PAVEMENT-VEHICLE INTERACTION RESEARCH AT CAPTIF

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ABSTRACT

New Zealand pavement design and construction practices are significantly indigenous, having evolved to suit the local conditions. This has provided the impetus for developing an accelerated pavement testing facility. The development of and projects conducted at the Canterbury Accelerated Pavement Testing Indoor Facility (CAPTIF) are described in this paper. 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 tyre and load configurations at high rates of accelerated loading. The research projects conducted since 1986 and the significant results are discussed.

INTRODUCTION

The major components of the New Zealand pavement are the unbound granular base and subbase layers; the thin surfacings provide a wearing surface and a waterproof membrane over the basecourse. The New Zealand performance model for thin-surfaced, unbound granular flexible pavements is based on multi-layer linear elastic theory. The model assumes that the surface thicknesses of less than 35 mm do not contribute to the structural capacity of the pavement and the stresses are dissipated through the depth of the granular cover layers above the subgrade. The main criteria applied in the design of thin-surfaced unbound granular pavements is the vertical compressive strain in the subgrade, because the design theory presupposes that the primary mode of structural failure is permanent deformation in the subgrade. The pavement thickness design charts in the State Highway Design and Rehabilitation Manual [5] are derived from the same subgrade strain criterion as used in the Shell Pavement Design Manual [4], but with some adjustments for local conditions; the criterion is:

$$\epsilon_{CVS} = 0.021\ N^{-0.23} \quad \mathbf{(1)}$$

where ε_{cvs} is the vertical compressive strain in the subgrade, and
N is the number of repeated equivalent design axle loads.

Because of both the road user charges incurred by heavy vehicles and the dependence on thin-surfaced flexible pavements, a major research effort has been undertaken to isolate the influence of 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 inappropriate. Thus, trials utilising full-scale equipment and pavements are necessary, either in the field or in a test track under controlled conditions. Transit New Zealand and the National Roads Board have been cooperating with the University of Canterbury in accelerated testing of full-scale pavements since the first installation was constructed in 1969.

The first machine was used for a number of pavement research projects, and, in 1983, finally became unserviceable. An assessment was made of the need for a new, improved accelerated trafficking facility; four primary topics suitable for accelerated testing were identified:

a) evaluating the performance of aggregates, such as marginal materials;
b) expanding research in surfacings;
c) evaluating pavement design assumptions by collecting data on the long-term performance of pavements; and,
d) investigating the relationship between vehicle loading and pavement deterioration for a wide spectrum of pavement and loading characteristics.

The type of facility needed was also evaluated. Accelerated pavement testers have been constructed in a variety of configurations. The facilities are generally classified as being either circular or linear test tracks. A circular test track in which full scale pavements could be constructed and a machine capable of realistic heavy vehicle loading was selected because:

* The machines can be operated continuously without being interrupted for direction changes, thereby greatly increasing the rate of load cycling.
* After initial acceleration, the speed of the loading system can be kept constant for long periods of time or varied, depending on the requirements of specific projects.
* Circular tracks can be divided into a number of either annular rings or longitudinal segments, each containing a pavement with some unique characteristics, and all segments can be tested simultaneously under the same or varying loading conditions.
* The configuration of each loading assembly in a multi-armed machine, such as tyre types and pressures, axle numbers and weights, suspensions and loads, can be altered; thus the response of the same pavement under various loading conditions can be determined.
* It is also possible to study the interaction of pavement and loading dynamics by using a combination of unsprung and sprung masses possessing realistic damping characteristics.

DESCRIPTION OF THE FACILITY

The Canterbury Accelerated Pavement Testing Indoor Facility (CAPTIF) is located in Christchurch. CAPTIF is housed in a hexagon-shaped building that is 26 m wide and 6 m high. A circular concrete tank, 1.5 m deep and 4 m wide, confines the bottom and sides of the track, enabling the control of moisture contents in the subsurface systems and drainage. 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.

Simulated Loading And Vehicle Emulator

An elevation view of SLAVE is presented in Figure 1. A sliding frame within the central platform is moved horizontally a maximum of 1 m (from stop to stop) by two hydraulic rams; this radial movement produces multiple wheel paths. The total width of track that can be trafficked is 1.44 m, which includes dual tyre widths of 0.22 m each. The base elevation can be altered by up to 150 mm, to maintain the dynamic balance of the machine if the pavement surface level changes or has to be built up.

Each vehicle consists of an assembly of the axle, hydraulic motor, suspension, a frame, instrumentation, and standard wheel hubs

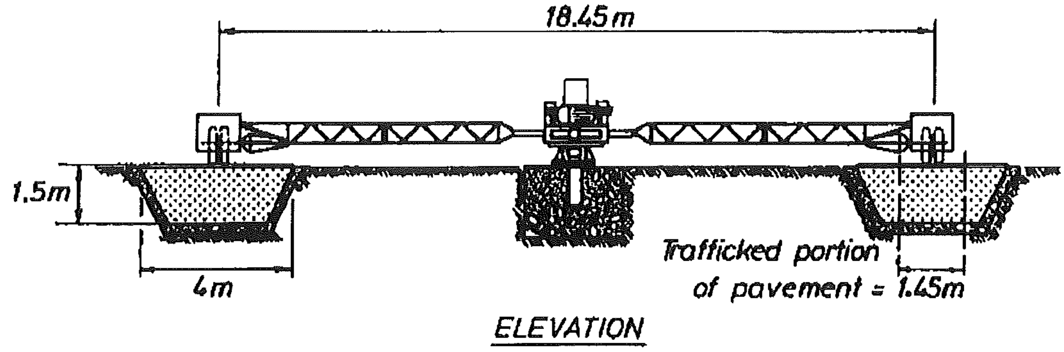

Figure 1 Elevation View of SLAVE and Cross-section of Track

and truck tyres. The standard SLAVE vehicles are equipped with half-axle assemblies and multi-leaf suspensions that can carry either single- or dual-tires; their load can be adjusted to between 21 and 60 kN (42-120 kN axle loads) by adding or removing steel weights. The suspensions can be multi-leaf steel spring, a parabolic steel leaf spring or an air spring; each vehicle can carry the same or a different suspension for simultaneous testing. The speed can be set or varied at any value between 0 and 50 km/h, and can be varied while running.

SLAVE operations are directly controlled by its internal electronics. The external or on-shore computer is an IBM-compatible personal computer. Whenever a parameter is to be altered, the new command is sent by the external computer through a communications link under the track and a slip ring within the central pedestal. SLAVE and the computers can be safely left running without supervision.

Testing routines can be programmed in terms of parameters such as start/stop times, distance or revolutions to be run, travelling speeds, and tracking pattern of wheelpath positions, to name only a few.

Instrumentation and Data-acquisition

Electronic systems have been acquired or are being developed to measure dynamic and residual strains and displacements, surface profiles, rebounds and temperatures in the pavement and subgrade. The CAPTIF Deflectometer measures the elastic response of a pavement under the influence of a wheel load. The Deflectometer is a modified version of the Geobeam device developed by Tonkin and Taylor Ltd. of Auckland. The Deflectometer probe is positioned between the tyres of a dual-tyred wheel and, as the wheel is moved away, the elastic vertical rebound of the pavement is read, to the nearest 0.01 mm, every 50 mm of horizontal movement. An electro-magnetic gap measuring sensor at the end of the beam measures the vertical distance between the sensor and a target disc placed on the pavement surface. The CAPTIF Profilometer measures transverse surface profiles using similar electronics. The output signals are digitised by electronics contained within the devices, and the digital data are captured by a Psion hand-held computer. A DIPStick profiler is used to measure the longitudinal surface profiles, for roughness surveys. The output from temperature probes installed in the pavements and subgrade are recorded hourly and automatically by a Taupo F-10-24K-48A datalogger. A Hewlett Packard 3852S microprocessor-based unit and computer capture data signals from accelerometers mounted on the chassis and axles of each vehicle, for measuring the dynamic loads being applied by the axles. The data is downloaded from all the units to a desktop computer for analysis.

A modified version of the Saskatchewan Soil Strain/Displacement-measuring (SSSD) system is used to determine subsurface strains with high resolution using Bison Soil Strain sensors. The sensors use the principle of inductance coupling between two free-floating, flat, circular wire-wound coils coated in epoxy. The strain discs are installed during the formation of the subgrade and the overlying pavement layers, resulting in negligible disturbance to the materials A typical array of strain sensor coils is shown in Figure 2. The SSSD was developed by Saskatchewan (Canada) Highways and Transportation, and is essentially a computer and associated unit containing custom-built control, general purpose input/output, transmitter and receiver boards. Once triggered by the moving vehicles cutting a light beam, the sensors in the array are scanned simultaneously every 30 mm of vehicle travel, and a continuous bowl of strain/displacement versus distance travelled is obtained.

PAVEMENT RESEARCH PROGRAM

In all of the projects, the subgrade and the granular cover layers were spread by a small bulldozer and compacted by a 40 kN dual drum roller, in non-vibratory and vibratory modes depending on the layer and its condition. The surface of the basecourse is finished with a pneumatic-tyred roller.

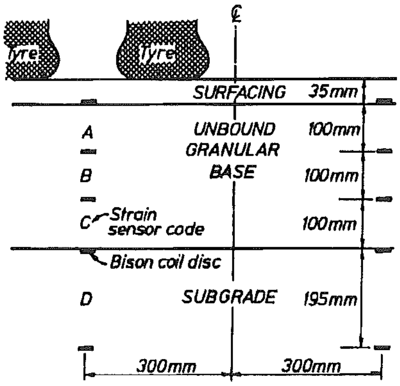

Figure 2 Array of Strain Coil Sensors

Inaugural Project

The purpose of this project was (i) to commission the SLAVE and evaluate its capabilities and (ii) to monitor the performances of four prototype pavements, in order to provide an initial evaluation of the construction and operation techniques required for utilising the accelerated trafficking facility. A clayey loess was used for the subgrade material. The average California Bearing Ratio (CBR) of the subgrade was 30. The granular pavement thicknesses ranged from 150 to 300 mm, in 50 mm increments. The granular cover was a well-graded aggregate with a maximum particle size of 40 mm, except the uppermost lift had a maximum size of 18 mm. The surfacing was a double seal coat.

Each SLAVE vehicle was loaded to 40 kN, which is the wheel load applied by the standard Equivalent Design Axle (EDA). SLAVE applied 1.53 million EDA loads to the pavement during the project. There was no significant difference in the performances of the four pavements; the main conclusion was that unbound granular pavements consisting of compacted well-graded crushed aggregate can sustain large numbers of 80 kN axle load repetitions in the absence of deleterious ground moisture and environmental factors [2].

Comparative Rutting of Tyre Types

The vertical deformation caused by a single low-profile radial tyre (14.00/80 R 20) and dual standard radial tyres (10.00 R 20) were compared. The pavement consisted of a 40 mm thick surfacing of a open-graded bituminous mix , a 150 mm thick basecourse of a high-quality crushed aggregate and a 150 mm thick subbase of coarse aggregate with a maximum particle size of 65 mm. The subgrade material was a clayey loess with an average CBR of 30. The load applied by each wheel set was 40 kN. After 16,000 loading cycles, the average permanent deformation created by the single low profile radial tyre was 92 percent greater than that of the dual radial tyres [3].

Behaviour of Lime Stabilised Subbase

The behaviour of lime-stabilised layers in flexible pavements under normal vehicle loads was investigated. Three pavements were constructed, two subbases of thicknesses 150 mm and 250 mm containing a lime-stabilised clay, and the third subbase contained an unstabilised high quality, well-graded crushed aggregate. The laboratory CBR of the unstabilised and stabilised clay specimens were 5 and 20, respectively. The surfacing was a 25 mm thick layer of asphaltic concrete and the basecourse consisted of a 150 mm thick layer of high quality, well-graded crushed aggregate for all three pavements; the subgrade CBR was 3. The performance of the pavements was quantified by measuring horizontal tensile strains and vertical compressive pressures within the subbase, and elastic deflections and permanent deformation of the pavement surface.

The pavement containing the 150 mm thick lime-stabilised layer performed substantially better than the same thickness of unstabilised aggregate. Increasing the stabilised subbase thickness by 100 mm yielded a fifteen-fold increase in the life of the pavement. Failure in all pavements was defined as vertical deformation greater than 30 mm. The moduli of the lime-stabilised layers were lower than that predicted by both computer analyses and laboratory testing [1].

Response of Unbound Granular Pavements to Different Loading Conditions

The primary loading variables were the load magnitude, tyre inflation pressure and basic tyre type, all on dual tyred wheels. The pavement consisted of a 40 mm surfacing of asphaltic concrete and a 300 mm thick granular layer of well-graded, crushed aggregate, all over a weak silty clay subgrade (CBR of 4).

Vehicle A carried a constant half-axle load of 40 kN with dual bias ply tyres inflated to 550 kPa, and was the reference throughout the testing routine. The characteristics of vehicle B were modified. The experimental matrix consisted of three tyre inflation pressures (550, 700 and 825 kPa), four wheel loads (21, 31, 40 and 46 kN), and two tyre types (10.00R20 radial ply and 10.00x20 bias ply).

In the upper basecourse, the elastic compressive strain actually *decreased* (in magnitude) slightly as the inflation pressure *increased*, in every load category. 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*. In the subgrade, vertical compressive strain also *decreased* (in magnitude) as the inflation pressure *increased* (Figure 3).

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

For the specific conditions of this investigation, the tyre type (10.00R20 radial and 10.00x20 bias ply) had an insignificant effect on the dynamic vertical strain response, the tyre inflation pressure (between 550 kPa and 825 kPa) had a minor effect on the response of the pavement, and the effect of increasing the wheel load was approximately linearly elastic.

Effect of Binder Modification on Asphalt Pavement Performance

The project involved six flexible pavement test sections, and was set up to conduct two trials simultaneously: one for British Petroleum International (BPI) to determine the effect on pavement performance of different binders used in the asphaltic concrete, and one for Transit New Zealand. The latter trial is described later.

The BPI trial involved constructing six test sections of various asphaltic concrete mixes over 200 mm of unbound granular basecourse and a silty clay subgrade possessing a CBR of 13. All test sections were designed for the a design life of 1.0 x 10^6 EDA; the depth of the asphaltic concrete varied from 80 mm to 125 mm, depending on the predicted performance of the different mixes.

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 40 km/h. Altogether, SLAVE applied 3.2 million EDA to the test pavements. Details of the project and results are provided in Stock *et al* [6]. The test sections exhibited negligible deterioration in their structural condition and minimal surface distress.

Stock *et al* [6] concluded that the thinner asphaltic concrete layers constructed with modified binders and the high-stiffness binder provided performance equivalent to that of the thicker layer containing a conventional binder. They also concluded that the design procedure was conservative, because pavements designed for 1 x 10^6 EDA should have exhibited greater deterioration after 3.2 x 10^6 EDA.

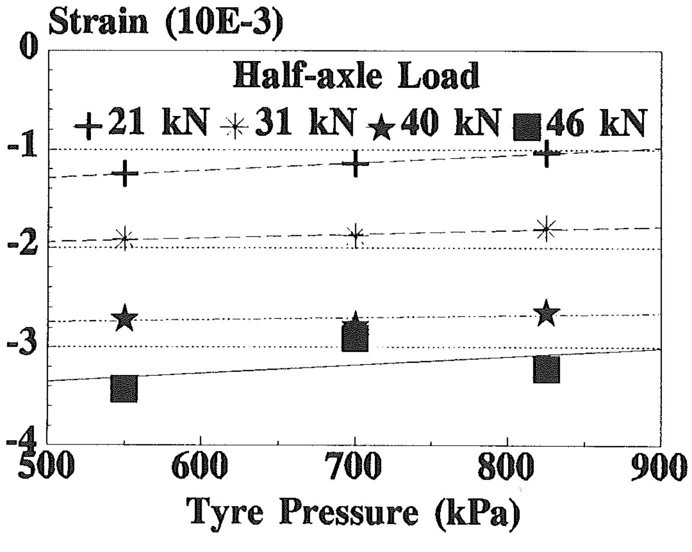

Figure 3 Peak Subgrade Strains

Measurements in the Unbound Granular and Subgrade Layers

The pavement (simultaneously one of the six test sections for the BPI project described above) had an asphaltic concrete surfacing 85 mm in thickness, over 200 mm unbound granular basecourse over a clayey subgrade. The *in situ* CBR of the subgrade for the test section was 13. The basecourse aggregate was a well-graded, crushed gravel. The asphalt binder was a plastomer-modified bitumen (Practiplast).

The surface deflection bowls, the vertical strains at various depths in the pavement and subgrade, longitudinal and transverse profiles, and temperatures in the bottom of the asphalt layer and in the basecourse were measured after specified intervals of loading cycles. 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 ply tyres in both vehicles were inflated to 700 kPa, and the vehicle speed was 40 km/h. SLAVE applied over 3.2 million EDA to the test pavement. The total rut depth was only 4 mm. The project concluded before the pre-defined failure criterion of a maximum surface rut depth of 25 mm occurred because the pavement design was conservative and the maximum expenditure on the project was reached.

The peak vertical compressive strain was in the range of 300 to 220 μm/m. The relationship between the magnitude of the vertical compressive subgrade strain and cumulative loading is shown in Figure 4. Increasing the wheel load from 40 kN to 46 kN, after 920,000 EDA, resulted in a negligible change in the magnitude of the vertical compressive strain responses in the subgrade (from 1200 to 1250 μm/m) and no change in the basecourse strain.

The nominal magnitude of the vertical compressive strain in the subgrade varied between 900 and 1400 μm/m, and the pavement survived 3.2 x 10^6 EDA without incurring any substantial permanent deformation in the pavement or subgrade. If the pavement had failed at that loading, then, according to equation (1), the maximum allowable vertical compressive strain in the subgrade should have been only 660 μm/m. The pavement thickness design procedure was conservative. Also, the lack of adverse environmental effects would have contributed to extending the life of the pavement.

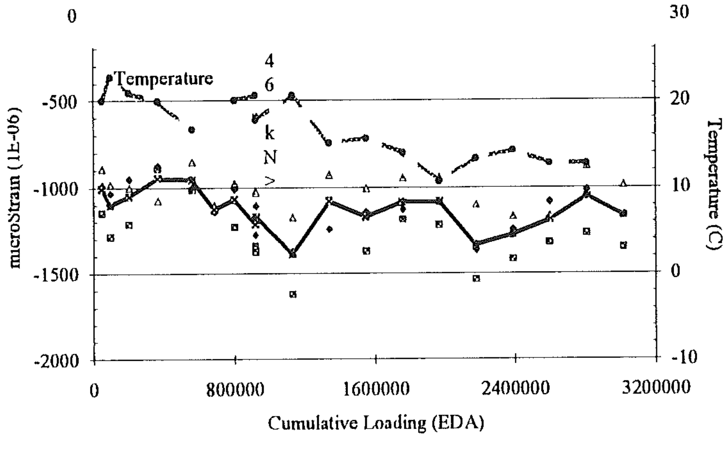

Figure 4 Peak Vertical Compressive Strain in the Subgrade and Asphalt Layer Temperature

Life-cycle Performance of a Thin-surfaced Unbound Granular Pavement

The test pavement consisted of a 25 mm asphaltic concrete surfacing layer over 135 mm thick basecourse on a clay subgrade. The pavement was subjected to a constant loading condition (40 kN load and dual radial tyres inflated to 825 kPa) until the trial concluded at 740,000 EDA, when the maximum permanent vertical deformation (rut depth) of the surface reached 28 mm (the predefined definition of failure was a maximum rut depth of 25 mm). The maximum rut depths of the rest of the pavement ranged from 15 to 22 mm. The maximum permanent deformation in the asphaltic concrete surfacing and unbound basecourse layers were 8 mm and 7 mm, respectively, while the permanent deformation in the subgrade varied between 1 and 13 mm. The deformation was due primarily to shallow shear within the basecourse layer. 75% of the permanent deformation occurred in the first 100,000 EDA, then the rutting progressed at a relatively constant rate of 9 µm/ EDA.

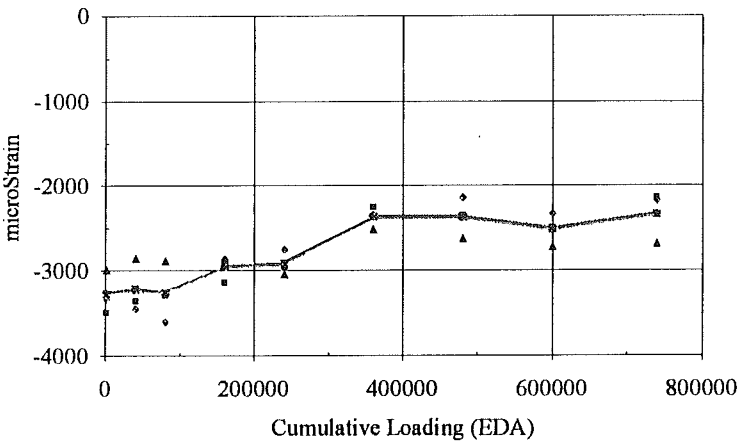

Figure 5 Vertical Compressive Strain in the Basecourse

After the initial sharp increase in magnitude in the peak vertical compressive strain in the subgrade (ε_{cvs}), the strain-cumulative loading relationship curve tended to exhibit a concave-up pattern, except for the decrease in magnitude at 220,000 EDA (Figure 5). Conversely, Figure 6 illustrates how the average magnitude of the peak vertical compressive strain in the basecourse generally decreased during the first 300,000 loading cycles, from 3200 to 2350 µm/m, then remained relatively constant until the pavement failed.

Except for a 0.15 mm increase in surface deflection that occurred between 100,000 and 200,000 cumulative EDA, the peak surface deflection was a relatively constant 1.6 mm throughout the life of the pavement. The deflection bowl shapes were constant temporally, indicating that the relative moduli of the various layers did not change during the trial.

During the initial traffic compaction (until approximately 300,000 EDA), the pavement exhibited fluctuating surface deflections and vertical compressive strain levels in the basecourse and subgrade layers, and the pavement layers densified substantially. The basecourse strain levels tended to decrease in magnitude, while the magnitude of the subgrade strain tended to increase. Then, the pavements reached a relatively stable condition, with minor fluctuations in the response to load.

Using equation (1), and substituting 740,000 EDA for N (number of loading cycles to failure), the maximum allowable vertical compressive strain in the subgrade is 940 µm/m, which is substantially less than the actual strains recorded (shown in Figure 6) of 2800 µm/m (nominal value). The actual strains are two to three times the theoretical maximum allowable, which suggests that the criterion on which the pavement thickness design charts are based could be conservative.

Effect of Suspension Dynamics on Pavement Wear

The objective of the current research programme is to compare the pavement wear caused by dynamic loads generated under different types of suspensions. Using the accelerometers fitted to the SLAVE vehicles, vertical dynamic loads created by the vehicle bounce are related to pavement profile measurements and sub-surface strains.

Altogether, five pavements will be constructed and tested sequentially. Sufficient subgrade soil and basecourse aggregate were procured for five pavements and have been stockpiled, to ensure that the material properties of the pavement are the same for each suspension. The well-graded basecourse aggregate of crushed gravel was produced to stringent specifications by a local contractor using a newly developed portable aggregate blending plant.

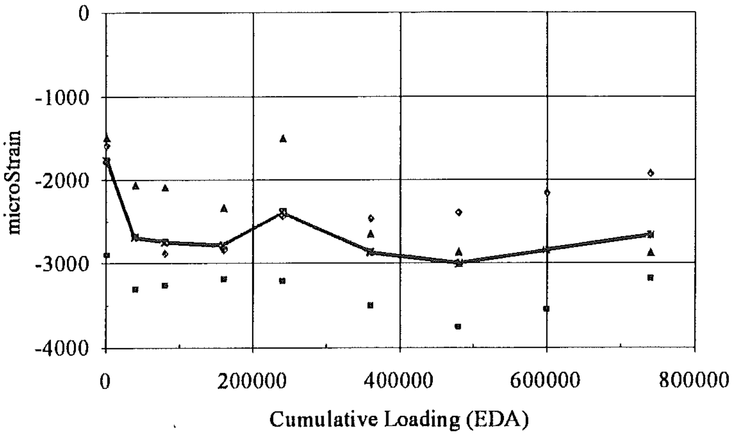

Figure 6 Vertical Compressive Strain in the Subgrade

The first pavement tested was a New Zealand thin-surface design, consisting of a 30 mm asphalt layer over 250 mm of crushed rock basecourse and a silty clay subgrade of CBR 12. The CAPTIF "vehicles" were fitted with wide-based single tyres in order to maximise the separation between the wheel paths of the two "vehicles", and were loaded to 3.8 tonnes. One "vehicle" was fitted with a steel parabolic leaf spring and a shock absorber, while the other was fitted with a multi-leaf steel suspension. The suspensions were characterised using a test procedure for rating a suspension "equivalent-to-air". This procedure involves driving the vehicle at crawl speed up a defined ramp which culminates in an 80 mm drop and measuring the suspension response. To be rated "equivalent-to-air" a suspension must respond with a natural frequency less than 2 Hz and have a damping greater than 20% of critical with at least half this damping being provided by the shock absorber. The vehicles operated at 40 km/h.

The pavement failed much sooner than the design life predicted but the mode of failure was extremely valuable with respect to the aims of the project. Both inner and outer wheelpaths showed clearly the effect of dynamic loading with severe depressions in the pavement at intervals relating to the dynamic characteristics of the two different suspension types.

SUMMARY AND CONCLUSIONS

The research conducted at CAPTIF since 1987 has contributed to the understanding of the behaviour and performance of thin-surfaced unbound granular pavements and the effect of vehicle dynamics on pavement wear.

With respect to pavement response to loading, and for the specific conditions of the investigation, the tyre type (10.00R20 radial and 10.00x20 bias ply) had an insignificant effect on the elastic vertical strain, the tyre inflation pressure (between 550 kPa and 825 kPa) had a minor effect on the response of the pavement, and the effect of increasing the wheel load was approximately linearly elastic.

The relationship between vertical compressive strains in the materials and the cumulative loadings becomes stable after the pavement is compacted under initial trafficking (in the absence of adverse environmental effects).

The actual strain magnitudes measured are substantially greater than the levels predicted by the models that are the basis of current flexible pavement design procedures, for the same number of loading repetitions to failure: the subgrade strain criterion is conservative. For the performance trials, the vertical compressive strain levels in the unbound basecourse aggregate tended to decrease slightly in magnitude under cumulative loading, while the magnitude of the subgrade strain tended to increase. The basecourse aggregate consolidated under repetitive loading, then reached a stable condition. The above conclusions are valid for the materials, loading characteristics and environmental conditions used in the projects.

CAPTIF was designed to generate realistic dynamic wheel loads rather than attempt to eliminate them. The CAPTIF "vehicles" which apply the loads are fitted with suspensions based on actual heavy vehicle components. The most recently completely project provided the first measured evidence of a direct link between peak dynamic loads and pavement damage ever reported.

The facility has been beneficial in evaluating the performance of aggregates and pavement design assumptions by collecting data describing the long-term performance of pavements, and investigating the relationship between vehicle loading conditions and the deterioration of pavements for a wide spectrum of pavement and loading characteristics.

ACKNOWLEDGMENTS

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