THE USE OF THE S.A.S.W. TO EVALUATE THE DETERIORATION OF PAVEMENT PROPERTIES WITH INCREASE IN WHEEL LOADS

J C Engelbrecht:
Senior Lecturer. Department of Civil Engineering, University of Stellenbosch
Republic of South Africa
M van de Ven:
Professor. Department of Civil Engineering , University of Stellenbosch
Republic of South Africa
E Sadzik:
Department of Transport and Public Works Gauteng Province
Republic of South Africa

ABSTRACT

The application of a non destructive test method for the determination of elastic properties of pavement layers and soil layers is being discussed. This method makes use of the seismic wave theory through the analysis of surface waves S A S W (Spectral analysis of surface waves). The SASW method is based on generation and detection of elastic stress waves, known as surface waves. Surface waves have a unique characteristic that, if the wavelength is varied, the velocity of propagation of the surface waves also varies. This phenomenon is called dispersion. The dispersion characteristic of surface waves can be utilised to determine the layering and modulus profiles of pavement systems quite accurately.

The method is non-destructive. Measurements are made at strains below .001 % where the elastic properties of the materials are independent of the strain amplitude.

The method is such that both the source and the receivers are located on the ground surface. The source is simply a transient vertical impact, which generates a group of surface waves of various frequencies that the medium transmits.

A pilot study was conducted on a test site, with different test sections, that was situated on the road D 2388 near Cullinan in Gauteng Province. These test sections were constructed with different base course materials as part of a labour intensive project. The aim was to find out how well the SASW method could be applied to obtain information on the deterioration of the pavement, in terms of the change in stiffness, with the increase in number of wheel load repetitions.

The results obtained were such that a relatively complete picture of the status of the structure of the road could be obtained. The deterioration with the increase in load repetitions was well defined. The testing contributed to a better knowledge and understanding of what is happening underneath a loaded pavement structure.

1. INTRODUCTION

The Department of Transport and Public Works of the Gauteng Province contracted the Institute of Transport Technology (ITT) of the University of Stellenbosch to do a pilot study, on the use of Spectral Analysis of Surface Waves (SASW).

The aim was to obtain information on the deterioration of the pavement, in terms of the change in stiffness, with the increase in number of wheel load repetitions, and how well the SASW method could be applied to measure this. The focus of the research was on the evaluation of the base (ref. 5). Together with the study of changes in the stiffness, on the trafficked section, a request for the testing of a number of different test sections was made. These test sections were constructed with different base course materials as part of a labour intensive project These sections consist of similar profiles as the trafficked section except for different base courses and thickness.

The typical pavement structure, at the HVS test section, was as follows:

- An asphalt surfacing 35 mm,
- Base course
- Cemented sub base.
- Selected subgrade on top of the natural subgrade.

The test site was situated on the road D 2388 near Cullinan in Gauteng Province.

The tests at the HVS position were conducted after three levels of number of loading repetitions.

2. TESTING PROGRAMME

The HVS test section was visited three times during the phase of the application of load repetitions by the HVS

Due to delays in obtaining the testing equipment, the first series of tests could only be done after more than 400000 load repetitions had been completed.

The structure with the150 ETB (150mm thick emulsion treated base), at the HVS testing site, was tested in the wheel path of the heavy vehicle simulator as well as on an intact section next to the wheel path.

The testing programme is shown in table 1.

Table 1: Test programme

Date	HVS site	
	Outside wheel path No Load repetitions	In wheel path (Load repetitions)
10 March 2000	Yes	432482
3 April 2000	Yes	764499
28 April 2000	No	912638

3. TESTING METHODOLOGY

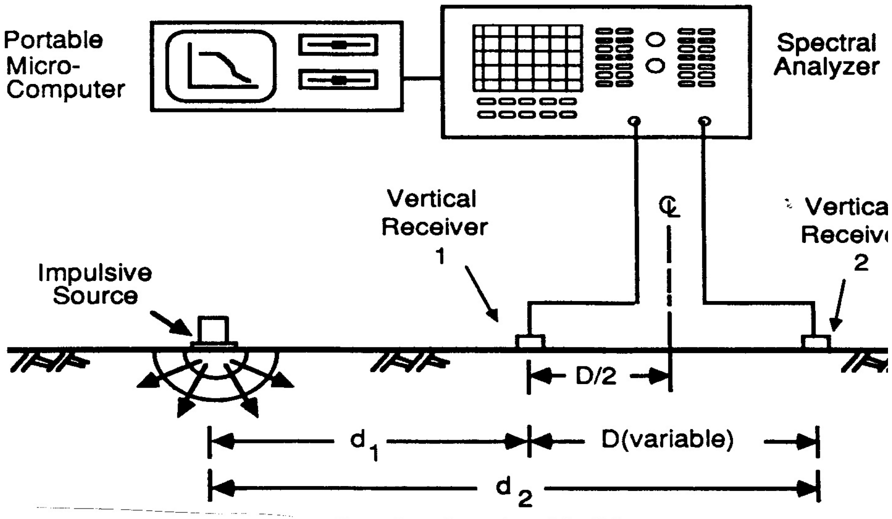
A seismic method for the in-situ measurement of elastic modulus profiles of pavement has been developed at the Center for Transportation Research at the University of Texas at Austin TX. For an extensive description of the SASW method, see references 1 and 4.

This method is called the Spectral-Analysis–of Surface–Waves (SASW) method. The method is based on generation and detection of elastic stress waves, known as surface waves. There are three different kinds of waves that can be generated. The types of waves are; Surface - or Raleigh waves, shear waves and pressure waves. The key points in SASW testing are generation and measurement of surface waves, which makes up more than 67% of the response. Surface waves have a unique characteristic that, if the wavelength is varied, the velocity of propagation of the surface waves also varies.

This phenomenon is called dispersion. The dispersion characteristic of surface waves can be utilized to determine the layering and modulus profiles of pavement systems quite accurately.

The method is non-destructive. Measurements are made at strains below .001 % where the elastic properties of the materials are independent of the strain amplitude.

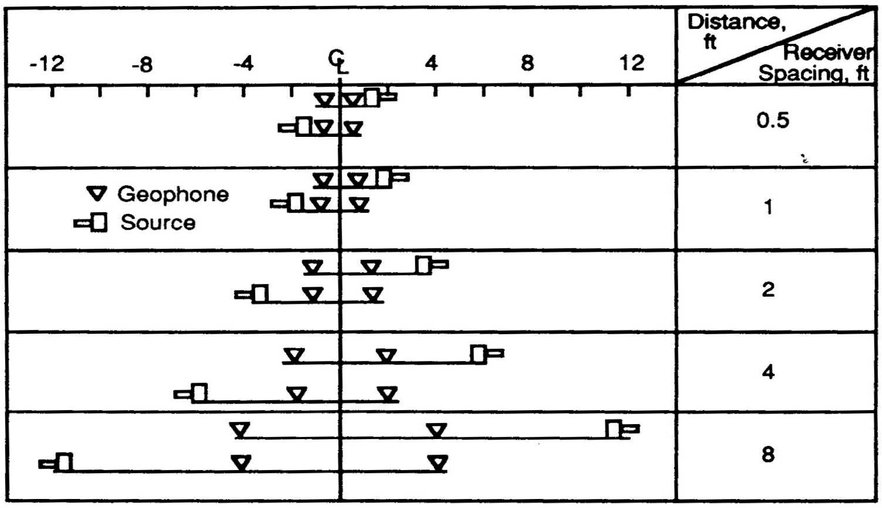
The method is such that both the source and the receivers are located on the ground surface, see figure 1. The source is simply a transient vertical impact, which generates a group of surface waves of various frequencies that the medium transmits. Two vertical receivers, located on the surface, monitor the propagation of surface wave energy past them. By analysis of the phase information of the cross power spectrum for each frequency determined between the two receivers, phase velocity, shear wave velocity and finally elastic moduli are determined.



General configuration of SASW testing.

Figure 1

The methodology used was to measure a number of spacing distances between receivers, starting at 50mm apart up to 600mm apart. The equipment used could only measure from 50 mm upwards. For the very close distances a small ball bearing was used as source and at the greater distances a small hammer was used. The temperature of the asphalt in the HVS section was about 25^0 Celsius, due to the shade from the HVS machine. The testing was done according to the mid-point concept, as shown in figure 2. At each site a central line was established as the mid-point. The receivers were placed equidistant from the mid-point at a spacing of 50mm increasing in steps of 50mm up to 600mm. Per spacing a total of five impulses were generated.



Schematic of experimental arrangement for SASW tests.

Figure 2

The analyser recorded the average of the five phase differences of the cross power spectrum, as well as the coherence, of the signals between the two receivers. From the phase difference and with a known frequency, it was possible to obtain the surface wave velocities and wavelengths. A plot of wavelength against velocity is called a dispersion curve.

4. ANALYSIS OF TEST DATA

The experimental dispersion curves were obtained from the data of the phase difference as given by the cross power spectrum. This was done through a process of masking, whereby that part of the cross power spectrum, with poor coherence is removed from the calculations. The part with poor coherence is contaminated with the background noise or reflected waves. A number of experimental dispersion curves are constructed from the data of surface wave velocities through all the different pavement layers. These curves are then grouped together in a compact curve. Theoretical velocity and density profiles, with layer thickness, are then assumed and the equivalent theoretical dispersion curve obtained. The idea is to get as close a fit as possible between the experimental and theoretical curves. This exercise is called forward modelling.

In order to obtain the theoretical curves it was necessary to define each layer according to thickness, Poisson's ratio, density, and shear wave velocity. Prior knowledge of layer thickness is not necessary, but it can assist with the interpretation of the results, if known

From this forward modelling process, the shear wave profiles were drawn up for each of the test positions. The stiffness profile for each testing position could then be calculated.

4.1 Calculation of the Stiffness Values.

From the SASW surface wave velocity the SASW ("raw") modulus can be determined using Equation 1. The equation is based on the linear-elastic relationship between the shear and Young's modulus elasticity, and the assumption that the surface wave velocity is about 90% of the shear wave velocity (Ref 2).

$$E_{Raw} = 2 * 10^{-6} \rho V_s^2 (1 + \upsilon) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{Eq 1}$$

Where:

E_{Raw} = raw modulus in MPa

ρ = average density in kg/m^3

V_s = shear wave velocity (~1.1 times the surface wave velocity (V_R)) in m/s

ν = Poisson's ratio

Because of the visco-elastic behaviour of the asphalt surface layers, the stiffnesses were corrected for temperature as well as frequency.

The raw pavement AC moduli were normalised to 30Hz frequency and 21^{o}C using the following Equations: (Ref 2)

Frequency Correction to 30Hz

$$E_{f_{30Hz}} = E_{Raw} * \left(\frac{f_m}{f_{30Hz}} \right)^{-A} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{Eq. 2}$$

Temperature Correction to 21^{o}C

$$E_{T_{21\ C}} = \frac{E_{f_{30Hz}}}{(1.51 - 0.00729(1.8T_m + 32))} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{Eq. 3}$$

Where:
E_{Raw} = raw pavement AC modulus in MPa.
E_{f30Hz} = pavement AC modulus normalised to 30Hz frequency in MPa.
E_{T21C} = pavement AC modulus normalised to 21°C (70°F) in MPa
ρ = average pavement AC density in kg/m^3
V_s = shear wave velocity (~1.1 times the surface wave velocity (V_R)) in m/s
ν = Poisson's ratio (~0.33)
A = temperature dependent factor
f_m = frequency at the time of measurement obtained from SASW velocity-wavelength curve in Hz
f_{30Hz} = 30Hz frequency
T_m = pavement temperature at the time of SASW measurement in °C

The frequency is related to the velocity and wavelength by the following equation:

$$V = \lambda f \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{Eq. 4}$$

Aouad (ref. 2) stated that the frequency of 30 Hz is equal to the operating frequency of the FWD and by normalising to this frequency, it should be possible to compare the results of the two testing methods. It should however be borne in mind that the two testing methods are completely different and that no real deflections would be experienced with the SASW method.

It was possible to establish assumed velocities through the process of forward modelling. The surface layer distinctly influenced the form of the combined experimental dispersion curve for all the layers. The slope of the dispersion curve in the vicinity of the very short wavelengths depends mainly on the stiffness of the upper layer. During the forward modelling it became apparent that the best curve fitting could be obtained by accepting the shear wave velocities for the surface layer as shown in the tables.

The assumed velocities for the asphalt layer can be greatly under-estimated, because of the thin asphalt layer. The shortest spacing that could be obtained was 50 mm with frequencies of 20 KHz. The velocities obtained are, in fact, combinations of the velocities in the asphalt and base layers. Some of the layers in the profiling tables are expressed in terms of a combination of two layers. This happens because of the sampling of the SASW testing method. The velocities of the surface waves are determined by more than one layer at a time, because the waves travel through more than one layer, with receiver spacing at 100mm or more. Most of the dispersion curves are combinations of velocities and wavelengths of one or more layers at a time. From this it can be understood that it is of great help to have information about the layer thickness beforehand.

5. TEST RESULTS

The results are expressed in the form of predicted stiffness profiles with depth, based on forward modelling.

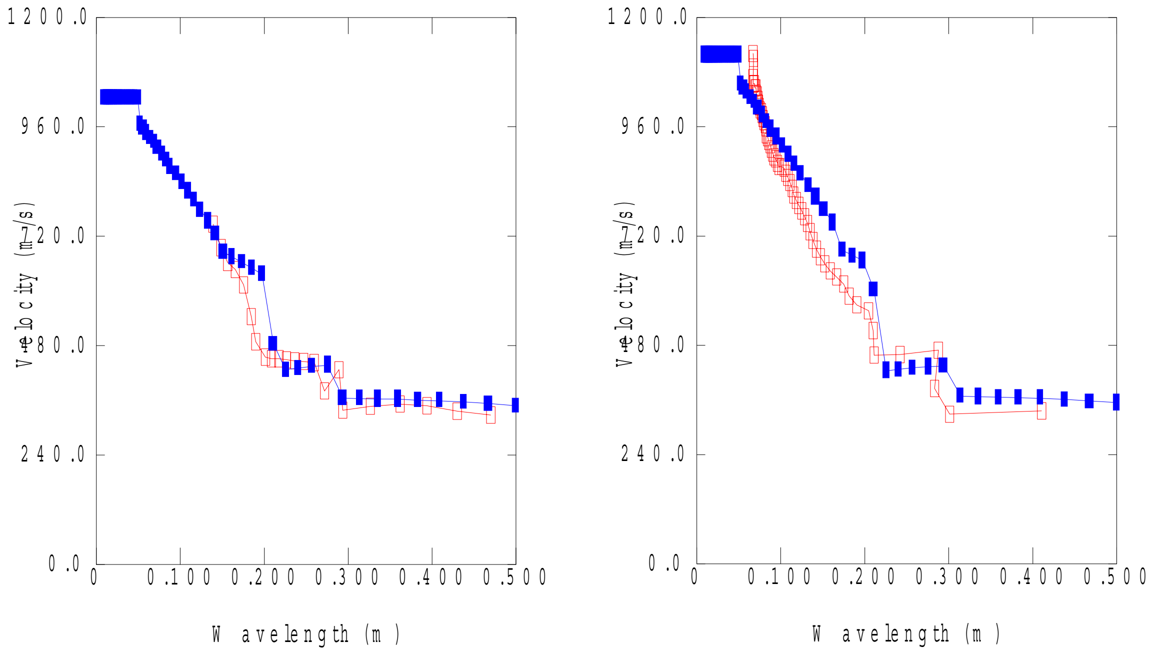
The test results are presented in the form of graphical presentations of dispersion curves, and stiffness profiles with depth.

Figure 3 gives the dispersion curves obtained on an intact section outside the wheel path, after the first and second series of tests. The calculated stiffness profiles are given in Table 2. The three dispersion curves, as depicted in Figure 4, are results of tests inside the wheel path, after each of the three test series. The resultant stiffness profiles are presented in table 3.

For comparison purposes, the stiffness profile at zero load repetitions has been repeated.

Figure 3: Experimental and theoretical dispersion curves after forward modelling (Outside wheel path) 150mm ETB (0 –loads)

Legend ─□─ Experimental- ─■─ Theoretical (after forward modelling)



(a) After 432 482 Load Repetitions (b) After 764 499 Load Repetitions

Table 2: Calculated stiffness Profiles (outside wheel path)

(a) After 432 482 Load Repetitions

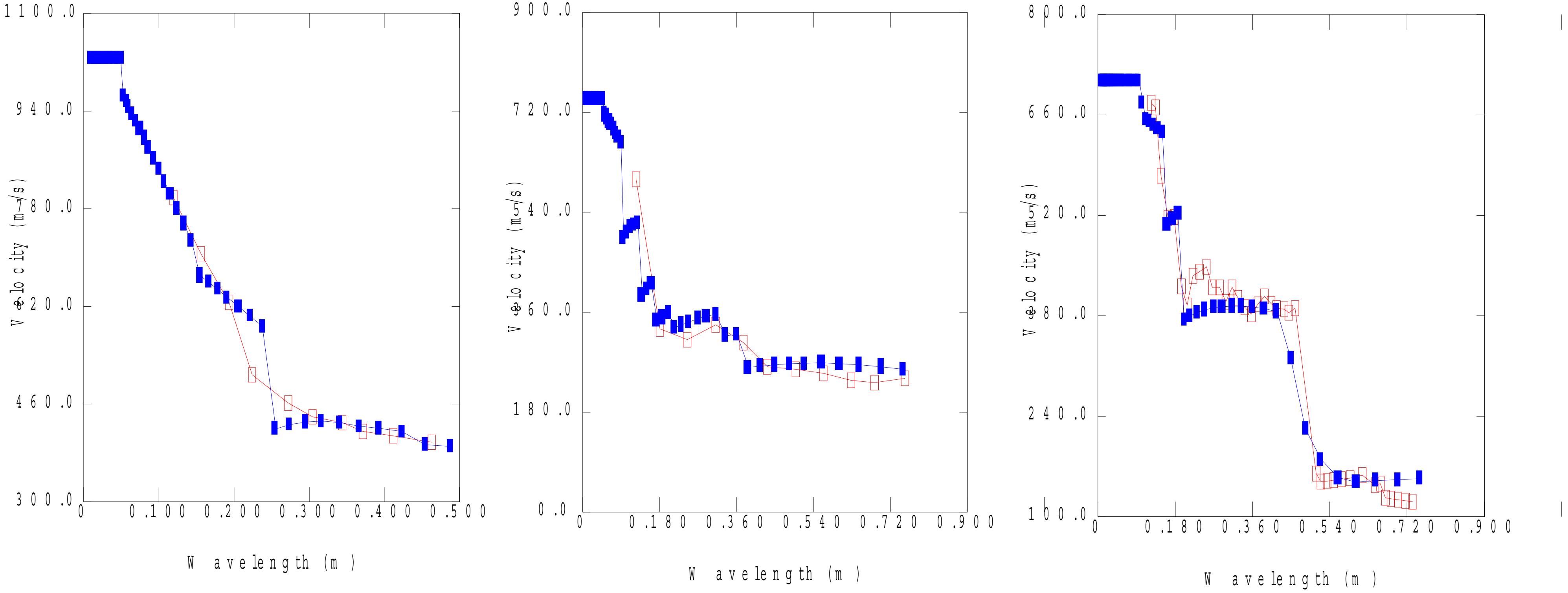
Layer	**Material**	**Thickness (mm)**	**S-Wave Velocity (m/s)**	**Poisson's ratio (ν)**	**Density (kg/m^3)**	**Estimated Modulus (MPa)**
1	Asphalt	50	1 200	0.33	2 318	**1 843**
2	ETB	150	350	0.33	2 090	**681**
3	CTB	100	450	0.33	2 068	**1 114**
4	Natural gravel ++	300++	150	0.33	1 968	**118**

(b) After 764 499 Load Repetitions

Layer	**Material**	**Thickness (mm)**	**S-Wave Velocity (m/s)**	**Poisson's ratio (ν)**	**Density (kg/m^3)**	**Estimated Modulus (MPa)**
1	Asphalt	50	1 100	0.33	2 318	**1 549**
2	ETB	150	350	0.33	2 090	**681**
3	CTB	100	460	0.33	2 068	**1 164**
4	Nat. Gravel	300++	150	0.33	1 968	**118**

Figure 4: Dispersion curves after forward modelling for 150mm ETB (Inside the wheel path)

Legend: ☐ Experimental- ■ Theoretical (after forward modelling)


(a) After 432 482 load repetitions

(b) After 764 499 load repetitions

(c) After 1 000 000

Table 3: Calculated stiffness Profiles (Inside the wheel path)

(a) At zero Load Repetitions (based on results outside wheel path Table 2b)

Layer	Material	Thickness (mm)	S-Wave Velocity (m/s)	Poisson's ratio (ν)	Density (kg/m^3)	Estimated Modulus (MPa)
1	Asphalt	50	1 100	0.33	2 318	**1 549**
2	ETB	150	350	0.33	2 090	**681**
3	CTSB	100	460	0.33	2 068	**1 164**
4	Selected/ Nat. gravel	300++	150	0.33	1 968	**118**

(b) After 432 482 Load Repetitions

Layer	Material	Thickness (mm)	S-Wave Velocity (m/s)	Poisson's ratio (ν)	Density (kg/m^3)	Estimated Modulus (MPa)
1	Asphalt	50	1 250	0.33	2 318	**1930**
2	ETB/CTB	200	400	0.33	2 090	**890**
3	CTSB/ Selected.	200	525	0.33	2 068	**1 516**
4	Selected/ Nat. gravel	300++	200	0.33	1 968	**212**

(c) After 764 499 Load Repetitions

Layer	Material	Thickness (mm)	S-Wave Velocity (m/s)	Poisson's ratio (ν)	Density (kg/m^3)	Estimated Modulus (MPa)
1	Asphalt	50	800	0.33	2318	**1110**
2	ETB	160	360	0.33	2090	**720**
3	CTSB	180	270	0.33	2068	**401**
4	Selected/ Nat. gravel	300+	120	0.33	1968	**75**

(d) After 912638 Load Repetitions

Layer	Material	Thickness (mm)	S-Wave Velocity (m/s)	Poisson's ratio (ν)	Density (kg/m^3)	Estimated Modulus (MPa)
1	Asphalt/ ETB	80	760	0.33	2318	**994**
2	ETB	140	335	0.33	2090	**624**
3	CTSB	200	200	0.33	2068	**220**
4	Selected/ Nat. gravel	300+	115	0.33	1968	**69**

5.1 Analysis of results

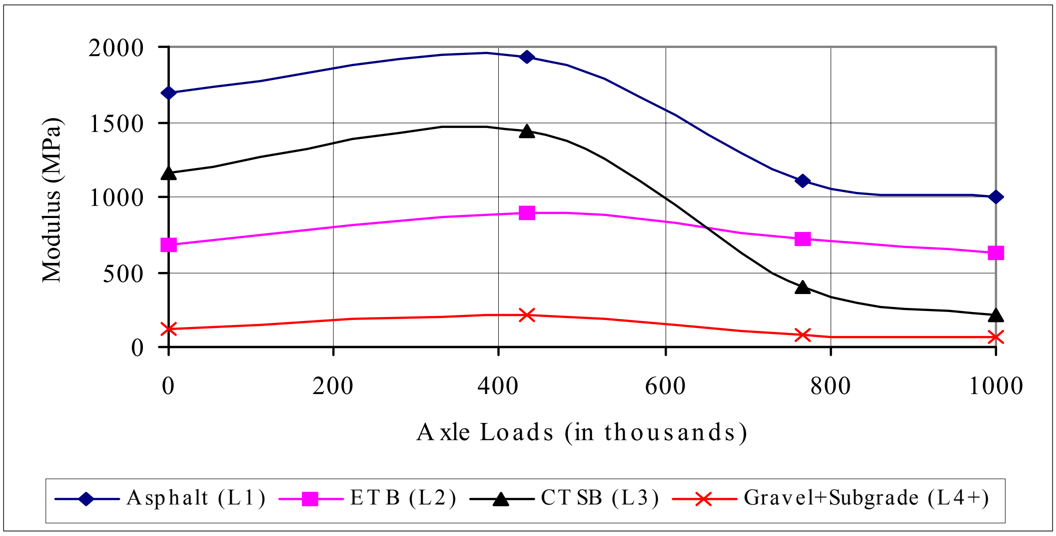
From the profiles of the layers at the different loading repetitions, it could be noticed that the thickness of the layers, were not very well defined. Because of the influence of the layers on each other, small apparent changes in the thickness could be detected. In reality the change in thickness of a specific layer is due to it being expressed as a combined layer. For example the asphalt layer thickness, with actual thickness of 35mm, appeared to have increased from 50mm to 80mm after 912638 cycles of the load (in table 3d.). This is because part of the ETB layer was included during the sampling of the surface layer. The same can be said for all the cases where the layer thickness is expressed as a combination of two layers.

5.2 Discussion of the results

As explained in the Testing programme, the first series of tests could only be done after more than 432000 load repetitions had been completed.
In the analysis of the results the assumption was made that the stiffness obtained outside the wheel path would not have changed. These results (outside the wheel path) were used as a representation of the stiffness of the test section in the wheel path, at zero load repetitions, before the start of the HVS testing. Compare Tables 2b and 3a.

An analysis of the interim results, obtained after completion of the second series of tests, showed an apparent increase in stiffness of the cement treated sub base with the increase in load repetitions from 432500 to 764500. This increase from about 1100 MPa to about 1450 MPa is unlikely in a cemented layer. Normally it is assumed that the stiffness would at best stay the same, but more likely go down with an increase in number of loads, due to the onset of cracks. The explanation for this apparent increase could be that the stiffness was obtained at two different positions on the pavement as explained above. The stiffness of the cemented sub base outside the wheel path of the HVS must have been lower than the stiffness in the wheel path.

Figure 5: Predicted modulus change with load repetitions, using the zero values outside the wheel path



Figures 5 shows the modulus change with increase in load repetitions,. There was an increase in the stiffness from zero to 432500 repetitions. The decrease in stiffness in the wheel path, during the last two test series, must be attributed to the fact that the pavement has cracked. The wave propagation, through the cracked medium, is not as well defined as through an intact medium, and it represents a calculated “stiffness of the layer”

For all the layers it can be seen that there has been a general downward trend. The base course being the least affected and the cemented sub base the most. The cemented sub base must have started to crack severely between 432500 loading cycles and 764500 cycles. This cracking became worse with a further decrease in stiffness towards 912638 cycles. The same trend but not to the same extend was observed for the asphalt surfacing. The base course, however, showed only a slight decrease to about the same stiffness that was obtained at the start before any loading cycle. The decrease in stiffness of the subgrade, is more difficult to explain. A possible explanation could be that the first tests were only executed to a distance of 400mm apart, thereby sampling only to a depth of 400mm The last tests were taken to a distance of 600mm apart, for more realistic values. This means that sampling was done to a greater depth as before picking up information of the stiffness lower down in the profile. The influence of the change in the CTSB could also contribute to these lower values.

5.3 Conclusions

As expected, distinct differences in layer stiffness were noticeable between the results in the wheel path and those of the intact control section. The deterioration of the test section under the wheel path of the HVS is of particular importance. At first an increase in stiffness has been observed from 0 to 432500 repetitions of the load, probably due to densification. However, with the further increase to 764500 repetitions there has been a marked decrease in stiffness. From a visual inspection of the pavement it was apparent that extensive cracking has occurred. This same downward trend continued until the final tests were done at 912638 loading cycles.

The tests done outside the wheel path on the 150mm thick ETB showed a remarkable similarity, even with a three- week interval between tests.

6. REFERENCES:

1. Aouad M F, Engelbrecht J C. March 2000**. A short course in Non-destructive Testing for Civil Engineering Infrastructure** University of Stellenbosch.

2. Aouad M. F, Stokoe II K. H, and Briggs R. C, 1993. **Stiffness of Asphalt Concrete Surface Layer from Stress Wave Measurements.** Transportation Research Record 1384, Washington, DC, pp. 29-35.)

3. Ming L , Aouad M. F, Olson L D. **Applications of the SASW Method to Pavements, Structures and Geotechnical Sites Paper P200**

4. Van de Ven MFC, Engelbrecht J C, 2000 **. Introduction into the spectral analysis of surface waves (SASW) technique. Project ITT 3- 2000, Institute of Transport Technology, University of Stellenbosch**.

5. Engelbrecht J C , Van de Ven MFC 2000. **Investigation into the changes in stiffness of test sections with different base courses, using the SASW Testing Method. February 2000 Project ITT 3 –2000. Institute of Transport Technology, University of Stellenbosch.**

CURRICULUM VITAE

Name: Johann Charl Engelbrecht

Date of birth: 8 June 1945

Married with 4 children

Academic qualifications:

B Sc B Eng 1969
M Sc Eng 1981 (Cum Laude)

Current Position:
Employed as Senior Lecturer in Civil Engineering at the University of Stellenbosch

Membership of Institutes:
Member of SAICE
Member of ECSA
Member of the Geotechnical division of SAICE

Field of speciality:
Pavement materials, determining elastic parameters with seismic tests.
Geotechnical engineering. Dynamic properties of sands including liquefaction.
Geotechnical investigations and design.