DYNAMIC RESPONSE OF FLEXIBLE PAVEMENTS TO TYRE TYPES LOADS & PRESSURES

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DYNAMIC RESPONSE OF FLEXIBLE PAVEMENTS TO TYRE TYPES, LOADS AND PRESSURES

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SUMMARY

The purpose of this project was to develop and verify instrumentation and a procedure for scientifically examining some fundamental loading parameters that influence the behaviour of thin surfaced granular pavements. The primary loading variables were the load magnitude, tyre inflation pressure and basic tyre type, all on dual tyred wheels. The main pavement response parameters were the surface deflection basins and the vertical dynamic strains at various depths. The results have shown that the tyre type has an insignificant effect and the tyre pressure has only a minor effect on the response of the pavement, while the effect of increasing the wheel load has the greatest influence. Further development of the instrumentation and data-acquisition systems was soundly justified, and has continued.

INTRODUCTION

The road transport industry strives to increase the efficiency of the system and is pressing to have some load and tyre regulations relaxed, but the existing database is inadequate to permit extrapolation of the present pavement design techniques for untested loading conditions. New Zealand's pavement engineers have long recognized that criteria and design procedures developed overseas can be applied only after comprehensive testing is conducted because virtually all highway traffic is carried by sophisticated, unbound or lime-stabilised granular pavements with thin bituminous surfacings. Thus, this project was devised to scientifically examine some fundamental loading parameters that influence the behaviour of thin surfaced granular pavements.

BACKGROUND

The load equivalency factors used in the Transit New Zealand pavement design model are based on the AASHO Road Test results and linear elastic multi-layer pavement response theory. The loading condition applied in New Zealand's model represents the standard axle load of 80 kN (8200 kg) on a dual-tyred single axle, which is termed the Equivalent Design Axle load (EDA) and is based on the wheel load condition commonly used at the time of the AASHO Road Test; the EDA was defined as causing **one** unit of wearing effect during one passage over a point. The multi-layer linear elastic program BISTRO was used to determine the stresses, strains, and deflection caused by the reference loads for various tyre and axle configurations. Then, the equivalency exponent for translating axle loads into EDA is 4 (the "Fourth-power rule"). The main criteria applied in the design of thin-surfaced flexible

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pavements is the vertical compressive strain in the subgrade, because the design theory presupposes that the primary mode of failure is permanent deformation. Subgrade deformation is less expensive to remedy than failure in the granular cover layers, so the cover has to be of sufficient depth to protect the subgrade. The basecourse aggregate properties are specified to sustain shear stresses. The background to the numerous issues involved can be found in **Pidwerbesky (1989a).**

Because of New Zealand's unique situation, with respect to both the road user charges incurred by the road transport industry and the dependence on thin-surfaced flexible pavements, a major research effort is needed to address the dynamic vehicle/pavement interaction subject and would yield amazing value. The research must isolate the various components of the vehicle/pavement interaction system, such as the static and dynamic components of vehicle loading, and the relative effects of vehicles, the environment and the pavement materials. Laboratory testing and computer analysis alone are insufficient. Trials utilising full-scale equipment and pavements are necessary. Therefore, Transit New Zealand has undertaken a programme of research projects using both field trials and accelerated full scale tests under controlled conditions.

ACCELERATED PAVEMENT TESTING

The Canterbury Accelerated Pavement Testing Indoor Facility (CAPTIF) in Christchurch is being utilised to investigate the *Fundamental Behaviour of Unbound Granular Pavements under Various Loading Conditions*, as part of a Transit New Zealand project. The track has a median diameter and circumference of 18.5 m and 58.1 m, respectively. Normal field construction and compaction equipment is used in the facility. The main feature of CAPTIF is the Simulated Loading And Vehicle Emulator (SLAVE), which can apply a myriad of loading conditions via an array of vehicle types and assemblies. SLAVE was designed for the accelerated testing and evaluation of subgrades, pavements and surfacings by replicating the effect on the pavement of actual road traffic conditions. Some of the relevant important aspects are briefly discussed; a full description of its characteristics is available (Pidwerbesky 1989b).

A vehicle consists of an assembly of the axle, hydraulic motor, suspension, a frame, instrumentation, and standard wheel hubs and truck tires. The standard vehicles are equipped with single- or dual-tyred half-axle assemblies; their load can be adjusted to between 21 and 50 kN (42-100 kN axle loads) by adding or removing steel weights, in increments of 2.75 kN. SLAVE can also drive a tandem-axle vehicle. The maximum wheel loads are 38 kN (per half-axle) for the design tandem axle vehicle. Trials could be conducted with any pair of similar vehicle types or with a different vehicle on each arm. The wheels are driven themselves, thereby simulating tractive forces, which facilitates the study of horizontal strains in the pavement. The speed of SLAVE is variable in increments of 1 km/h up to a maximum of 50 km/h. SLAVE's operations are directly controlled by its internal electronics, which continues operating using default values and the most recent input regardless of whether the external computer is connected. The external computer can be communicated with via telephone modems.

INSTRUMENTATION

Electronic systems have been acquired or developed to measure dynamic and residual strains and displacements, surface profiles, rebounds and temperatures in the pavement and subgrade. A Hewlett Packard 3852S microprocessor-based unit and Hewlett Packard PC-308 controller comprise the strain and temperature data-acquisition system. The 3852S unit is capable of taking 100,000 readings per second, and processing the data using stored algorithms. The unit accepts a wide range of interface modules, for capturing data from a variety of sensors. Two other primary devices are the CAPTIF Deflectometer, which measures the elastic response of a pavement under the influence of a wheel load, and the CAPTIF Profilometer, which measures transverse surface profiles. Both produce digital data output that is captured by a Psion hand held computer. The data is later downloaded to a desktop computer for analysis. A DIPstick Profiler, H-bar strain gauges, soil suction sensors and temperature probes are utilised at CAPTIF, in addition to the following devices.

The soil strain measuring system determines extremely small strains with good resolution using Bison Soil Strain sensors. The sensors use the principle of inductance coupling between two free-floating, flat, circular wire-wound induction coils coated in epoxy. One of the two discs which comprise a single sensor is connected to an oscillator and acts as the transmitter coil. The oscillator produces an alternating voltage, and the current flowing through the wound wires of the transmitter coil creates an electro-magnetic field in the surrounding soil. The field induces a voltage and an electrical current in the receiving coil. The magnitude of the induced current is inversely proportional to the spacing between the two coils in a non-linear relationship. The gauge length is the separation distance between each paired coil. The sensors can measure resilient or dynamic strain, residual strain, absolute permanent deformation, and subsurface deflection bowls when positioned in an array. Each array consisted of coils placed as shown in Figure 1.

Two strain-measuring systems have been developed. The portable system was devised as the first stage of the development process, as an interim system until the permanent system was commissioned. The portable system also served to trial the measurement procedures and to confirm that the basic technology was appropriate. The portable system has been and will continue to be used in field installations.

The permanent CAPTIF strain-measuring system is derived from a prototype Saskatchewan Soil Strain/Displacement measuring system (SSSD) developed by Saskatchewan Highways and Transportation, Regina, Canada. The SSSD is driven by a dedicated HP Vectra AT computer containing a specially built General Purpose Input/Output (GPIO)

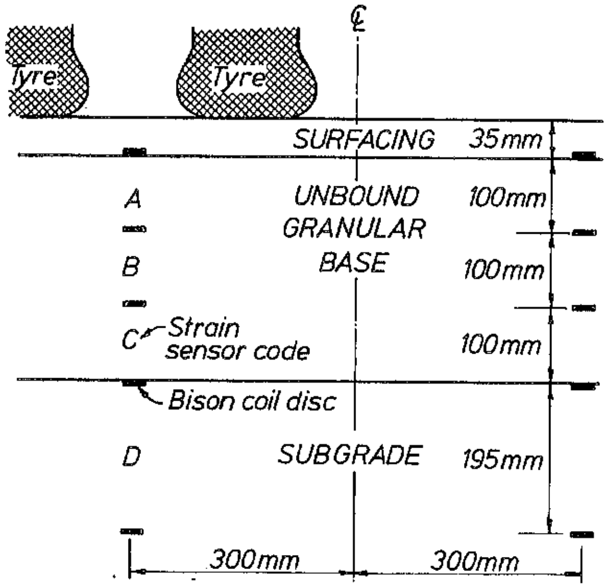


Figure 1 Strain-measuring Array

board. The GPIO board communicates with the strain-measuring systems located around the track. Each station includes a minimum of three circuit boards, depending on the number of channels to be included in each segment of the track. A Control Circuit board interfaces with the computer and decodes information for control and measurement of the transmitter and receiver board. All analog-to-digital (and vice versa) conversions are processed on this board. Each Receiver board provides calibrated conditioning for up to 4 receiver coils, amplification of the signals, rectification and output selection for static strains, sample-and-hold dynamic strains and digital-to-analog voltage-referenced dynamic strains. Each transmitter Circuit boards provides precision output voltage levels and selected frequencies for up to 16 transmitter coils. The signal generation provides instant output when required and smooth phase changes when different frequencies are selected. Once triggered, the sensors in an array are scanned simultaneously every 30 mm of vehicle travel, so that a continuous bowl shape of strain versus distance travelled is obtained.

Dynamic Wheel Forces

The dynamic loads imparted by the SLAVE vehicles are quantified by accelerometers mounted at difference locations on each of the vehicles. The accelerometers used are PCB 308B, which are a piezoelectric type with a linear response from 1-3000 Hz of 100 mV/g. The accelerometers are connected to a PCB 483A 12 channel signal conditioning unit. This unit supplies power to the accelerometers and extracts the signal for output. The signals are recorded on a Hewlett-Packard 3968A instrumentation recorder, which is an eight-track frequency-modulation (FM) tape recorder. The analogue signals are digitised using the HP 3852 data acquisition system sampling at 200 Hz per channel. The system was devised and installed by staff of Department of Scientific and Industrial Research - Auckland Industrial Development (DSIR-IDA), directed by John de Pont.

FIVE YEARS OF RESEARCH AT CAPTIF

The commissioning of SLAVE was the first project carried out at CAPTIF for the National Roads Board[#], between April 1987 and March 1988. Following preliminary trials of the systems and operating software, SLAVE applied 1.53 million loadings to four test segments of different granular pavement thicknesses under a seal coat, and performed the required capabilities and design parameters as originally specified (Pidwerbesky 1988, 1989). Following this, in mid-1988, trials of differing radial ply tyre configurations showed that a single wide based low profile radial ply tyre 14/80 R 20 created rut depths 92 percent greater than standard dual 10.00 R 20 radial ply tyres for the same loading (Pidwerbesky and Dawe 1990).

Trials of basecourse aggregate particle shape and gradation over nine separately constructed segments followed during September 1988 to January 1989. From January 1989 to April 1989, lime stabilisation of clay subbases in three segments under granular pavements was investigated. Between September 1990 and June 1991, concurrent with the project described below, CAPTIF was utilised to examine the performance of different asphaltic concrete mixes for BP International Ltd. SLAVE applied 2.12 million loadings over six separate segments and as each 60 000 loading interval was completed, the data gathered was sent to the BP U.K. research centre by electronic mail.

[#] Transit New Zealand is the new authority responsible for land transport.

RESPONSE OF GRANULAR PAVEMENTS UNDER VARIOUS LOADING CONDITIONS

The primary aims of this project are to develop and verify instrumentation and a procedure for scientifically examining some fundamental parameters that influence the behaviour of unbound granular pavements, and evaluate the relative importance of each variable studied. The variables are the subgrade bearing capacity, granular cover thickness, load magnitude, tyre inflation pressure and basic tyre type.

The first phase involved selecting and developing instrumentation and data-acquisition systems, the second phase was to prepare the vehicles and track, and the third phase was to construct, and apply a loading routine to, the first subgrade and pavement. The remainder of this paper describes this third phase of the project and presents some preliminary results. The pavement consisted of 35 mm of bituminous mix over 300 mm of crushed well graded aggregate (*Transit New Zealand Specification M/4*) over a weak, silty-clay subgrade (CBR of 5%). Subsequent stages involve calibrating the dynamic responses with the life-cycle performance of different pavements and subgrades under selected loading conditions.

Each coil disc of the strain sensors was placed at an interface between the different layers of the pavement and the subgrade. Six duplicate arrays of strain sensors were installed, to ensure that at least three complete arrays survived construction. Four complete arrays survived, and the strain values for each layer (presented later) are the average of three strain sensors.

LOADING AND TESTING ROUTINE

It was anticipated that as the load repetitions accumulated, the granular layers would compact somewhat, thus becoming stiffer and the dynamic deflections would reduce in magnitude. Also, if a vehicle of constant loading characteristics and speed passes repeatedly over the same location, the natural frequency of the vehicle would result in the dynamic impact occurring at the same location each passage. These influences were minimised by applying sufficient loading repetitions to just achieve a constant speed and record valid strain outputs from the sensors for each loading condition.

Sequence of Loading Conditions

The sequence was devised on the ease of altering the variable. In order of decreasing ease, they were tyre pressure, vehicle weight and tyre type. Vehicle A carried a constant load of 40 kN with dual bias ply tyres inflated to 550 kPa, so that it was a reference throughout the testing routine. The tyres were inflated to only the maximum cold pressures allowed by the tyre supplier (700 kPa for the bias ply and 825 for the radial ply tyres) to mimimise the likelihood of blowouts during the testing. All radial and bias ply tyres were 10.00R20 and 10.00x20, respectively.

TABLE 1 : Sequence of Loading Conditions on Vehicle B

	Tyre Type	Tyre Pressure (kPa)	Wheel Load (kN)		Tyre Type	Tyre Pressure (kPa)	Wheel Load (kN)
1	Bias ply	550	40	9	Radial	825	46
2		700	40	10		700	46
3		700	21	11		550	46
4		550	21	12		550	31
5		550	31	13		825	31
6		700	31	14		700	31
7		700	46	15		700	21
8		550	46	16		550	21
				17		825	21
				18		825	40
				19		700	40
				20		550	40

Comparing Vehicles

A series of trials were done to confirm that the pavement response to and dynamic characteristics of each vehicle were similar. Representative results are presented in Table 2 below. The strains produced in the upper pavement and subgrade layers are nearly identical, especially considering that the noise in the signals equated to 100 x 10^{-6} strain (100 microstrain). The differences between the responses of the lower pavement layer were between 140 and 190 microstrain, which is only slightly greater than the noise. Also, the surface deflection basins for each vehicle were identical, with respect to both peak values and shape.

The data from the vertical accelerometers was analysed by DSIR-IDA. The following paragraphs are extracted from the report. Dynamic wheel forces are dominated by behaviour of sprung mass, so the wheel forces are the sum of the vehicle mass multiplied by the chassis acceleration and the unsprung mass multiplied by the vertical axle acceleration. Two loading conditions were measured, at a constant speed of 40 km/h. First, vehicle A was tested when loaded to 40 kN, and its dual bias ply tyres inflated to 550 kPa, while the load on vehicle B was 46 kN and its dual radial tyres were inflated to 825 kPa. Then, vehicle B was also tested with a load of 40 kN and tyre inflation pressures of 550 kPa.

The digitised data from the accelerometers were analysed using the ASYST program. The vehicles exhibited similar dynamic characteristics, and one aspect, the dynamic load coefficient (dlc) is presented in Table 3. An averaged Fourier transform of the frequency components of the dynamic wheel forces revealed that the SLAVE vehicles have two body modes in the 2-3 Hz range, and the amplitude of these modes was slightly greater for vehicle A than vehicle B.

TABLE 2 : COMPARISON OF STRAINS UNDER BOTH VEHICLES

Pavement Layer	**Sensor Array**	**Vehicle A[1]** Strains ($\times 10^{-6}$)	**Vehicle B[1]** Strains ($\times 10^{-6}$)
Upper	1	965	940
	3	1350	1310
Lower	1	1430	1640
	3	2130	2270
Subgrade	1	2080	2050
	3	NA	NA

[1] Dual biasply tyres, 550 kPa inflation pressure, 40 kN wheel load

TABLE 3 : DYNAMIC LOAD CO-EFFICIENTS (dlc)

VEHICLE	TYRE LOAD (kN)	TYRE PRESSURE (kPa)	TYPE	dlc
A	40	550	Biasply	0.22-0.24
B	40	550	Radial	0.22-0.24
B	46	825	Radial	0.16-0.18

$$\text{Dynamic load co-efficient (dlc)} = \frac{\text{Std Deviation of Wheel Forces}}{\text{Static Load}}$$

RESULTS AND ANALYSIS

Permanent Vertical Deformation

Failure of the pavement was defined as a surface rut depth of 25 mm. The total permanent deformation, as measured at the pavement surface, was only 7 mm. The maximum subgrade deformation was 6 mm. Figure 2 shows that most of the deformation occurred in the subgrade, and the deformation within the basecourse layers (the different between the two curves was 2-3 mm. Therefore, the permanent deformation was relatively small during the testing routine, and is not considered to have substantially affected the consolidation and thus the modulus of the layers.

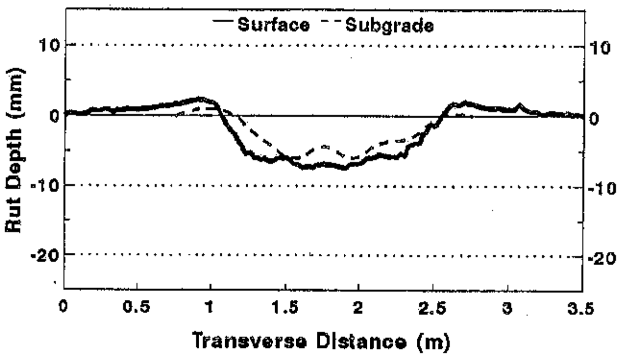


Figure 2 Vertical Deformation

Surface Deflection Basins

Deflection basins were measured at three locations on the test section, averaged to determine one basin for each experimental point and at least one location in the pavement. The deflection basins are plotted on a semilogarithmic graph, instead of the more usual arithmetic graph because the short, steep deflection basins are more readily interpreted from the former. The deflection basins were compared on the basis of (a) tyre type, (b) tyre inflation pressure, and (c) wheel load.

Neither tyre type nor tyre inflation pressure had a substantial affect on the deflection basin shape. Wheel load had a minor affect on the basin shape, but this was primarily due to the peak rebound value, as shown in Figure 3.

In general, the peak deflection value was independent of tyre type. Tyre pressure tended to have a negligible affect on peak value. As above, the major influence on peak deflection was the wheel load, as shown in Figure 4.

Vertical Compressive Strains

All strains are in the vertical plane, compressive and dynamic. The vertical compressive strains readings in three layers (upper basecourse, lower base and subgrade) for each of the 20 loading conditions were recorded; Figure 5 shows a representative sample of the original data from the subgrade, for one specific loading condition, which in this case, was dual radial tyres, inflated to 825 kPa and loaded to 40 kN. The longest spikes represent the passage of the test vehicle directly over the sensors, and the lessor spike is the passage of the control vehicle (dual bias ply type inflated to 550 kPa and loaded to 40 kN) at a transverse distance of .6 m, as illustrated in Figure 2.

The five cycles are averaged to yield a plot such as that shown in Figure 6. Under each loading cycle, a residual vertical compressive strain remained in the subgrade after the passage of the test vehicle. Then, when the control vehicle passed over the station, the residual compression disappeared and the subgrade reverted to the original situation. This phenomena repeated itself for all loading cycles and instrumented sections.

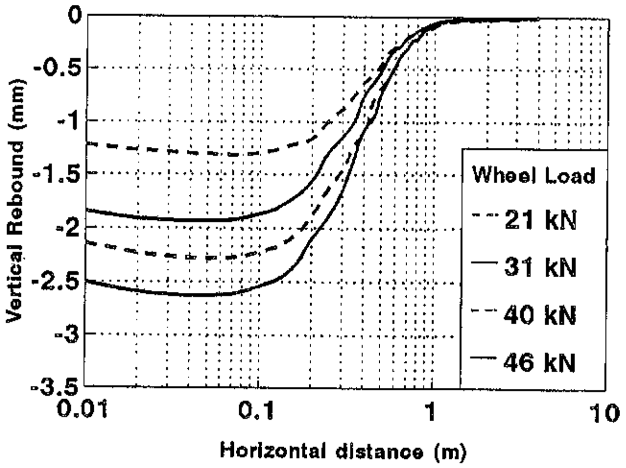
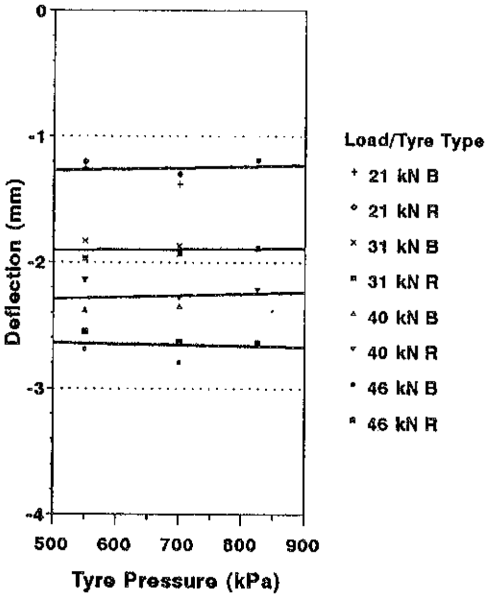


Figure 3 Deflection Basins (700 kPa)

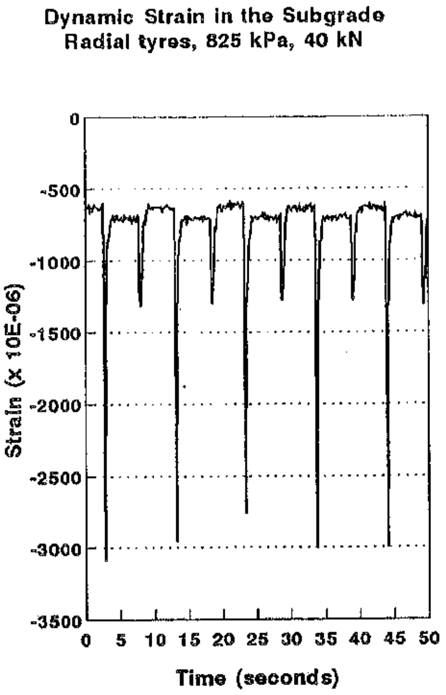
If it was simply a result of the coils being dislocated laterally from their coaxial position, then the effect would have increased with cumulative cycles, but this did not occur. Instead, the subgrade was compressed when one vehicle passed directly over the sensor. The shear forces created by the other vehicle, travelling in a wheel path 0.6 m away laterally, resulted in extension in the layer and the sensor returned to its original position.



B = Bias ply, R = Radial tyre

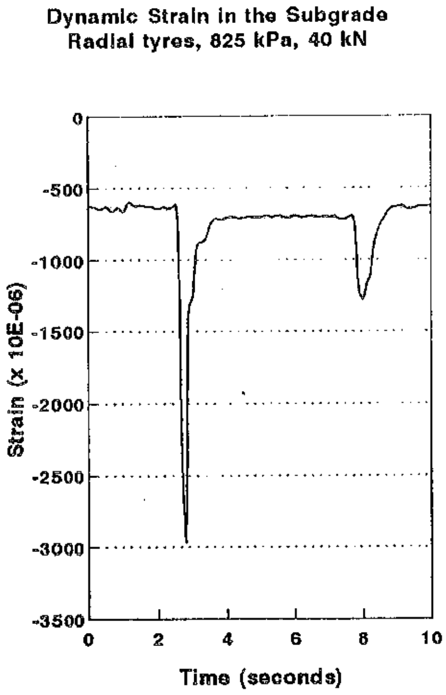
Figure 4 Peak Surface Deflections

Similarly, in the lower and upper basecourse layers, the residual compression induced by one vehicle passing directly over the sensors was eliminated by extension as the other vehicle passed over a point 0.6 m away transversely; however, in the basecourse layers, there was no discernible resilient compression as the second vehicle passed over (Figures 7 and 8). This cyclic compression and extension would not greatly exacerbate the permanent deformation of the layers, which is the primary criterion for the model describing the performance of thin-surfaced unbound granular pavements, but the effect on the degradation of the aggregate and soils in the pavement and subgrade could be even more significant. The phenomena would occur only in conditions similar to the test pavement: weak subgrades (California Bearing Ratio less than 6%) and pavement thicknesses of 300 mm or less.



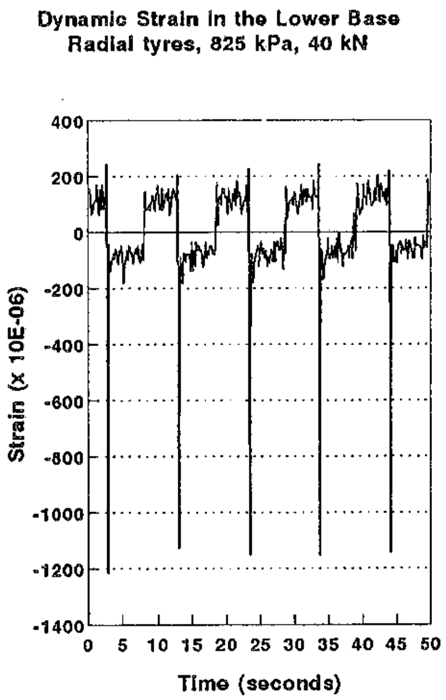
Sensor 1D @ 20 km/h

Figure 5 Subgrade Strain Signal



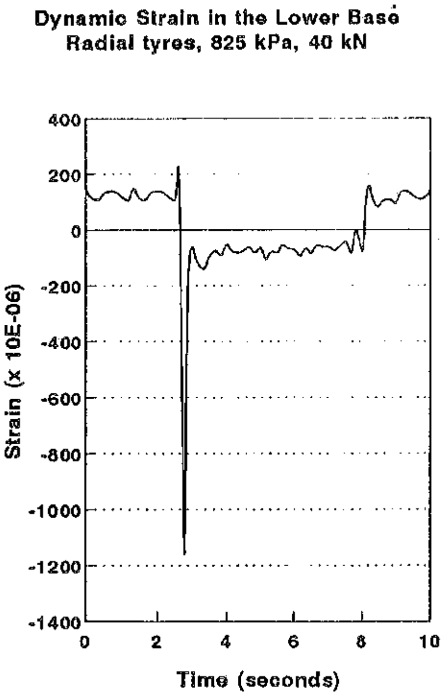
Sensor 1D @ 20 km/h Average of 5 cycles

Figure 6 Subgrade Strain (Average 5 cycles)



Sensor 1C @ 20 km/h

Figure 7 Lower Base Strain Signal



Sensor 1C @ 20 km/h Average of 5 cycles

Figure 8 Lower Base Strain (Average 5 cycles)

The peak compressive strains were determined for each loading condition. The peak compressive strains are defined as the difference between the nominal average residual strain recorded prior to the approach of the test vehicle to the sensor and the maximum strain (averaged over five cycles) measured under the test vehicle. For 550 kPa, for each wheel load, the subgrade strain under radials was 0%-$^+$5% greater than bias ply tyres. For 700 kPa, the differences vary from -17% to +4% and no trend is discernible.

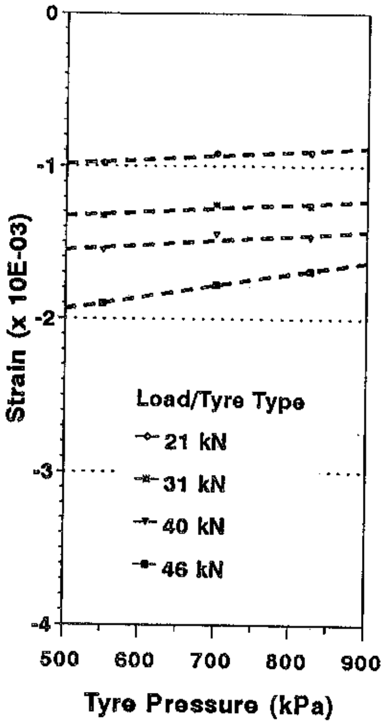


Figure 9 Strains in Upper Base

The analysis of strain versus tyre inflation pressure concentrates on the radial tyre trials because a wider range of pressures (550 kPa to 825 kPa) were involved; as explained above, the maximum inflation pressure in the bias ply tyres was 700 kPa. Contrary to expectations, in the upper basecourse, the dynamic compressive strain actually *decreased* slightly as the inflation pressure *increased*, in every load category (Figure 9). In the lower base, the results were mixed, with the lightest and heaviest loads exhibiting negligible change due to different pressures, while the mid-range loads showed a definite *decrease* in strain as the tyre pressure *increased* (Figure 10). The most surprising result occurred in the subgrade, where the vertical compressive strain also *decreased* as the inflation pressure *increased*, in every load range (Figure 11).

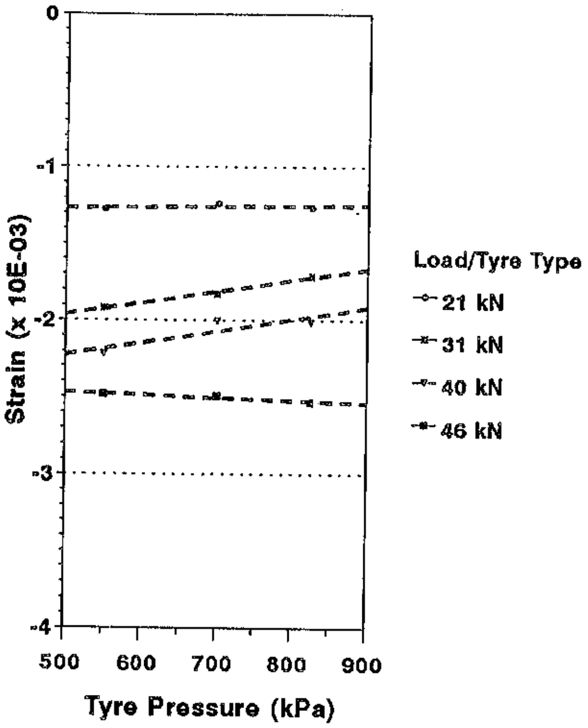


Figure 10 Strains in Lower Base

Radial tyre

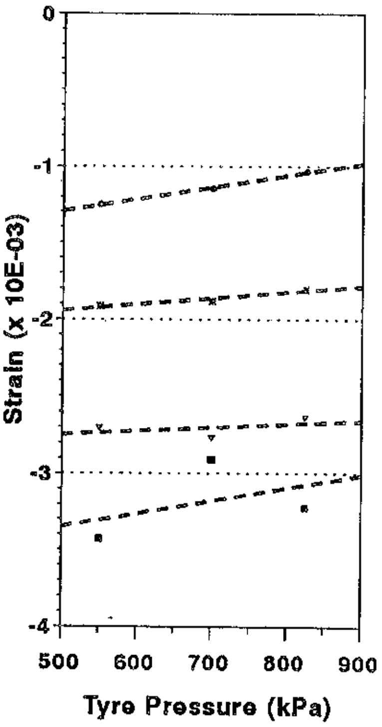


Figure 11 Strains in Subgrade

The strain in the lower layers must be dependent upon the zone of influence, which is related to load, contact area and speed of vehicle travel. Thus when the speed is constant and the contact area is reduced, at higher tyre inflation pressures, the zone of influence in the pavement and subgrade is reduced, thereby reducing the impact.

Multi-layer Linear Elastic Modelling

Through an interactive iterative procedure, using ELSYM5 computer software and initial estimates of layer modulii derived from a relationship between elastic modulus (E) and inferred CBR[+], nominal values for the strains in all three layers and surface deflection basins were calculated for each wheel load. As the wheel load increased, the peak surface deflection, averaged over all tyre types and inflation pressures, increased at approximately the same rate as that predicted by multi-layer linear elastic modelling (Figure 12). The relationship between

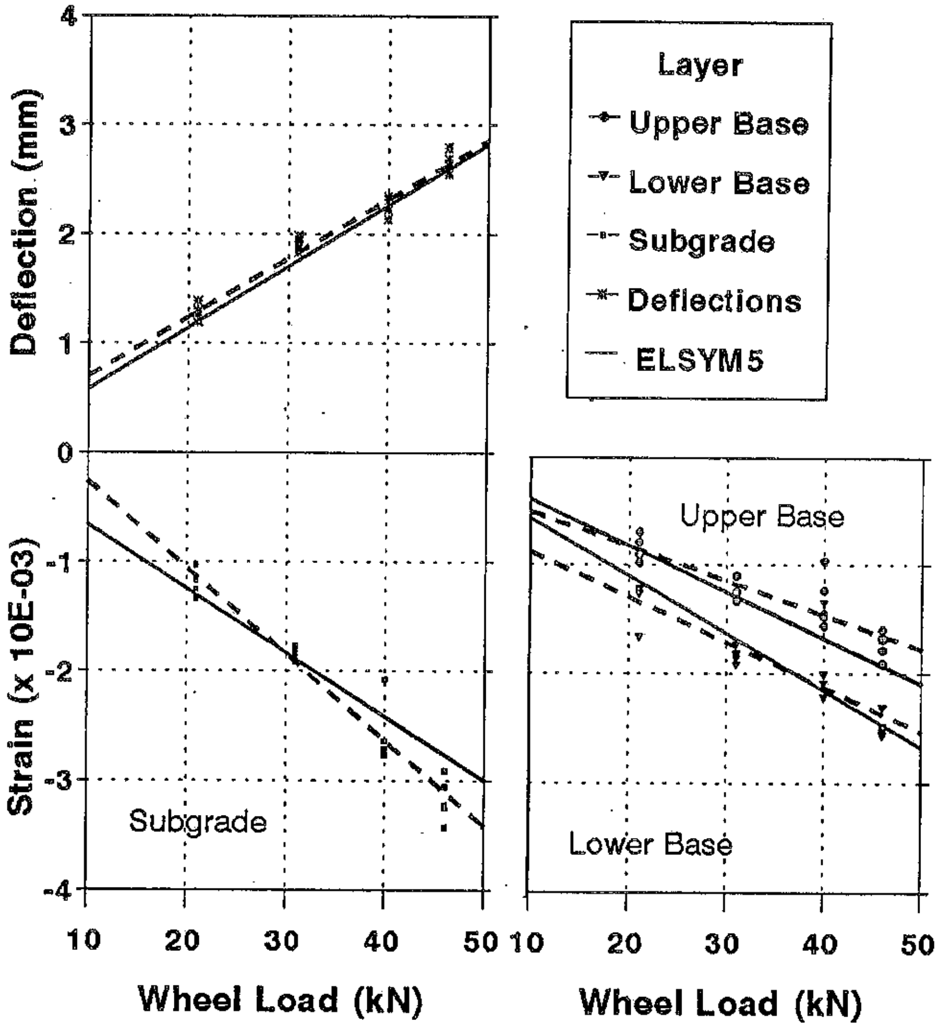


Figure 12 Comparisons of Actual and Calculated Responses

[+] $2 < E_{upper}/E_{lower} < 4$, and $E_{subgrade}=20(CBR)^{0.64}$

peak surface deflection and wheel load is approximately linear, suggesting that despite the incongruous assumptions of the linear elastic model and non-linear behaviour of granular materials in laboratory triaxial tests, the unbound granular pavement and subgrade system as a whole has a linear response. This was also exhibited in the strain curves for the granular cover layers. However, the vertical compressive strain in the subgrade increased, with respect to load, at a rate slightly *greater* than that predicted by elastic modelling, whereas the obverse occurred in the granular layers.

SUBSEQUENT STAGES

The next stage of the experiment involved instrumenting a flexible pavement consisting of 85 mm of asphaltic concrete over 200 mm of unbound granular basecourse and a silty clay subgrade possessing a CBR of 11%. The subsurface strains and surface deflections were measured before loading began, and then every 120,000 loading cycles of the SLAVE. Temperatures at various depths in the pavement were measured every hour.The wheel load was 40 kN for both vehicles for the first 920,000 loading cycles, and 46 kN for the remaining 1.2 million loading cycles. The dual radial tyres in both vehicles were inflated to 700 kPa, and the vehicle speed was a constant 40 km/h. Altogether, SLAVE applied over 3 million EDA to the test pavement.

The final stage of the project involves constructing two test pavements with the variable being granular cover thickness over a common subgrade condition and applying a constant loading condition until the pavement fails or 2 million loading cycles are applied (approximately two months of loading at 40 km/h). The response of the pavement to different vehicle speeds will also be determined, with respect to subsurface strains.

CONCLUSIONS

The procedure for quantifying the effect of different loading conditions on pavement response and performance has been confirmed and trialled. The results confirmed that proceeding with the final development of the permanent strain-measuring system was justified.

For the specific conditions of this investigation, the tyre type (radial and bias ply) has an insignificant effect on the dynamic strain and deflection responses of the subgrade and granular pavement, and the effect of increasing the wheel load approximated that predicted by the multi-layer linear elastic model. As the inflation pressure increased from 550 kPa to 825 kPa, the vertical compressive strains within the subgrade and granular cover layers *decreased slightly*

Further trials should be conducted using a range of tyre sizes, higher tyre pressures, greater wheel loads and tandem axle configurations.

ACKNOWLEDGEMENTS

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