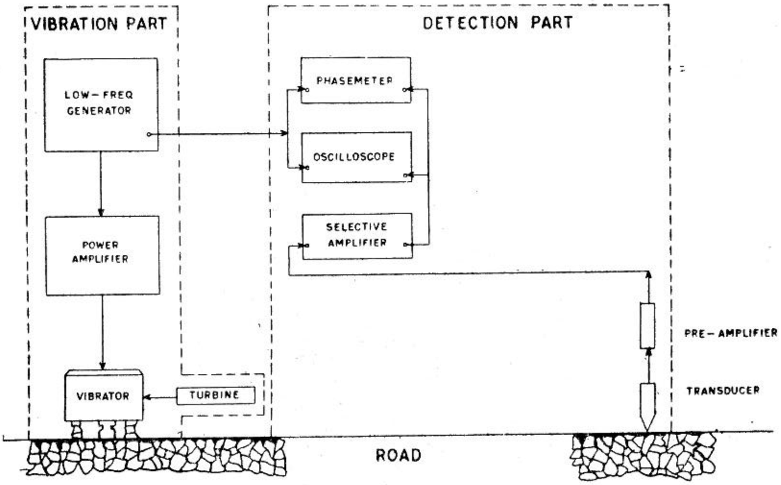


FIGURE 3 Block diagram of apparatus used

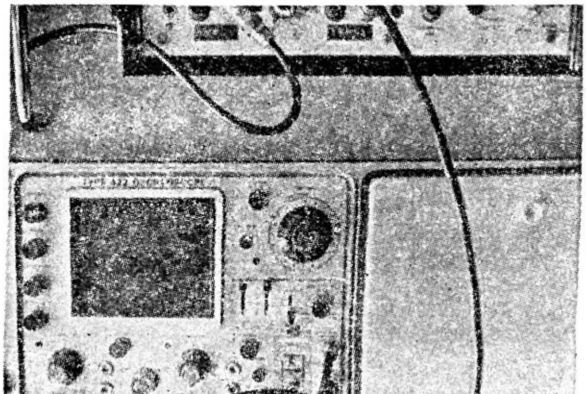


FIGURE 4 Two sinusoidal waves (reference wave and picked up wave) as seen on the dual-trace oscilloscope

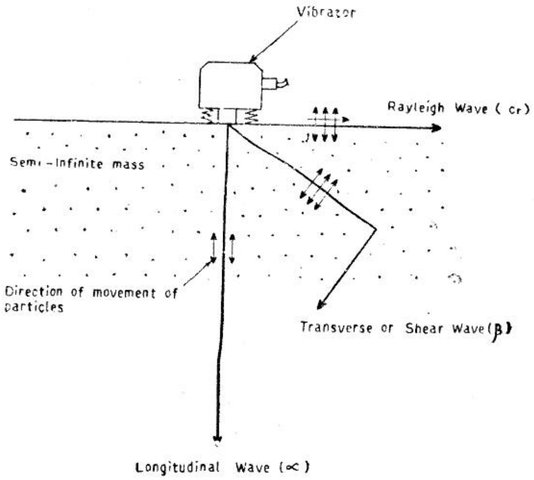


FIGURE 5 Modes of propagation of waves in a semi-infinite mass.

transverse/shear and the surface/Rayleigh waves generated. The longitudinal waves (fastest) which propagate in the direction normal to the surface tend to get attenuated in the system unless they are specially reflected back. The surface waves (slowest) are normally associated with the top position and propagate over long distances without undergoing much loss in amplitude. It has been brought out that as much as two-third of the energy is radiated as surface waves in the case of a typical elastic semi-infinite solid (Miller et al 1955). In the upper layers, there are either only surface waves or combinations of surface waves and shear waves. Monitoring for lower layers is largely in respect of shear waves. The behaviour and characteristics of the propagating waves have been theoretically analysed by a few researchers for plates as well as semi-infinite solid media. Analysis of wave propagation in a multilayered structure becomes fairly complex. Solutions available are generally limited to the case of a layer of finite thickness resting on another layer of infinite depth (Jones 1960).

Test Measurements and Data

Using the equipment explained in Section Equipment used, work was taken up on study of pavements in and around the Institute. These measurements covered typical cases of both flexible and rigid pavements as under.

(*a*) *Rigid pavement* (with granular sub-bases)	Plain cement concrete, cement concrete with partial replacement of cement with puzzolana and cement concrete pavement with bituminous overlays.
(*b*) *Flexible pavement*	Asphaltic concrete, bituminous maçadam, WBM and stone soling.
(*c*) *Subgrade*	CL—ML. type of soil

The equipment in the van is quite sensitive to the prevailing temperatures. As the airconditioning is yet to be installed in the van, measurements were limited to winter months and cooler hours (morning & evening) during summer months when the air (shade) temperature was 20-25° C. As considerable part of the carriage-way was occupied for the test, arrangements had to be made for traffic diversion while dealing with highway sections. Vibrations/electrical noise caused by passing vehicles generally did not interfere with the measurements. The vibrator was positioned at the centre line of single lane carriageway way, and at least 1.5—1.8 m. from the edge of two multi-lane carriage ways. Start was made with low frequencies, monitoring wave propagation for phase angles at various radial distances for a length of about 2 metres. The equipment had limitation beyond this radial distance. The frequency was increased in steps and generally measurements were made at each locations with 15-20 different frequencies.

For each such measurement, wave length is arrived at from phase angle measurement (Figure 6). Knowing the frequency and the related wave length, velocity of wave propagation is determined. Knowing velocity of wave propagation, Young's modulus/shear modulus is arrived at from the following relationship.

Shear modulus, $G = \frac{dC^2}{p^2 g}$ ...(1)

or Young's modulus, $E = \frac{2(1+\mu)\, dC^2}{p^2 g}$ ...(2)

Where G = Shear modulus (kg/cm^2)
E = Young's modulus (kg/cm^2)
C = Phase velocity (cm/sec)
d = Density (kg/cm^3)
g = Acceleration due to gravity (cm/sec^2)
p = A constant which is equal to 1.0 for shear waves, but varies from 0.91 to 0.96 for Rayleigh waves depending upon Poisson's ratio, μ.

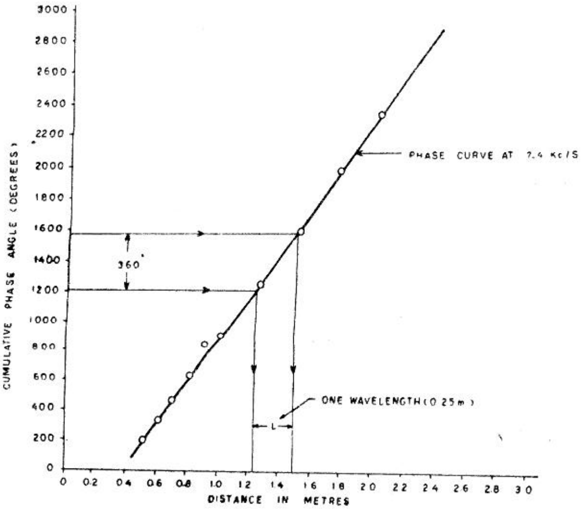


FIGURE 6 A typical phase curve

Given in Figure 14 is the nomogram for obtaining, conveniently, Young's modulus as per Equation 2. The phase velocity, *C*, in the nomogram is shear wave velocity (i.e. $p = 1.0$). For Reyleigh wave velocity, the value obtained from the nomogram is to be adjusted slightly as per changes in the value of *C* as above.

After obtaining the phase velocity, plots were made correlating phase velocity and wave length. A few of these typical plots, known as dispersion curves, are given in Figures 7-13. The actual pavement composition is also indicated by the side of the corresponding dispersion curve. It is to be observed from these Figures that there are discontinuities, essentially corresponding to the distinctly different layers. There have been a number of different approaches for the interpretation of these dispersion curves with discontinuities. Earlier work had pointed to the hypothesis that the wavelength corresponds to twice the depth of that layer (Maxwell 1960). Data in Figures 7-13 as well as work from elsewhere (Jones 1960) go to indicate that such is not the case.

In fact there are no satisfactory means as yet available for delineation of layers in multilayered pavement. Techniques have been developed viz. the superposition technique and the least square technique given by Guillemin and Gramsammer (1971) whereby the thickness of superior top layer can be estimated with an accurancy of 10 to 15 per cent. The superposition technique (an example is shown in Figure 15) does require a measure of experience for satisfactory results. It is, therefore, to be said that wave propagation measurements with the equipment under reference are not able to define adequately the thicknesses of lower layers. This part of measurement can in any case be done directly without much inconvenience or delay.

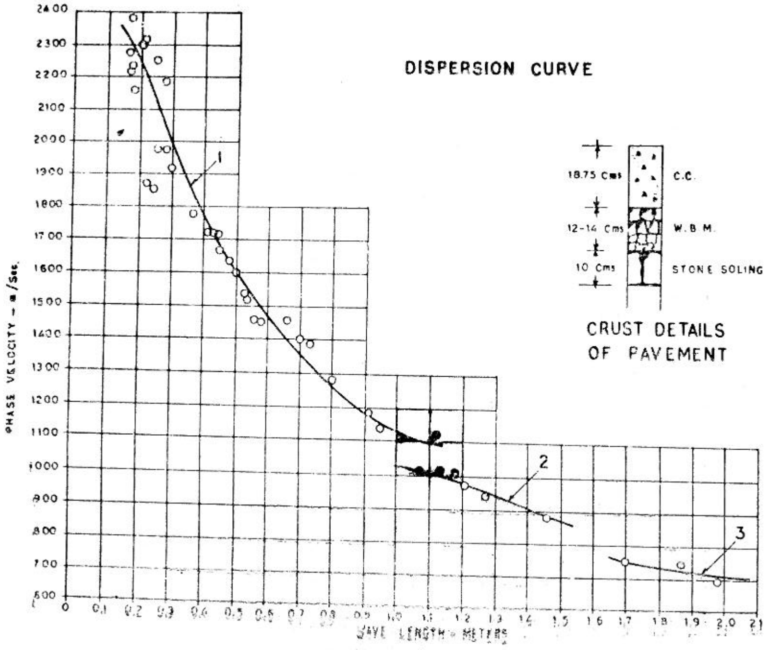


FIGURE 7 Cement concrete pavement

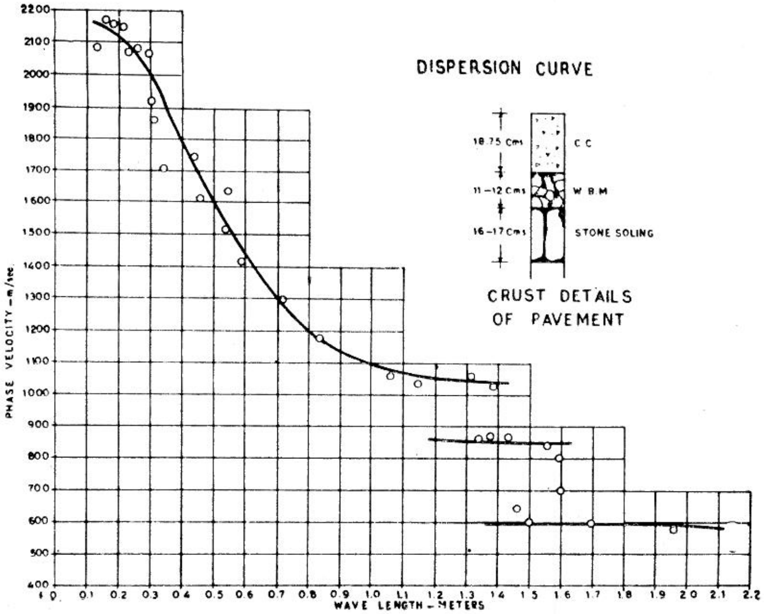


FIGURE 8 Puzzolana concrete pavement

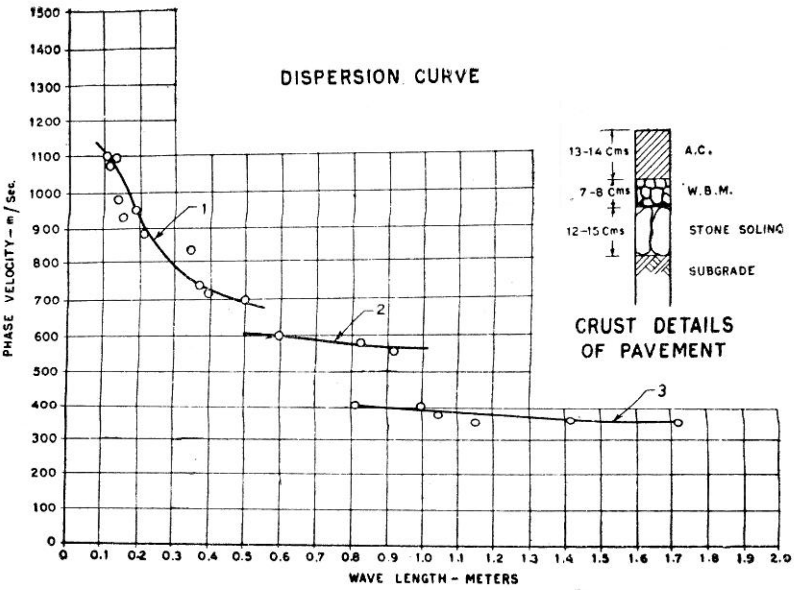


FIGURE 9 Flexible pavement

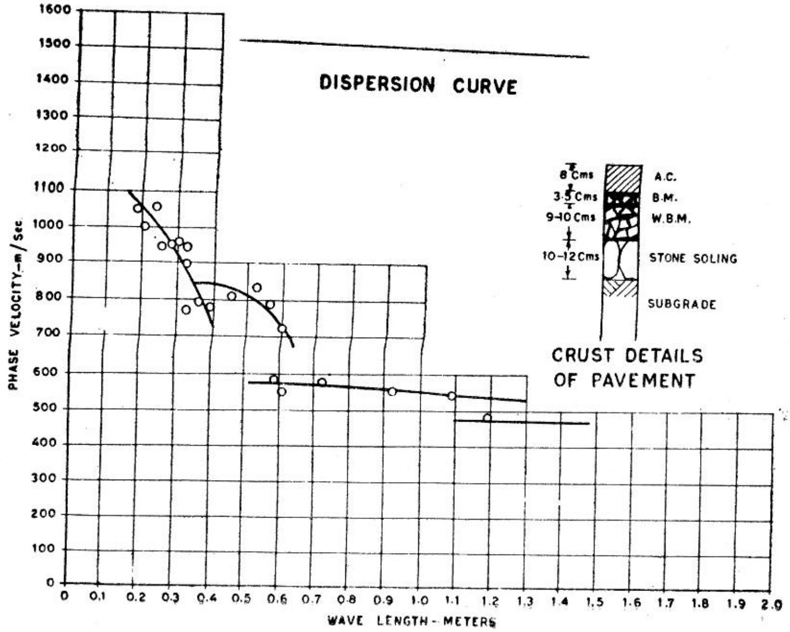


FIGURE 10 Flexible pavement

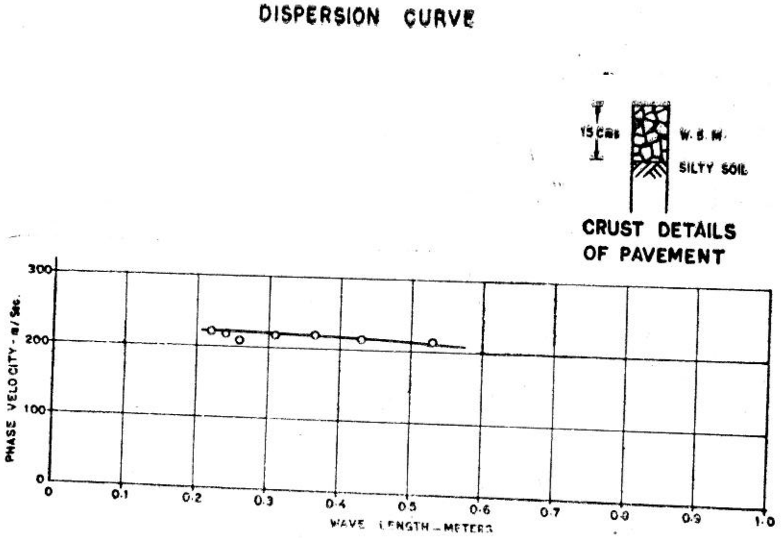


FIGURE 11 W.B.M. Surface Course

On closer study it is seen that the discontinuities in the dispersion curve are indeed an indicator of distinctly different layers present. The top (intersection with ordinate corresponding to zero wave length) of enveloping curve (No. 1 in Figure 7) is seen to correspond with the phase velocity for the top layer. Essentially Rayleigh/surface waves account for this segment. The other two segments are seen to have relatively little steepness and their peak values (shear waves) correspond to the elastic

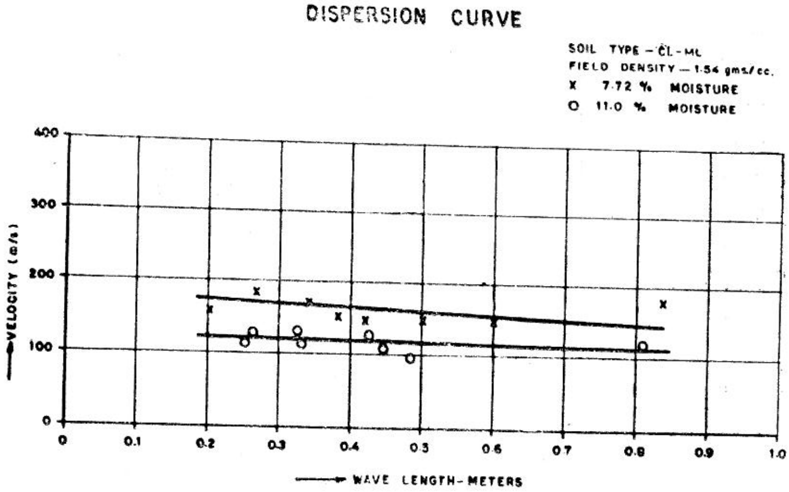


FIGURE 12 Soil Subgrade

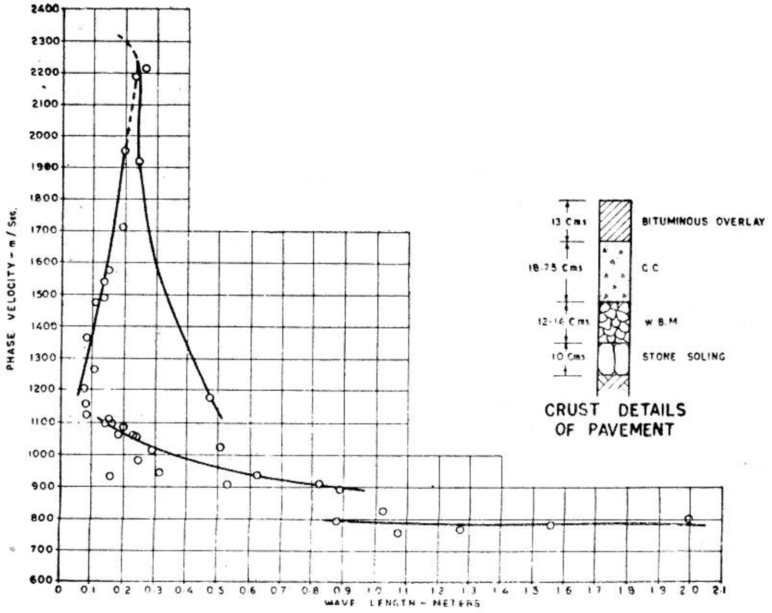


FIGURE 13 Bituminous over lay on concrete pavement

properties of the second and the third layer respectively. Where there were three or more constituent layers, it was difficult to monitor the bottom most layer i.e. the subgrade etc. Shown in Figure 11 is the dispersion curve for the case of 15 cm thick W.B.M. lying on silty subgrade. Figure 12 shows two dispersion curves for a subgrade (*CL—ML*) at two different moistures. The dispersion curve given in Figure 11 refers to a case of 18.75 cm thick distressed (degree unknown) cement concrete slab overlaid with 13 cm, thick bituminous surface courses. There is not only greater scatter but the dotted portions are less definitive. The special

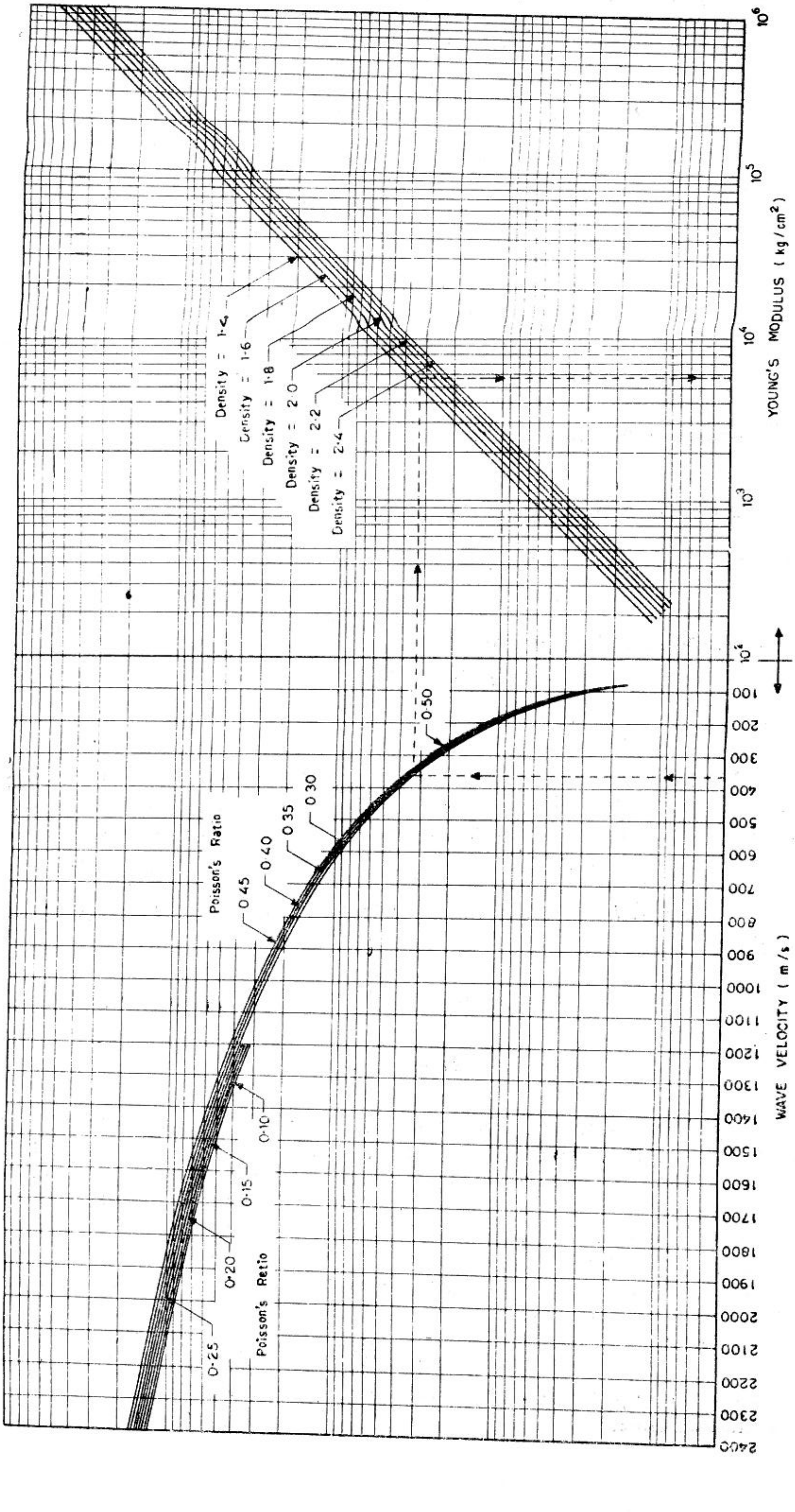


FIGURE 14 Nomogram correlating Young's modulus, Poisson's ratio, density and wave velocity

characteristic component of this dispersion curve is the drop in phase velocity for the bituminous overlay. The extrapolation of this curve upto $L=0$ is considered to give, approximately, the Rayleigh wave velocity for the top overlay layer.

For a more accurate delineation of the top layer in respect of both the thickness and the modulus of elasticity, a few researchers have been working on various possibilities. One approach is by Guillemin and Gramsammer (1971) where in the least square method is used. In this is assumed a theoretical exponential curve of the following type.

$$\frac{C}{C_r} = Ae^{B(L/H)} \qquad \ldots(3)$$

Within the interval of $0.2 < \frac{C_{min}}{C_r} < 0.7$.

where C_r = Rayleigh wave velocity of top layer

H = Thickness of top layer

L = Wavelength

C = Phase velocity as explained in this section

A and B are constants.

The equation can also be written as,

$$C = A_1 e^{B_1 L} \qquad \ldots(4)$$

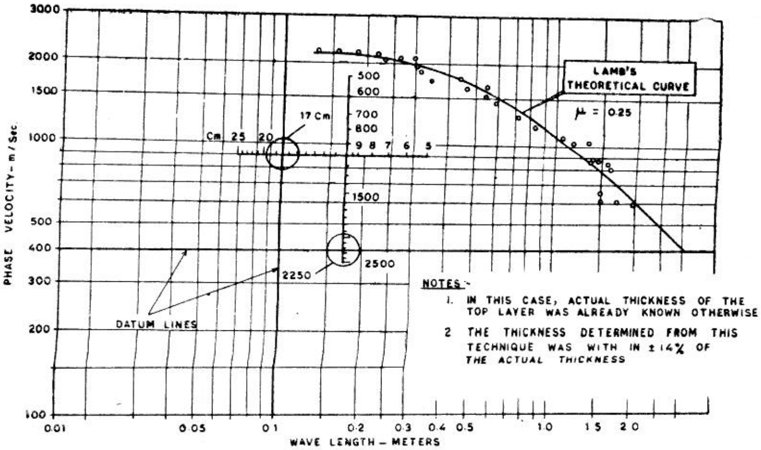
where, $A_1 = AC_r$, $B_1 = B/H$

Using the least square method on the experimental data, A_1 and B_1 are determined. A_1/C min. is also calculated and made use of for obtaining A and B from a nomograph developed by the above said authors. The approach is based on the theoretical analyses of elastic plate of finite thickness resting on semi-infinite foundation of low shear modulus. Once the constants A and B are known C_r and H can be readily obtained from the equations:

$$C_r = \frac{A_1}{A}$$

$$H = \frac{B}{B_1}$$

Reasonable estimates of the thicknesses of the top layers can be obtained with this least square method. A superposition technique has also been developed for the same purpose. The technique essentially consists in following a graphical adjustment procedure, after assuming the Poisson's ratio and the thickness for the top layer material. Shown in Figure 15 is a typical case of this graphical procedure. In this case the actual thickness was known and therefore a fairly accurate fit could be arrived at. This trial and error procedure, where thickness cannot be initially estimated, is not so convenient for determining the thickness of the top layer. In the case of Figure 15 (actual top layer thickness already known otherwise), the superposition technique gave a value of 91 per cent of the actual thickness.



NOTES :-

1. IN THIS CASE, ACTUAL THICKNESS OF THE TOP LAYER WAS ALREADY KNOWN OTHERWISE
2. THE THICKNESS DETERMINED FROM THIS TECHNIQUE WAS WITH IN ± 14% OF THE ACTUAL THICKNESS

FIGURE 15 Superposition technique adopted for obtaining the thickness of a concrete pavement

Given in Table 1 are the comparative values of thickness and Rayleigh wave velocity for the top layer, obtained by using the least square method and the superposition technique. The values of actual thickness of top layer are also given for comparison. The least square method is considered to be preferable. The superposition technique gave results closer to the actual values in these cases where the actual thicknesses were otherwise known. The least square method is more direct and does not depend upon a fairly accurate initial estimate of the thickness.

Given in Table 2 are the values of the Young's modulus obtained for different layers with surface wave propagation technique. For subsurface layers, the dispersion curve plot was read for the shear wave velocity and the modulus determined using appropriate relationship. For the top layer the wave velocity was read as Rayleigh wave velocity. The same was adjusted as per the least square method. The wave velocity values given in Table 2 are the thus-adjusted values.

The results may be summarised as under:

Material	*Range for Edyn. Value (kg/cm^2)*
1. Cement Concrete	3.642 to 4.204 × 10^5
2. Puzzolana Cement Concrete	3.648 × 10^5.
3. Asphaltic Concrete	0.874 to 1.144 × 10^5
4. W.B.M.	0.030 to 0.641 × 10^5
5. Stone Soling	0.108 to 0.369 × 10^5
6. Subgrade	0.014 × 10^5

Even though all the measurements are in respect of location within a radius of about 20 Km., the values at different locations are generally not comparable because of quality variation, stipulated in design or otherwise. All the same, some interpretations and derivations would appear to be in order. Firstly, knowing that the dynamic values are to be somewhat higher than those obtained from the static measurements, the values

TABLE 1

Values of Rayleigh wave velocity and thickness of top layer obtained with different methodes

Sr. No.	Material	Actual thickness of top layer (at edge) in cm.	Rayleigh wave velocity and Thickness of Top layer as per			
			Least Square Method		Superposition Technique	
			Thickness in cm.	Rayleigh wave velocity (m/s)	Thickness in cm.	Rayleigh wave velocity (m/s)
1.	Plain Cement concrete	18.75	15.00	2412	16.20	2240
2.	Plain cement Puzzolana Concrete	18.75	16.70	2247	20.50	2086
3.	Plain Cement Concrete	18.75	16.00	2393	17.25	2250
4.	Plain Cement Concrete	18.75	16.30	2245	17.00	2150
5.	Asphaltic Concrete	13.00	11.00	1075	12.50	1100
6.	Asphaltic Concrete + Bituminous Macadam	8.00 +3.50	*10.00	1230	12.50	1100

Notes :

1. *Using only the top portion of the dispersion curve.
2. In all these cases, the actual thickness of the top layer was already known for trials with the superposition method.

obtained for Young's modulus with surface wave propagation technique are generally quite reasonable. There is a large rangeof the modulus values for WBM constructed in all cases with the Delhi quartzite aggregate. When WBM was the surface course, a low value of 0.03×10^5 kg/cm^2 was obtained. WBM under cement concrete yielded value in the range of 0.412 to 0.641×10^5 kg/cm^2. Again, WBM under asphaltic concrete yielded Edyn value in the close range of 0.211 to 0.226×10^5 kg/cm^2. Similarly the modulus values for stone soling under cement concrete and WBM were in the range of 0.236 to 0.369×10^5 kg/cm^2. When stone soling was under asphaltic concrete and WBM, the value was in the range of 0.108 to 0.151×10^5 kg/cm^2.

This significant variation in the determined modulus value of the particular layer with change in its surroundings is considered to be of notable significance and this aspect needs to be taken up for a more detailed study under relatively controlled conditions.

TABLE 2

Dynamic Young's Modulus values determined using Surfaces Wave propagation technique

Pavement layers	Wave velocity m/s	Edyn. value	
		$kg/cm^2 \times 10^5$	$(lbs/in^2 \times 10^6)$
Cement Concrete	2412	4.204	5.967
W.B.M	1010	0.641	0.910
Stone Soling	*750*	*0.369*	*0.524*
Cement Puzzolana Concrete	2247	3.648	5.181
W.B.M.	860	0.464	0.659
Stone Soling	600	0.236	0.336
Cement Concrete	2393	4.138	5.876
W.B.M.	940	0.555	0.788
Stone Soling	600	0.236	0.336
Cement Concrete	2245	3.642	5.172
W.B.M.	810	0.412	0.585
Stone Soling	640	0.269	0.382
Asphaltic Concrete	1075	0.874	1.240
W.B.M.	600	0.226	0.321
Stone Soling	405	0.108	0.153
Asphaltic Concrete	1230	1.144	1.624
W.B.M.	580	0.211	0.300
Stone Soling	480	0.151	0.215
W.B.M. Surface Course	220	0.030	0.043
Soil Subgrade (only)	165	0.014	0.020

Notes:

1. The wave velocity values given above were obtained as under :
   - —for subsurface layers, the values were read directly from the dispersion curve plot as shear wave velocity.
   - —for the top layer, the Rayleigh wave velocity was read directly from the dispersion curve & then adjusted as per the least square method.
2. The measurements relate to air shade temperature in the range of 20-25°C. Moisture was not monitored, generally.
3. The Young's modulus was determined for the following values of Poisson's ratios :
   - —Cement concrete and puzzolona cement concrete—0.25
   - —Asphaltic concrete —0.35 —W.B.M. —0.40
   - —Stone soling —0.40 —Subgrade Soil —0.45

As stated earlier, the wave propagation measurements were carried out in temperate weather only i.e. when the air shade temperature was in the range of 20-25°C. Towards a limited study of the effect of moisture measurements were carried out on a bare subgrade (soil) at two different moisture contents (7.2 and 11.0 per cent). The test data are shown in Figure 12. It is seen that for this subgrade (*CL-ML*), the increase in the moisture content did yield separate dispersion curves resulting in approximately 53 per cent decrease in Young's modulus. There was a drop of 58 percent in the corresponding CBR value. For this limited data, the Edyn value (kg/cm^2) was found to be approximately equal to (numerically) 180 times the CBR value.

Significance and uses of wave propagation measurements

Obviously, the surface wave propagation technique provides very convenient and expeditious means for qualitative checking of uniformity of construction. It can be expected to give a qualitative idea of variations in composition, processing, structural state, etc. of a pavement layer. It is possible to estimate at present at least the thickness of the top layer. The modulus values can be ascertained for the top three to four layers. It is to be recalled that the modulus determined here is essentially in a stress free condition for the prevailing temperature and moisture conditions. One can conceive a broad pavement design/evaluation system in which performance data provide the back bone and the procedures of Edyn. determination are normalised through adjustments with the help of theoretical analyses, so as to conform to the performance data. This can hardly be called a simple effort but, when carried out, can lead to a relatively simple method of layer/material evaluation.

Further work

Further work is considered to be indicated on the following lines

(*i*) A controlled study on specially prepared test sections may be taken up where both plate bearing load tests (static and repetitive) and wave propagation measurements be carried out layer by layer so as to (*a*) study the relationship between the moduli obtained with these methods, and (*b*) study the effect of the surroundings on the modulus value of a layer/material.

(*ii*) A larger volume of data on wave propagation measurements and their analyses, may be collected.

(*iii*) Theoretical analyses of stress/strain/fatigue aspects and study of relationship of wave propagation modulus values in the context of other indications (performance data, stresses/strains, deflections), may be taken up.

Concluding remarks

Even though wave propagation measurement technique was initiated before world War II it is yet to become an effective evaluation tool. The limited data presented and discussed in the paper would show that the technique is not without possibilities. Additional work is needed to establish further scope and limitations of this non-destructive technique. Work done so far shows that it is possible to make reasonable estimates of modulus of elasticity of various layers in a pavement when the number of layers is limited to three or so and when the constituent layers have distinctly different characteristics. With the currently available procedures, it is possible to make a fairly good estimates of the thickness of the top pavement layer. This however is not considered to be significant as the layer thickness can be fairly and readily determined by other direct methods.

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