Long Term Pavement Response Data System using In-Situ Instrumentation

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ABSTRACT

The large majority of New Zealand's road network is constructed from thin surfaced unbound flexible pavements where a granular layer provides the main structural strength of the pavement. The current AUSTROADS[1] empirical design theory states that permanent deformation is largely attributed to the subgrade and that shape loss in the granular layers is simply a consequence of a previously deformed subgrade. However, recent research have indicated that shear strains in unbound granular basecourses may be a significant contributor to rutting, which contradicts the traditional pavement design theory which presupposes that permanent deformation is caused by accumulation of residual vertical compressive strains in the subgrade. Hence the need for an *in-situ* direct measurement device that operates under the non-linear stress-strain characteristics of unbound flexible pavements was identified, and research undertaken to develop such a system.

The research concluded that the rosette coil arrangement was a feasible and accurate device for measuring *in-situ* strains in granular pavement layers. Finite element modelling confirmed the accuracy of the system. The system has since been installed in road pavements in service, which are being monitored.

The research also highlighted the dominance of longitudinal tensile strain and shear strain over the vertical compressive strain within granular layers. These pavement responses should be considered in further granular pavement research in addition to the commonly used vertical compressive strains.

The paper concludes by outlining some of the practical benefits of utilising such a system within a road and maintenance system and how these can be used to enhance the decision making process.

INTRODUCTION

Over the last decade, the New Zealand roading industry has undergone a substantial change in the way that road controlling authorities contract both new construction and maintenance projects. A significant shift has occurred whereby road authorities are moving away from traditional prescriptive contracts towards outcome-based contracts. The introduction of these outcome-focused, performance based construction and maintenance contracts have allowed contractors to be more innovative and share more of the responsibility for the project. This has essentially changed their role from a schedule of rates based contractor to an asset manager, and has required a better understanding of pavement response under loading especially as the contractor must utilise their knowledge of the asset to apply the correct treatments, in the most efficient way, and at the most effective time. Predominantly surface based tests and inspections are used to determine the serviceability of the pavement but these tests provide minimal information on the pavement's response to loading and consequently its structural integrity.

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[1] AUSTROADS is the Association of Australian and New Zealand highway agencies

Therefore the new challenge that is emerging for contractors is to better understand their road asset in order that optimum investment strategies can be identified in the decision making process.

Two significant parts of understanding the asset involves the pavement's serviceability and its structural integrity. With respect to the former, there have been substantial advancements in surface based methods to efficiently and accurately measure pavement condition indicators. However, with respect to the structural condition of the pavement, there is a genuine need for the development of an in-situ method of measuring long-term pavement response data that can operate under the non-linear stress-strain conditions of unbound flexible pavements. Such a system would substantially improve the understanding of road asset consumption by heavy vehicles and therefore allow for more structurally appropriate designs and more informed maintenance decisions. This paper describes the development of an *in-situ* method of measuring compressive and tensile principal and shear strains in the pavement induced by heavy vehicles loads.

BACKGROUND

More than 95% of New Zealand's roads are flexible pavements consisting of an unbound granular base and subbase with either a chip seal or thin asphaltic concrete surface. The unbound granular layers provide the load bearing capacity for the pavement and their function is to distribute the applied loads to the underlying subgrade layer. The current New Zealand design procedure for unbound flexible pavements is based on the AUSTROADS Pavement Design Guide *(1)* and its companion document, the New Zealand Supplement *(2)*. The AUSTROADS thickness design guide is an empirical procedure based on the subbase and basecourse thickness required for the design loading and the California Bearing Ratio (CBR) of the subgrade. Permanent deformation failure is attributed to excessive vertical compressive stress at the top of the subgrade and no consideration is given to shear failure in the granular layers, assuming that the granular materials and construction comply with national specifications (*3,4*).

However, there is a substantial amount of evidence to show that permanent deformation can be attributed to failure within the granular layers as well as the subgrade. For example, excavations on rutted unbound granular pavements that have been subjected to heavy vehicle loads have often shown significant permanent deformation in the granular layers, whereas the subgrade is often in good structural condition *(5)*. In addition to this, accelerated testing has shown that rut development can be viewed as an indication of base behaviour under load, if there is no appreciable subgrade consolidation *(6)*. Therefore subgrade deformation may make a significantly lesser contribution to surface rutting than the model assumes. Accelerated pavement testing in New Zealand produced strain measurements that implied significant shallow shear forces were developed which could affect the degradation of the pavement *(7)*.

Based on the evidence supporting basecourse shear strains as a substantial contributor to overall rut development, a two year research project was undertaken to develop an in-situ method of accurately measuring the shear strains induced in the basecourse by heavy vehicles.

STRAIN MEASUREMENT SYSTEM

In order to measure shear strains within granular layers, free floating induction coils were used due to their ability to accurately measure vertical and horizontal stains in granular layers *(8)*. However, as opposed to previous investigations that have utilised induction coils to measure only sub-surface vertical and horizontal strains, a method was required to measure shear strains.

Various coil arrangement and orientation designs were evaluated in the laboratory; the coil rosette design was identified as the most feasible and accurate method of measuring shear strain. This design consists of three pairs of co-axial coils measuring the three principal strains within a hypothetical cube of granular material (Figure 1). Using the measured principal strains, Mohr's circle of strain can be plotted in order to determine the maximum shear strain on two planes. This type of analysis is based on the assumption that there is no shear strain acting on the faces of the material cube. Obviously small shear strains on the cube faces will be present due to the torque caused by the tyre and therefore the compressive and tensile strains measured by the coils are not the true principal strains. However, these strains were assumed to be small enough that neglecting them will not have a significant effect on the magnitude of the calculated maximum shear strain within the soil element. Finite element analysis was used to verify this assumption.

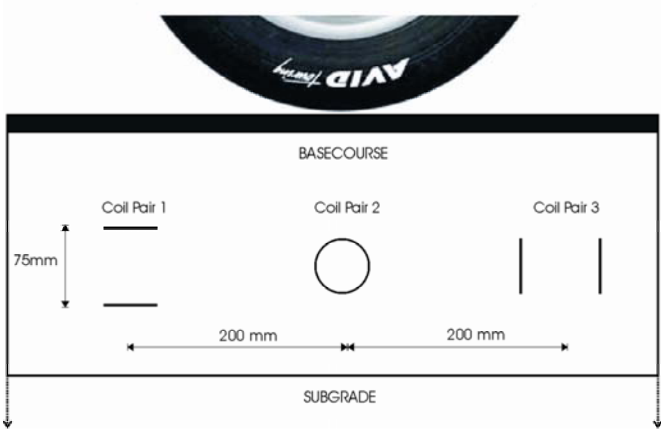


FIGURE 1 Side elevation of a pavement with rosette general design.

Based on the known speed of the test vehicle and the 200mm spacing between the coils, the measured strain profiles for each of the three coil pairs can be translated to one specific point. This would result in the same measurements that would have occurred if all three coil pairs were located around the same in-situ cube of material. A visual illustration of this is shown in Figure 2.

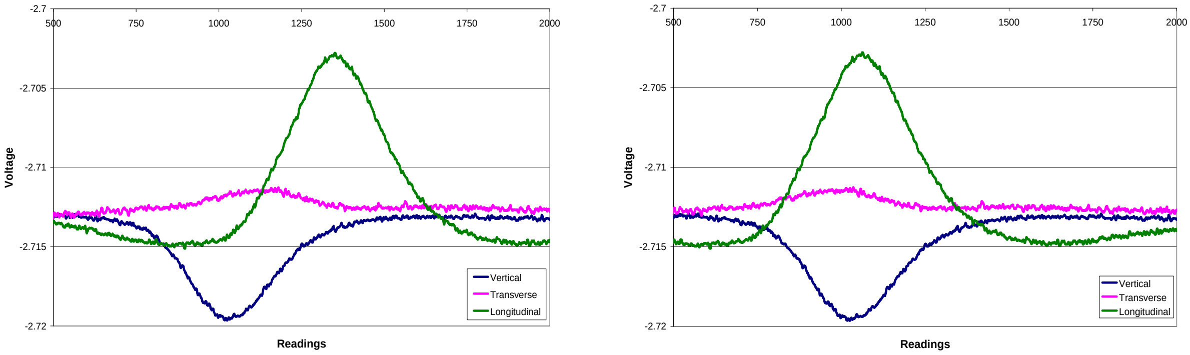


FIGURE 2 Original voltage traces from a rosette (a). Transverse and longitudinal voltage traces translated to vertical trace (b).

Shear Strain Calculation from Rosettes

Using the vertical and longitudinal principal strains and the vertical and transverse principal strains, two Mohr's circles can be constructed to determine the combination of normal and shear strains at any angle on the yy and xx planes. In addition to this, the magnitude of the maximum shear strain can be determined from the plot, where this value is equal to the diameter of the circle. For example, Figure 3 shows an element of material with the vertical and longitudinal strains measured. Based on these principal strains, Mohr's circle of strain is constructed and the maximum shear strain is determined. In addition to this, the circle indicates that this maximum shear strain occurs on a 45˚ plane within the element (shown by the dashed line on the element with shear arrows).

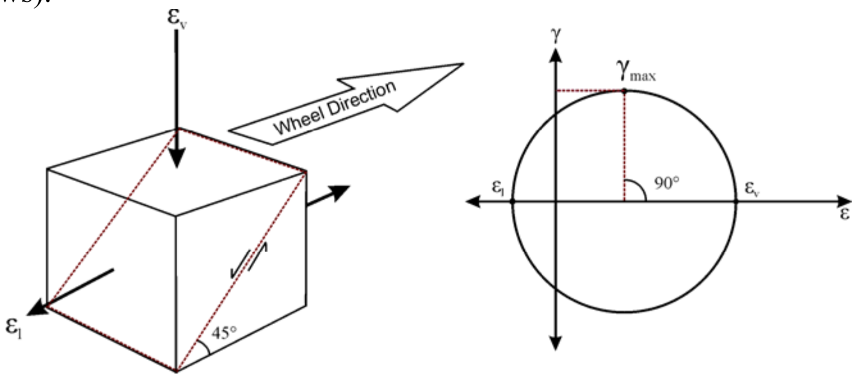


FIGURE 3 Two measured principal strains and corresponding Mohr's circle of strain showing maximum shear strain and plane this shear strain acts on

The rosettes were installed in two full scale test pavements at the Canterbury Accelerated Pavement Testing Indoor Facility (CAPTIF), located in Christchurch, New Zealand and monitored while the pavements were loaded with an 8.2 tonne dual wheel axle load for 1 million and 600,000 load applications, respectively. Rut depth testing occurred periodically throughout the test. Shear strains measured at CAPTIF were referred to as either longitudinal shear strains or transverse shear strains. Longitudinal shear strain is the strain that would cause shearing along a plane at an angle (eg 45º) to the yy plane in the direction of wheel travel (such as shown in Figure 3). The longitudinal shear strain is determined using the principal vertical strain and the principal longitudinal strain. Similarly, the transverse shear strain occurs along a plane at an angle to the xx plane (perpendicular to the direction of travel) and this strain is determined using the principal vertical strain and the principal transverse strain. The maximum shear strain is therefore the greater of either the longitudinal or transverse shear strains. This method of determining the maximum shear strain is based on the Tresca criterion (*9)* whereby although three principal strains are known, only the two strains with the greatest difference are used to calculate the maximum shear strain. This is illustrated in Figure 4 where although three principal strains are known, the smaller compressive strain (ε_t) is not used to calculate the maximum shear strain. In all cases, the longitudinal shear strain was substantially larger than the transverse shear strain and therefore the longitudinal shear strain was also the maximum shear stain. While being placed, granular materials tend to align themselves with the maximum dimension in the horizontal longitudinal direction (*10*). In addition to this, compaction equipment generally orientates the aggregate in the longitudinal direction and rarely in the transverse direction. The particles are thus further orientated towards the direction of travel. Thus, the longitudinal orientation of the material particles caused by gravity during deposition and construction techniques may have contributed to the longitudinal tensile strains having the dominant magnitude. Throughout this paper, only the maximum shear strains are discussed and analysed because the smaller (transverse) shear strain had a negligible effect on the magnitude of the maximum shear strain.

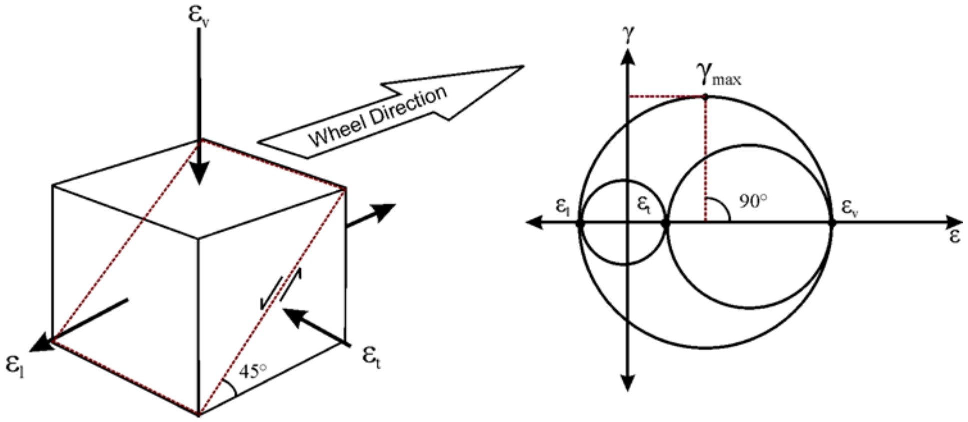


FIGURE 4 Maximum shear strain using Tresca failure criterion.

PAVEMENT CONSTRUCTION AND ACCELERATED TESTING

Two separate test pavements were constructed at CAPTIF during 2005 and 2006 in accordance with Transit NZ M/04 (*3)* and Transit NZ B/02 (*4)*. Both were unbound flexible pavements with an identical clay subgrade; the first pavement had a well-compacted basecourse (98% maximum dry density) whereas the second pavement was purposely compacted to achieve a lower density (94% maximum dry density). Both pavements had a thin, non-structural riding surface. Three coil rosettes were installed in each pavement, with the centroid of each rosette being located 250mm below the surface of the basecourse.

The first and second pavement was continuously loaded with 40 kN dual wheel load, (equivalent to a 8.2 tonne dual-tyred standard axle load) for 1 million and 600,000 loads applications, respectively. At various points during the test life, strain measurements were taken whilst accelerated loading continued, and rut depth profiles were measured using a automated profilometer.

PRESENTATION AND ANALYSIS OF RESULTS

After only 10,000 load applications, the first pavement's basecourse (which had been compacted to a higher density) failed in shear (this was subsequently confirmed with post mortem layer profiles) with rut depths exceeding 20mm. Strain testing was conducted during these initial load applications and shear strains in the order of 5000 micro-strain were calculated. A 70 mm granular overlay was constructed in order to strengthen the basecourse and sealed; however, these initial failure shear strain results give a good indication of the shear strain magnitudes expected during a rapid shear failure.

With the exception of the initial failure of the first pavement, both test pavements performed well for the remainder of the accelerated test life. Strains and rut depth profiles were measured at regular intervals throughout testing and the shear magnitude and accumulated rut depth profiles (expressed as the maximum vertical surface deformation) are shown in Figures 5 and 6, respectively.

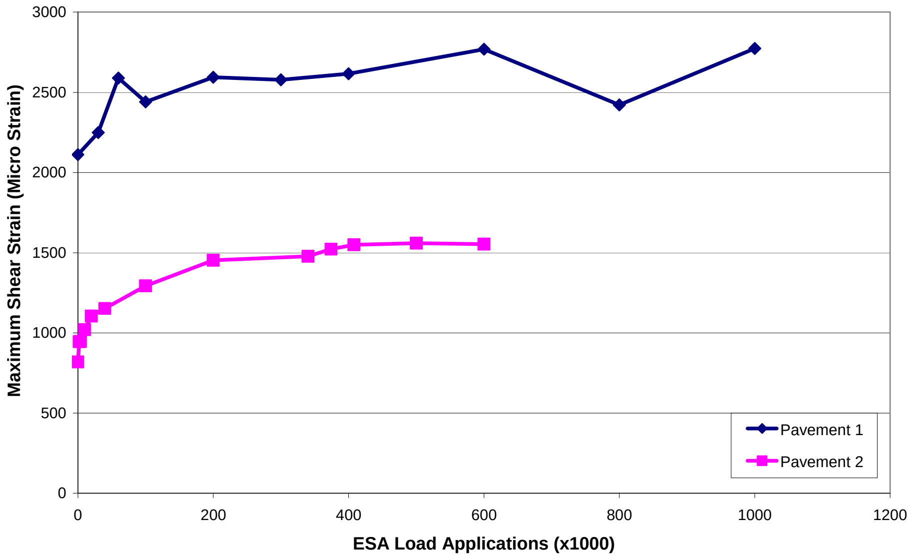


FIGURE 5 Maximum measured shear strain during pavements' test lives.

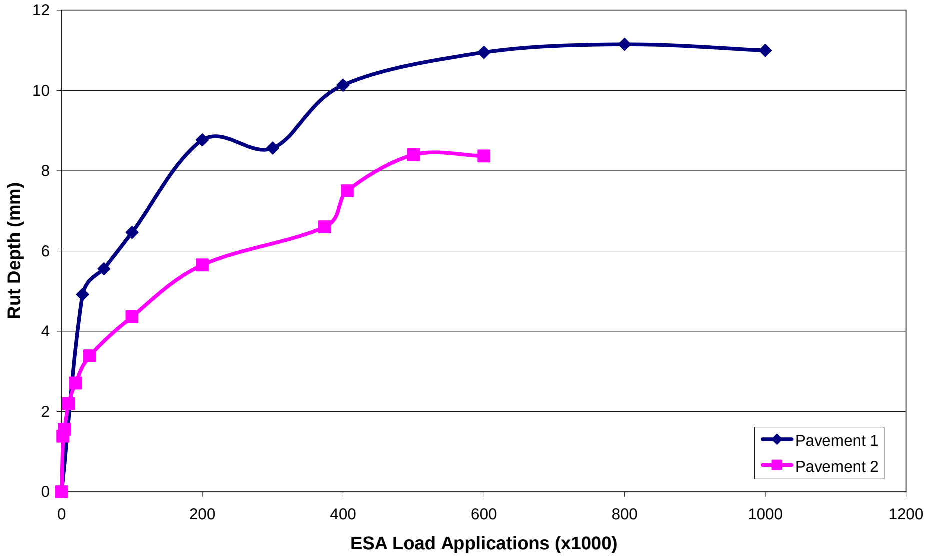


FIGURE 6 Accumulated rut depth during pavements' test lives.

The variation in shear strains during the first 100,000 laps is attributed to the *post construction compaction period* where the basecourse is further compacted and the material slightly realigned due to the application of the wheel load. An illustration of this period within a pavements life is shown in Figure 7.

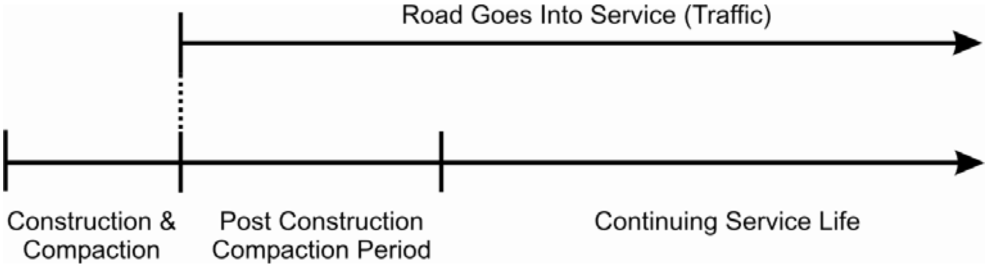
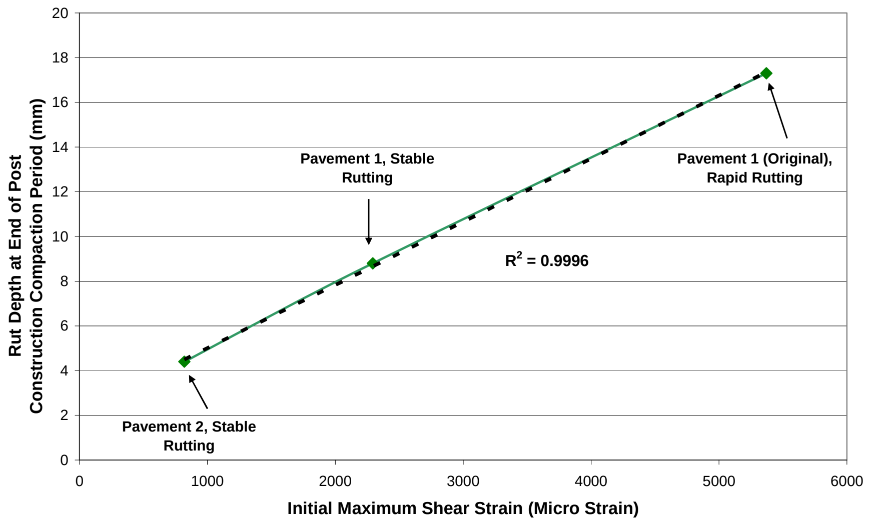


FIGURE 7 Post construction compaction period within a pavement's life.

The relationship between shear strain and rut depth for Pavements 1 and 2 is different between the post construction compaction period and the continuing service life. Therefore, the analysis that follows considers two separate phases in the pavements' lives: during the post construction compaction period and after the post construction compaction period has finished.

Post Construction Compaction Period Analysis

The magnitude of the shear strains in each pavement (including the first pavement before the shear failure) correspond with the initial increase in rut depth during the post construction compaction period. Figure 8 shows that a linear relationship exists between shear strain magnitude at the end of the post construction compaction period and rut depth at the end of this period. This relationship has a coefficient of determination (R^2) of 1.00 indicating a strong linear relationship exists based on the measured data.



The potential therefore exists for the strain rosette system to be used to estimate the rut depth after the post construction compaction period using measured shear strains. This is a very beneficial tool because previously it has been very difficult to estimate this significant portion of the total rutting. Researchers have focused their unbound flexible pavement rut depth modelling work on the development of permanent deformation after the post construction compaction period because of the "difficulty in determining the initial post construction compaction of a pavement"*(11)*. Due to the general behaviour of stable rut development, the rut depth at the end of this period typically makes up a large proportion of the total rut depth expected throughout the pavement life (assuming major rut failure does not occur). Coils could be installed either during the construction of a new pavement or after rehabilitation has occurred (for example a granular overlay). Shear strain measurements could then be taken using a vehicle with a 40 kN dual wheel assembly (8.2 tonne axle load) and the magnitude of the shear strain could be used to estimate the rut depth expected at the end of the post construction compaction period.

Remaining Service Life Analysis

Following this, the changes in shear strain magnitude from the end of the post construction compaction phase until the end of testing correspond well with the changes in rut depth accumulation after the post construction compaction period. The percentage increase in rut depth in both pavements is directly related to the percentage change in shear strain (Tables 1 and 2).

Two phases were identified after the post construction compaction period. The first development phase involved a slow but constant increase in both rut depth and shear strain. This phase lasted until the change in rut depth became negligible, which occurred after 600,000 and 250,000 load applications on the first and second pavements, respectively. The second phase involved a constant rut depth and minimal change in shear strain; this phase continued in both pavements until the end of testing. Based on the two pavements data, it was established that there was an approximately 4:1 ratio between the percentage change in rut depth and the percentage change in shear strain.

TABLE 1 Average changes in shear strain and rut depth from the end of the post construction compaction phase until the end of phase 1 development

		End of Initial Post Construction Period	**600000 Load Cycles**	**% Change**	**Ratio**
Pavement 1	Shear Strain	2594	2768	7	3.7
	Rut Depth (mm)	8.8	11	25	
Pavement 2	Shear Strain	1292	1560	21	4.4
	Rut Depth (mm)	4.4	8.4	91	

TABLE 2 Average changes in shear strain and rut depth from the end of phase 1 development until the end of testing (phase 2 development)

		600000/500000 ESA	**End of Test**	**% Change**	**Ratio**
Pavement 1	Shear Strain	2768	2774	0.2	0.0
	Rut Depth (mm)	11	11	0.0	
Pavement 2	Shear Strain	1560	1554	-0.4	0.0
	Rut Depth (mm)	8.4	8.4	0.0	

Therefore in summary, the results indicate that the magnitude of the initial shear strain appears to be directly related to the increase in rut depth during the post construction compaction phase. Further to this, the change in shear strain magnitude following the post construction compaction phase corresponds to the increase in rut depth after the post construction compaction deformation has occurred.

CONCLUSIONS AND RECOMMENDATIONS

1. A robust *in-situ* method of measuring compressive and tensile principal and shear strains in the pavement induced by heavy vehicles loads has been developed and its effectiveness has been confirmed. The strain measurement system uses a rosette configuration of free-floating induction coils that are designed to measure principal strains in three dimensions. The principal strains are used to construct Mohr's circle of strain in order to calculate the maximum shear strain occurring in the granular layer.
2. Contrary to traditional pavement design theory, which presupposes that permanent deformation is caused by accumulation of residual vertical compressive strains in the subgrade, shear strains in unbound granular basecourses are a significant contributor to rutting. Shear strain results were measured for an unbound flexible pavement that failed quickly due to basecourse shear. Shear strains with magnitudes of approximately 5000 micro-strain resulted in failure due to permanent deformation within 8,000 equivalent single axle load (80kN) repetitions.
3. In two trial pavements, longitudinal shear strains were significantly larger and more sensitive to load than the transverse shear strains and therefore the longitudinal strain (which is also the maximum shear strain using a Tresca criterion) was determined to be the most appropriate shear strain to be used in further analysis.
4. The potential therefore exists for induction coils to be used to estimate the rut depth after the post construction compaction period using measured shear strains, which is important for pavement design, maintenance, performance database and a host of other applications. Pavement deterioration models should be modified to reflect the significance of shear strain in rut development in unbound granular pavements.
5. The induction coils and emu system could be used in the field to estimate rut development rates throughout the pavement life after the post construction compaction period has ended. There is a strong relationship between change in shear strain magnitude and change in rut depth. The system could therefore be used to periodically measure the shear strain magnitudes under a standard axle load and based on the rate of strain change, the rate of rut depth development can be estimated. The system could be used as an intervention estimation tool. This would involve determining the rate of strain change from in-situ coils (after the post construction compaction period) and consequently determining the estimated rate of rut depth change. Based on the known rut depth at the end of the post construction compaction period (which would be measured on site) the estimated rate of rut development could be used to calculate the approximate time period until the pavement reaches a condition where maintenance intervention would be required. The change in rut depth rate could be systemically re-calculated throughout the pavement life to re-evaluate the estimated failure time. This tool could be used independently or utilised with pavement deterioration models to improve maintenance schedules and the timing of rehabilitation work.
6. The magnitude of the longitudinal strains measured is significantly larger than that expected by New Zealand pavement experts, and by both finite element and linear elastic models. Within the modelling side of pavement analysis, further work could be undertaken to more accurately predict these large strains and the consequent effect of large tensile strains in an unbound material with minimal tensile strength. This would involve determining factors to model the anisotropic nature of granular materials.

ACKNOWLEDDGEMENTS

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