Investigation of the Effect of Shoulder Properties, Axle load, and Tyre Pressure on Edge Failure of Thin Surfaced Granular Pavements

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Abstract

New Zealand has a tradition of building granular pavements surfaced with chipseals. This form of construction is used on most rural roads and can perform well under traffic volumes of over 10,000 vehicles/lane /day.

Because of New Zealand mountainous topography many highways have very narrow shoulders. Due to this lack of lateral support and the intrusion of heavy axle loads onto the edge of pavement, edge failure has been encountered on many of these roads. This has more recently been exacerbated by the growth in forestry which has seen large truck and trailer units transporting logs out of the forests.

The main objective of the research work reported here is to investigate how the pavement shoulder properties and load parameters affect this type of distress.

A three dimensional finite elements model and a half fractional factorial experimental design were made to study five factors, viz., shoulder width, shoulder stiffness, axle load, tyre pressure and pavement thickness. Each factor was studied at two levels to simulate extremely low and high conditions.

The results of the finite elements model have been validated to ensure accurate predictions. The multilayer elastic solution was carried out using Circly and Everstress software. Linear and nonlinear analyses using isotropic and cross-anisotropic material properties were compared to the actual strain measurements carried out at Transit New Zealand accelerated test track facility (CAPTIF). None of the analytical solutions perfectly matched the measured strains. In addition, the results of the multilayer and finite elements analyses were compared together at different locations and depths from loaded area. The multilayer and three dimensional finite elements solutions were reasonably close for stresses, strains and deflections. Only very slight differences were observed for stresses and strains near the surface because of the difference between the circular and rectangular shape of loading areas in the mulilayer and finite elements analyses.

The statistical experimental factorial analysis showed that the order of importance of the different factors affecting pavement response relies on the type of response and the location of that response. Three pavement responses were studied, maximum deflection between dual tyres, maximum deflection under the outer wheel load, and compressive stain at the top of the subgrade near the shoulder (300 mm from the centre of the dual). The axle load was the most significant factor affecting the deflection and strain at all locations. The interaction of shoulder stiffness, width and thickness has been shown to significantly affect the pavement response. It is proposed that the results of this research can be used by pavement designers to obtain an indication of the effect of lack of shoulder support on pavement performance.

Keywords

Edge failure, tyre pressure, axle load, finite elements, experimental design, factorial design, fractional factorial.

Introduction

From practical observation, it is apparent that a significant proportion of rural pavement failure in New Zealand is associated with failure near the edges of the pavement rather than by compressive failure in the centre. This failure mode is associated with the mountainous topography that makes constructing wide pavements expensive. It is also associated with the type of pavement construction used in New Zealand. New Zealand has a tradition of building granular pavements surfaced with chipseals. This form of construction is used on most rural roads and can perform well under traffic volumes of over 10,000 vehicles/lane /day.

When these relatively narrow pavements are subjected to heavy vehicles the edges tend to crumble due to lack of lateral support.

Ball and Patrick (1) carried out an investigation of the edge failure on New Zealand state highways and local authority roads utilizing data extracted from the Road Asset Maintenance Management system (RAMM) database. The data covered approximately 3,000 km of state highway and 3,000 km of local sealed roads.

Besides basic data such as location, surface type, length of inspection site, traffic and heavy traffic levels, etc., the following factors were particularly selected for statistical analysis: lane width, number of lanes, length of unpatched edge breaks, length of patched edge breaks, terrain type, and radius of curvature of both lanes. They found that the principal factors affecting the occurrence of edge breaks are lane width, seal age and total traffic per lane. Seal age in itself makes a significant contribution to the amount of edge breaks occurring. They concluded that because of the strong dependence of the probability of edge break on lane width, research to improve the strength of the pavement edge would have a significant potential to improve rural road performance. The hypothesis forming the basis of the research is whether by providing support to the sides of the pavement using trenches containing high-strength material, failure should be prevented.

As the strength, width and depth requirements of the lateral support are not known, the first stage of the research is to model and measure the stresses and strains generated by heavy traffic outside the wheel track.

A Finite Elements (FE) analysis of pavement stresses and strains is conducted at the University of Canterbury using ABAQUS general purpose finite elements software (HIIBBIT et al., 2003). The results of the modelling will be calibrated and validated using the measured pavement responses at the Transit NZ CAPTIF accelerated testing facility located in Christchurch and the outcome of this calibration will be published somewhere else. Only limited amount of vertical strains measurements were used to validate the three-dimensional finite elements model and the results of this validation are shown in this paper.

The Canterbury Accelerated Pavement Testing Indoor Facility (CAPTIF) is located in Christchurch, New Zealand see Fig 1. It consists of a 58 m long (on the centreline) circular track contained within a 1.5 m deep by 4.0 m wide concrete tank so that the moisture content of the pavement materials can be controlled and the boundary conditions are known. A centre platform carries the machinery and electronics needed to drive the system. Mounted on this platform is a sliding frame that can move horizontally by 1 m. This radial movement enables the wheel paths to be varied laterally and can be used to have the two “vehicles” operating in independent wheel paths. At the ends of this frame, two radial arms connect to the Simulated Loading and Vehicle Emulator (SLAVE) units. These arms are hinged in the vertical plane so that the SLAVE units can be removed from the track during pavement construction, profile measurement etc., and in the horizontal plane to allow normal vertical movement of the vehicles (Pidwerbesky, 1995).

Figure 1 - Transit New Zealand's Pavement Testing Facility, CAPTIF.

FINITE ELEMENTS MODEL

Model Geometry

ABAQUS (HIBBIT et al., 2003), a general-purpose finite elements code, was used to simulate the loading of a fully instrumented section in the accelerated test track, CAPTIF. A half model was developed to reduce the computational effort by making use of the symmetry in the geometry and the loading. Because most of the roads in New Zealand are made of thick granular base course which is either thin surfaced with AC or chip seal, only two layers were considered in the model to represent the base course and the subgrade. To carry out the experimental factorial design, different model geometries were considered. For example, two thicknesses for the base course were considered, 300 mm and 500 mm. The thickness of the subgrade is the difference between the CAPTIF tank depth (1500 mm) and the thickness of the base course. The 300 and 500 mm base course thicknesses were modelled using two and four elements, respectively. The thickness of the subgrade layer that ranges from 1000 to 1200 mm was modelled using eight and nine elements, respectively. The length of the finite elements section is 2000 mm. Figure 2 shows the three-dimensional finite elements model (3DFEM). The loaded area is composed of eight elements, four elements in each half of the model. The loaded area is modelled based on tyre imprints measurements carried out at the accelerated test track. It was found that the tyre imprint width is 225 mm and the length of the tyre imprint is 125 mm. However, these dimensions will vary based on the applied axle load and tyre inflation pressure. In this analysis, the tyre imprint width was maintained at 225 mm and the length of the tyre imprint was calculated according to the applied load and tyre pressure as shown below in Equation 1.

$$A = \frac{P}{q} \qquad \text{Equation 1}$$

A = Loaded area, m^2
P= Total load per tyre, kN
q = Tyre Pressure, kPa
For example, for an axle load of 80 kN, dual tyres and tyre inflation pressure of 400 kPa,

the loaded area under each tyre = $A = \frac{20}{400} = 0.05 \text{ m}^2$

$X = 225$ mm from actual measurements of the tyre imprints at CAPTIF
$A = 2 * X * Y$ (Because this is a half model), see Figure 2.
Y=111.1 mm

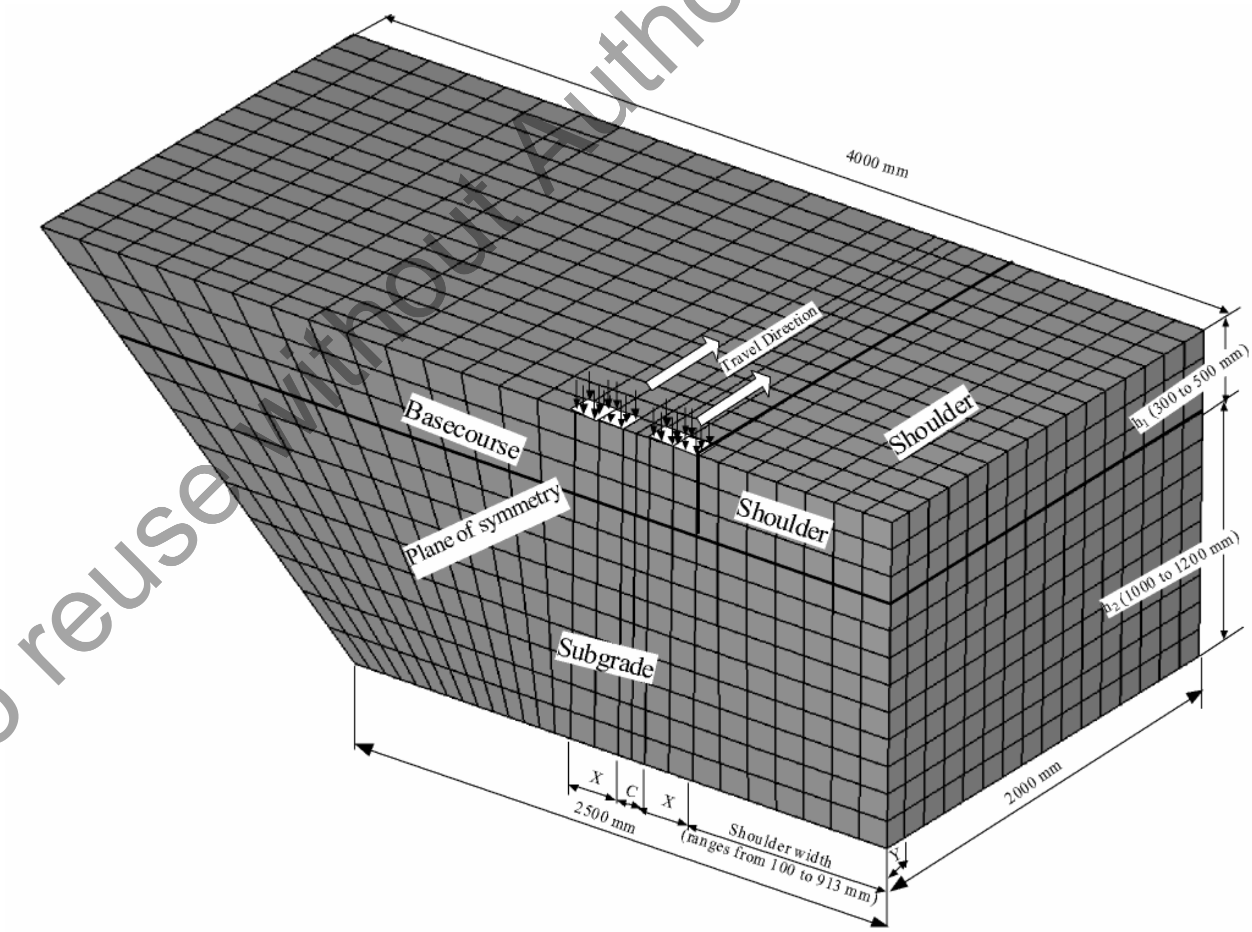

Figure 2 Three dimensional finite elements model

Where X is the width and Y is length of the loaded area in each half of the 3DFEM. The clearance (C) between the two loaded areas is 125 mm.

The length of the loaded area varies for different axle loads and tyre pressures and it can be calculated as shown above. For each run in the experimental factorial design, a separate 3DFEM model was developed to simulate the tyre pressure, axle load, pavement thickness, and shoulder properties. The aspect ratio is defined as the ratio of maximum to minimum characteristic dimensions in the element. This ratio affects the distortion of the elements during analysis, and it should not exceed 4.0. In addition, a good practice is to choose corner angles in the range of 30° to 120° (Chandrupatla and Belegundu, 1996). The average aspect ratio for all models is 1.34 and the worst aspect ratio is 2.45. The average minimum and maximum corner angles are 75.95° and 104.06°, respectively.

Element Type

The finite elements model was built using continuum three dimensional, eight-node, reduced integration elements (C3D8R). The reduced integration elements are preferred over the fully integrated elements to avoid the shear locking which is a problem with all fully integrated, first order, solid elements (HIBBIT et al., 2003). Shear locking only affects the performance of fully integrated elements that are subjected to bending loads.

Boundary Conditions

The rigid boundaries of the concrete tank in the accelerated test track, CAPTIF, were simulated in the finite elements model so that the bottom base of the subgrade is prevented from axial movements in the three directions. The sides of the model are only allowed to slide in the plane of the wall and are prevented from any movement perpendicular to the concrete wall. At the plane of symmetry, elements are only allowed to move vertically without any lateral displacement.

Multilayer Elastic Analysis

The pavement structure was modelled as three layers subjected to dual load. The distance from centre to centre of the dual is 350 mm (350 mm = C+X = 125+225mm). Figure 3 shows the load configuration and pavement layers properties used in the verification analysis of the finite elements model.

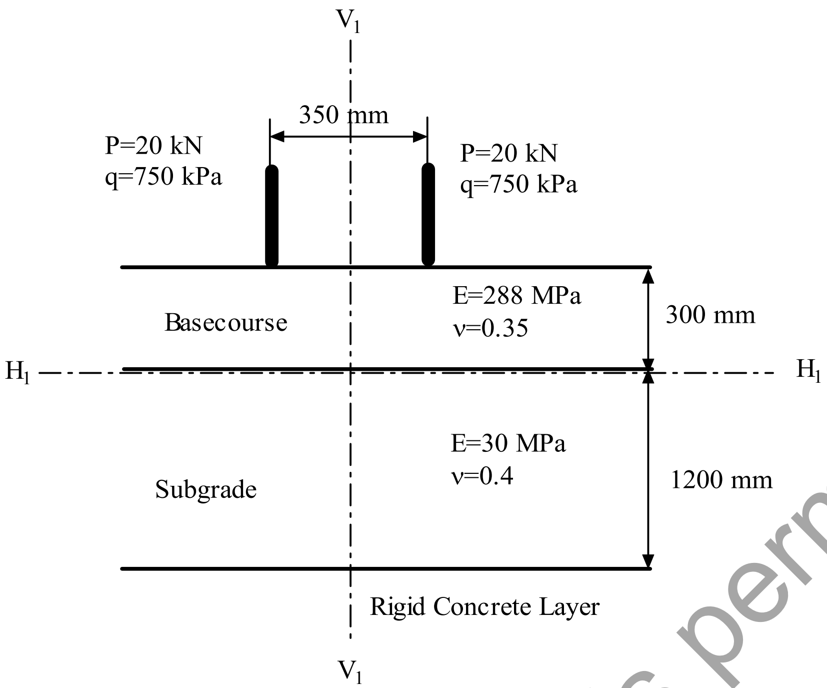

Figure 3 Multilayer elastic analysis model

Material Properties

The data from the repeated triaxial test for both the base course and the subgrade was used to determine the resilient modulus and the stress dependency of these materials. For the base course the k-θ model shown by Equation 2 and presented in Figure 4 showed excellent fit for the triaxial data with a coefficient of determination (R^2) value of 99.3%.

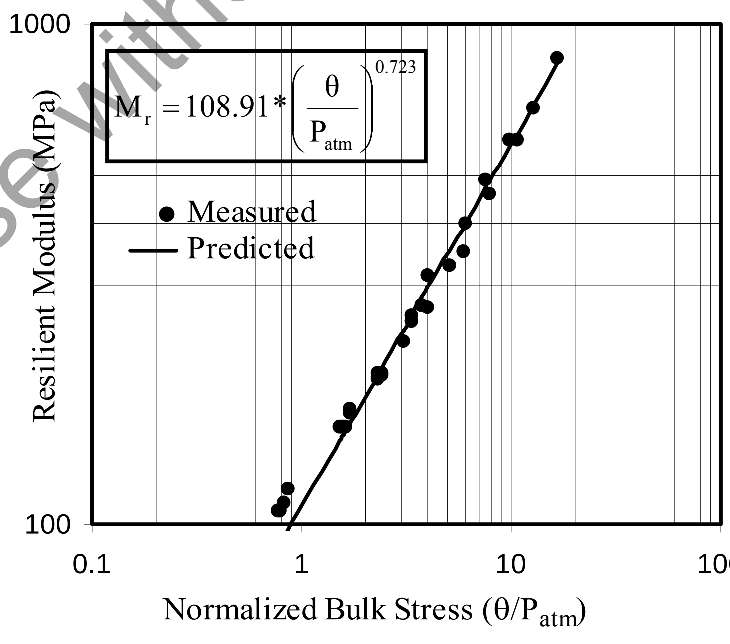

Figure 4 Relationship between resilient modulus and normalized bulk stress for the granular basecourse

$$M_r = 108.91 * \left(\frac{\theta}{P_{atm}} \right)^{0.723} \qquad \text{Equation 2}$$

M_r = Resilient Modulus (MPa)
θ = Bulk stress (kPa)
P_{atm} = atmospheric pressure (P_{atm}=101.4 kPa)
For the purpose of linear elastic analysis, the average resilient modulus for both the base course and subgrade was determined from the repeated triaxial test data as 288 and 30 MPa, respectively.

VERIFICATION OF THE 3DFEM

Comparisons between Different Analytical Solutions and Measured Strains

The pavement response predicted from the three dimensional finite elements (3DFEM) was compared with the multilayer elastic system solution. Linear and nonlinear elastic solutions were considered. In addition, isotropic and anisotropic analyses were carried out. In the cross-anisotropic solution, the horizontal resilient modulus was assumed half of the vertical resilient modulus value (i.e. $\frac{E_h}{E_v} = 2$). The cross-anisotropic linear elastic solution was carried out using Circly software (Wardle, 1977). Everstress software (1999) was used to carry out the nonlinear and linear isotropic elastic solutions. The solutions shown here are for a tyre pressure value of 750 kPa and 80 kN standard axle load. The material properties shown in Figure 3 and 4 were used in this analysis. Figure 5 shows the measured strains at the accelerated test track and the predicted strains using different analytical methods. None of the methods perfectly matched the measured strains. The 3DFEM solution came reasonably close to both the isotropic and cross-anisotropic solutions.

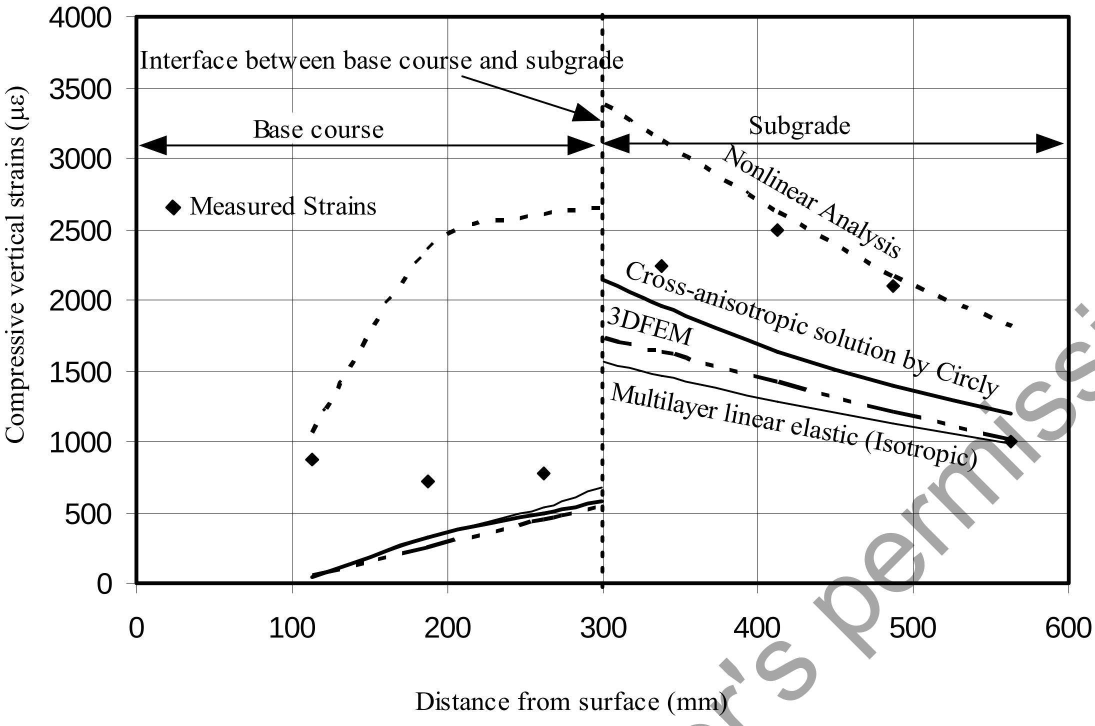

Figure 5 Comparisons between measured and predicted strains using different methods

Comparisons between Circly and the 3DFEM Solutions

In addition to the above verification, the deflections, vertical compressive stresses, and strains were determined at different depths under the centreline of the dual.

Figures 6 to 8 show comparisons between the multilayer solution using Circly software (using isotropic properties), and the 3DFEM solution by ABAQUS.

Deflections and compressive vertical strains by the 3DFEM and Circly are almost identical as shown in Figures 6 and 7. In Figure 8, compressive vertical stresses from Circly and the 3DFEM showed some differences near the surface and this could be due to the difference between the shape of the loaded areas (Circular versus rectangular), however after a depth of about 250 mm both solutions match each other. The close match between the 3DFEM and the multilayer elastic solution provide some confidence in the accuracy of the 3DFEM predictions.

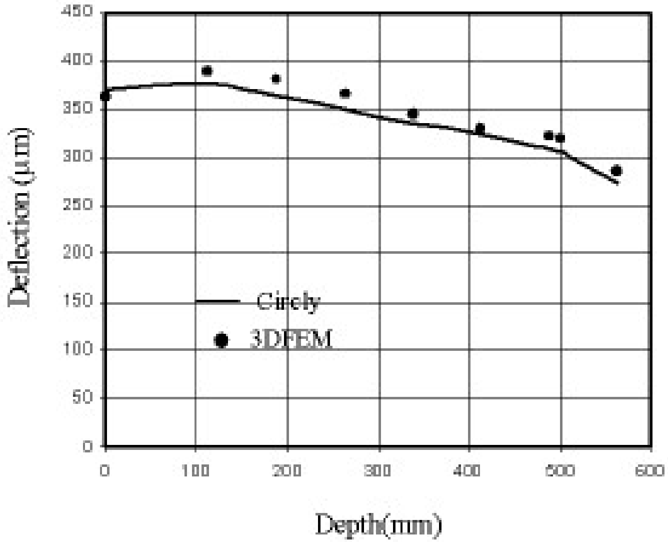

Figure 6 Comparison between deflections across v_1 plane for both Circly and 3DFEM

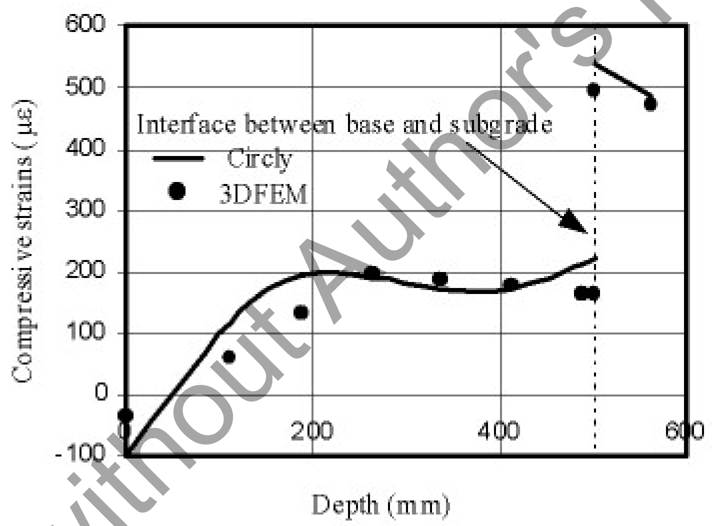

Figure 7 Comparison between compressive strains across v_1 plane for both Circly and 3DFEM

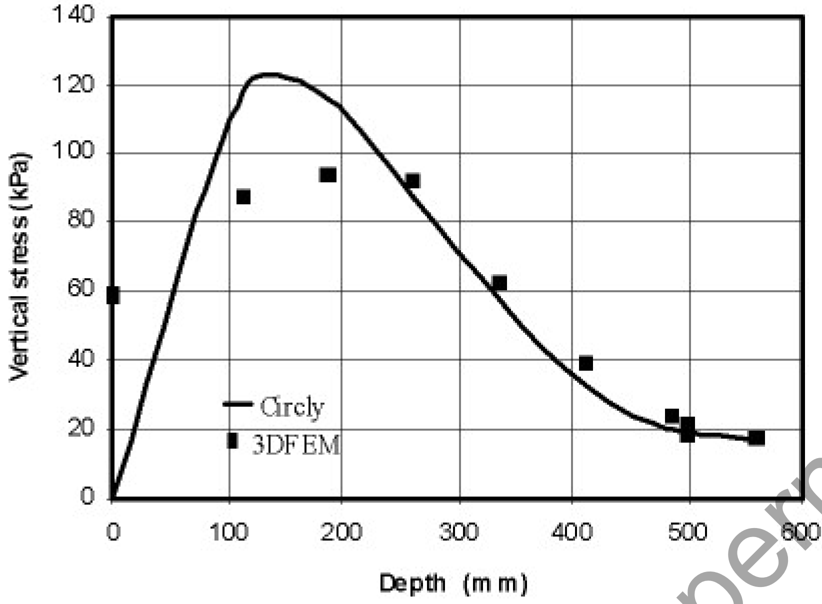

Figure 8 Comparison between compressive stresses across v_1 plane for both Circly and 3DFEM

Experimental Fractional Factorial Design

In the factorial experimental design, five factors; shoulder width, shoulder stiffness, axle load, tyre pressure, and pavement thickness were examined. Table 1 shows the different factors and the level of each factor. Each factor was set at two extreme levels in order to span a wide range of each factor. For example, tyre pressure was set at low value of 400 kPa and high value of 900 kPa while axle load spans range from standard axle value of 80 kN to heavy axle of 120 kN. The shoulder stiffness varies from very weak material which is similar to the subgrade soil with resilient modulus 30 MPa to strong material which is similar to the base course with resilient modulus of 450 MPa. The width of the shoulder was measured from the outside edge of the outer wheel load and ranges from 100 mm which represent extremely narrow shoulder with extreme encroachment from traffic, to 913 mm which is the maximum shoulder width in the Canterbury accelerated test track (CAPTIF) which represent a relatively wide shoulder in rough terrain rural state highway. The thickness of the base course ranges from 300 mm to about 500 mm.

For full factorial experimental design, a five-factor experiment each at two levels requires 2^5 =32 runs. This is a large number of computations, therefore, a half fractional factorial design was utilised and this reduced the number of runs to 16 runs.

Table 1 The factors and levels studied in this simulation

Factors	Units	Levels	
		Low Level	High Level
Shoulder Width	mm	100	913
Shoulder Stiffness	MPa	30	450
Axle Load	kN	80	120
Tyre Pressure	kPa	400	900
Pavement Thickness	mm	300	500

The pavement responses examined in this analysis are the maximum deflection between the dual, maximum surface deflection under the outer tyre and the compressive stain at the top of the subgrade at a 300 mm distance from the centre of the tyres as shown in Figure 9.

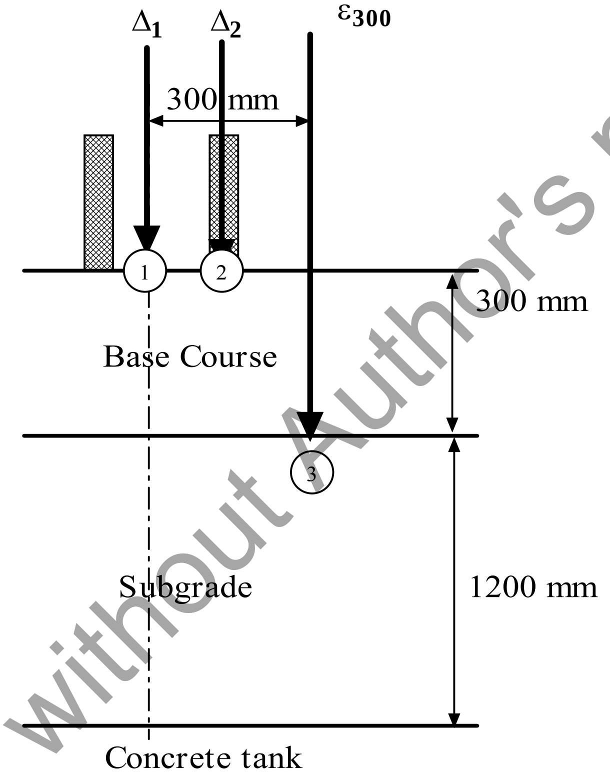

Figure 9 Locations of Calculated Deflections and Strain

Results and Analysis of the Experimental Factorial Design

Table 2 shows the results of the 16 runs of the experimental design for three pavement responses, maximum deflection between dual (Δ_1), maximum deflection under the outer wheel (Δ_2) and the compressive strain on the top of the subgrade at a 300 mm distance from the centre of the dual (ε_{300}). In table 2, the code 1 is used to indicate the high level of the factor while -1 to indicate the low level of this factor. The actual values of each factor are shown in Table 1.

Table 2: Experimental design results

Run	A	B	C	D	E	Δ_1	Δ_2	ε_{300}
1	-1	-1	-1	-1	1	795.088	962.828	921.388
2	1	-1	-1	-1	-1	795.088	916.38	1168.92
3	-1	1	-1	-1	-1	802.257	912.031	1247.88
4	1	1	-1	-1	1	388.941	379.481	390.992
5	-1	-1	1	-1	-1	1230.49	1608.02	1962.18
6	1	-1	1	-1	1	697.346	962.996	1047.64
7	-1	1	1	-1	1	759.859	934.563	1272.59
8	1	1	1	-1	-1	1017.01	876.511	1026.03
9	-1	-1	-1	1	-1	868.495	1220.64	1336.6
10	1	-1	-1	1	1	868.495	1220.64	725.162
11	-1	1	-1	1	1	537.191	697.794	879.764
12	1	1	-1	1	-1	719.928	655.158	656.58
13	-1	-1	1	1	1	856.329	1317.3	1399.15
14	1	-1	1	1	-1	1213.9	1510.86	1752.68
15	-1	1	1	1	-1	1213.9	1510.86	1876.91
16	1	1	1	1	1	596.409	596.535	591.418

A = shoulder width (mm)
B = shoulder stiffness (MPa)
C = Axle load (kN)
D = Tyre pressure (kPa)
E = Pavement thickness (mm) (the same as shoulder thickness)
Δ_1= Maximum deflection under the centre of the dual (μm)
Δ_2= maximum deflection under the outer tyre (μm)
ε_{300}= compressive strain on the top of the subgrade at a 300 mm from the centre of the dual (με).

The Design Expert software was used to carry out the analysis of the fractional factorial design (Design Expert). Figure 10 shows the normal probability plot of effects for the maximum deflection between dual for the 16 runs. Effects which lie on the straight line are the insignificant effects, and those who deviate the most from the straight line are the most significant effects (Douglas, 2001). Figure 10 shows that axle load is the most important factor affecting the maximum deflection between dual tyres. Shoulder stiffness and pavement thickness are the most significant pavement factors affecting the deflection response.. Equation 3 correlates the maximum defelction between dual and the significant factors. The correlation coefficeint (R^2) of this relation is 85.8 which is reasonably good fit. Figure 11 shows a sensitivity analysis of the factors affecting maximum deflection between dual. The percentage of change of each factor was depicted against the percentage change in the maximum deflection between dual tyres. Axle load is the most significant factor followed by pavement thickness then shoulder stiffness.

$$\Delta_{Dual}(\mu m) = -509.66 - 0.384 * \text{Shoulder Stiffness} + 20.27 * \text{Axle Load} + 2.178 * \text{Thickness} - 0.0365 * \text{Axle Load} * \text{Thickness} \quad \left(R^2 = 85.8\right) \qquad \text{Equation 3}$$

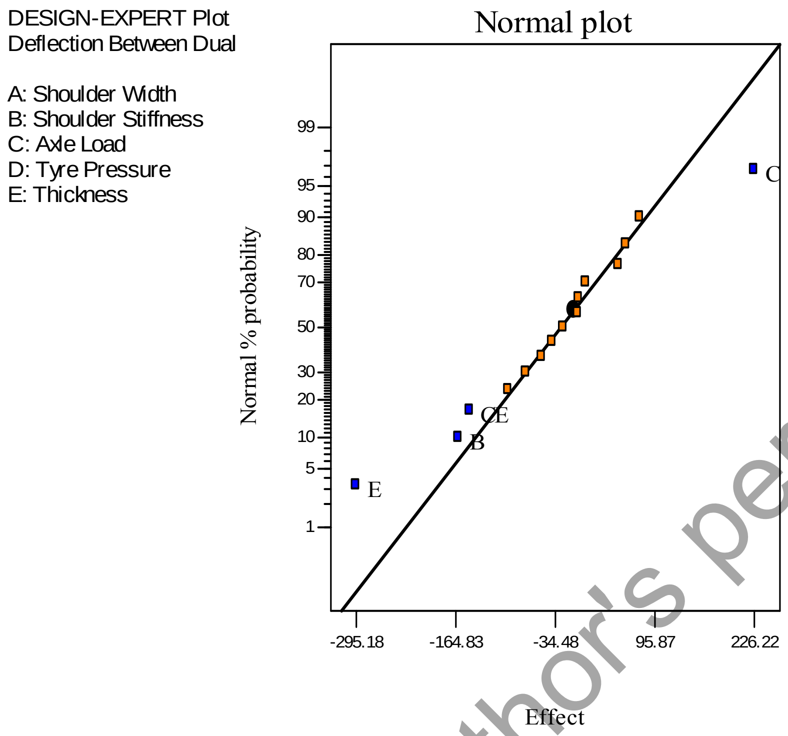

Figure 10 Significant factors affecting the maximum deflection between dual

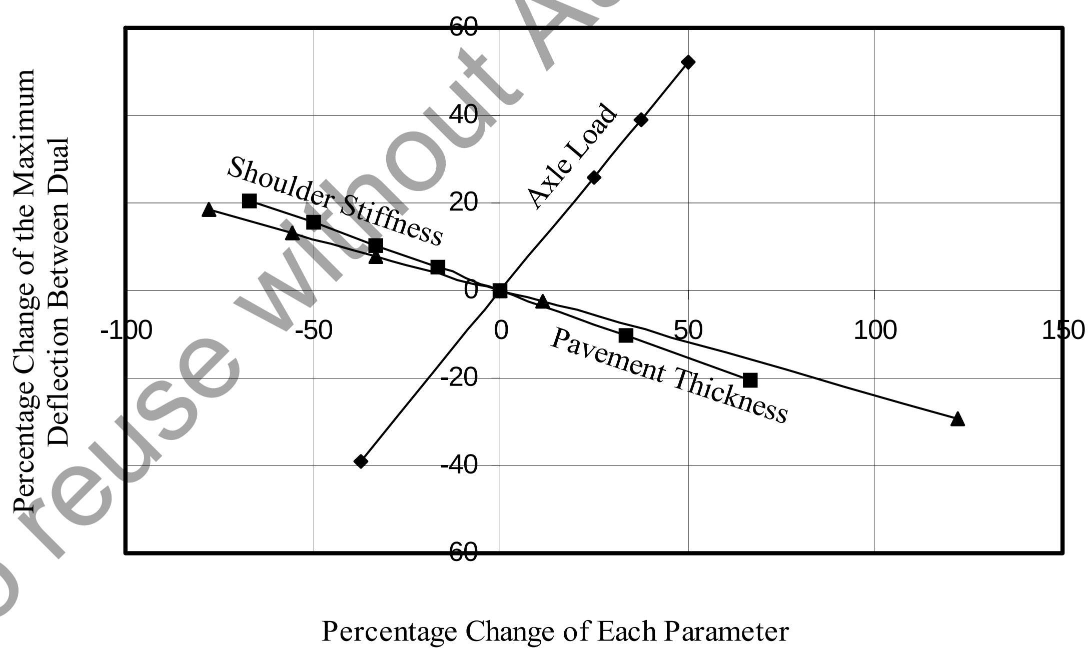

Figure 11 Sensitivity analysis of the significant factors affecting deflection between dual

Figure 12 shows the order of importance of the factors affecting the maximum deflection under the outer wheel load. Again axle load is the most significant factor followed by shoulder stiffness and shoulder width. Equation 4 is a regression equation that correlates the maximum surface deflection under the outer wheel load with the siginificant factors. Figure 13 shows a sensitivity analysis of the factors affecting the maximum surface deflection under the outer tyre.

$$\Delta_{Outer\ Tyre} = 1201.8 - 0.3145 * Shoulder\ \ Width - 0.9395 * Shoulder\ \ Stiffness + 7.3522 * AxleLoad - 1.3365 * Thickness \qquad (R^2 = 80.6) \qquad \text{Equation 4}$$

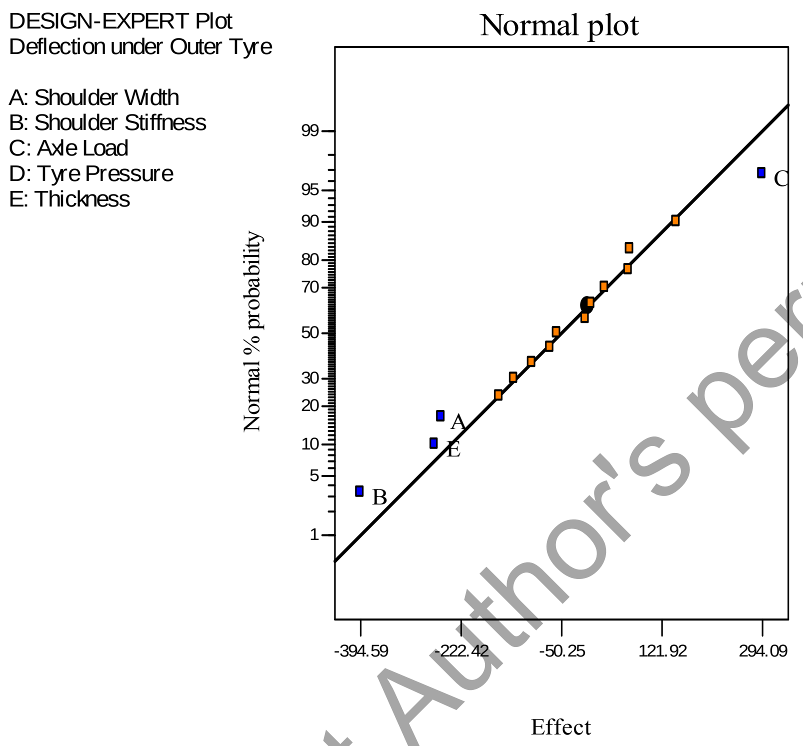

Figure 12 Significant factors affecting the maximum deflection under the outer tyre

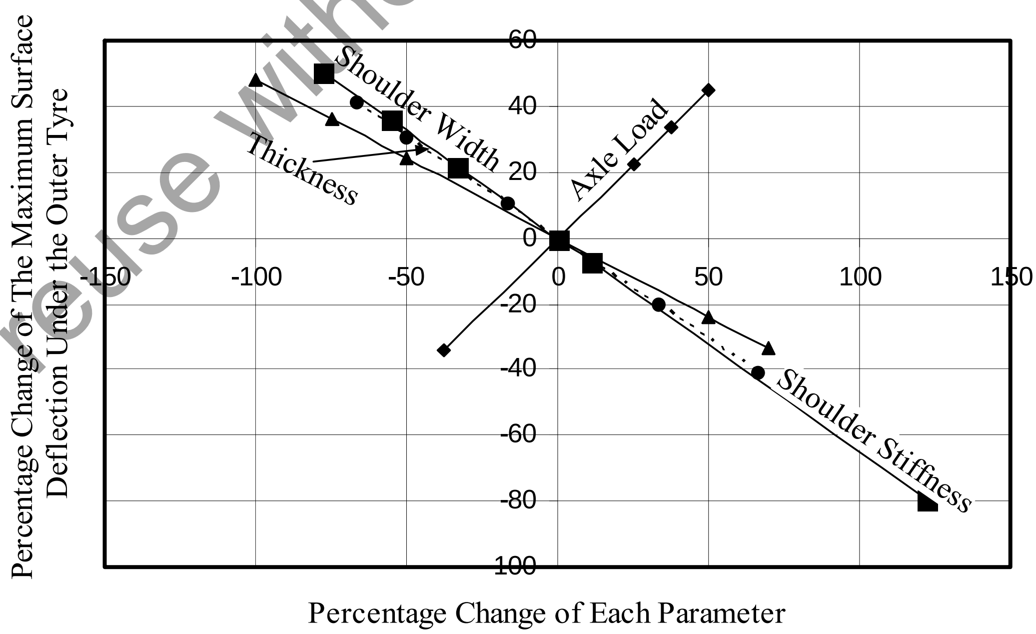

Figure 13 Sensitivity analysis of the significant factors affecting the maximum surface deflection under the outer tyre

In studying the factors affecting the compressive strain on the top of the subgrade in the vicinity of the pavement shoulder (300 mm from the centre of the dual tyres), Figure 14 shows that the most significant factor is the axle load followed by pavement thickness, shoulder width and then shoulder stiffness. Equation 5 represents the linear model correlating the compressive strain at the top of the subgrade and the significant factors. The coefficient of determination (R^2) value is 96.5 which is reasonably high and indicates a good fit. The sensitivity analysis presented in Figure 15 confirms the order of importance of the significant factors affecting the compressive strain on the top of the subgrade.

$$\begin{aligned}\varepsilon_{300}(\mu\varepsilon) &= 1260.18 - 0.2474 * \text{Shoulder Width} - 0.08015 * \text{Shoulder Stiffness} \\ &+ 11.254 * \text{Axle Load} - 2.3748 * \text{Thickness} \\ &- 1.2353 * 10^{-3} * \text{ShoulderWidth} * \text{ShoulderStiffness} \qquad (R^2 = 96.5)\end{aligned}$$

Equation 5

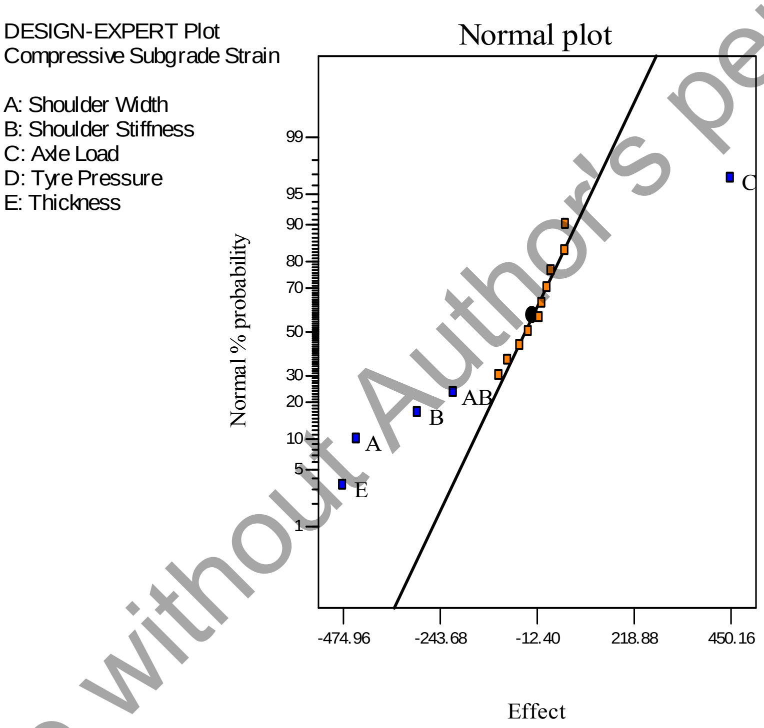

Figure 14 Significant factors affecting the compressive strain on the top of the subgrade

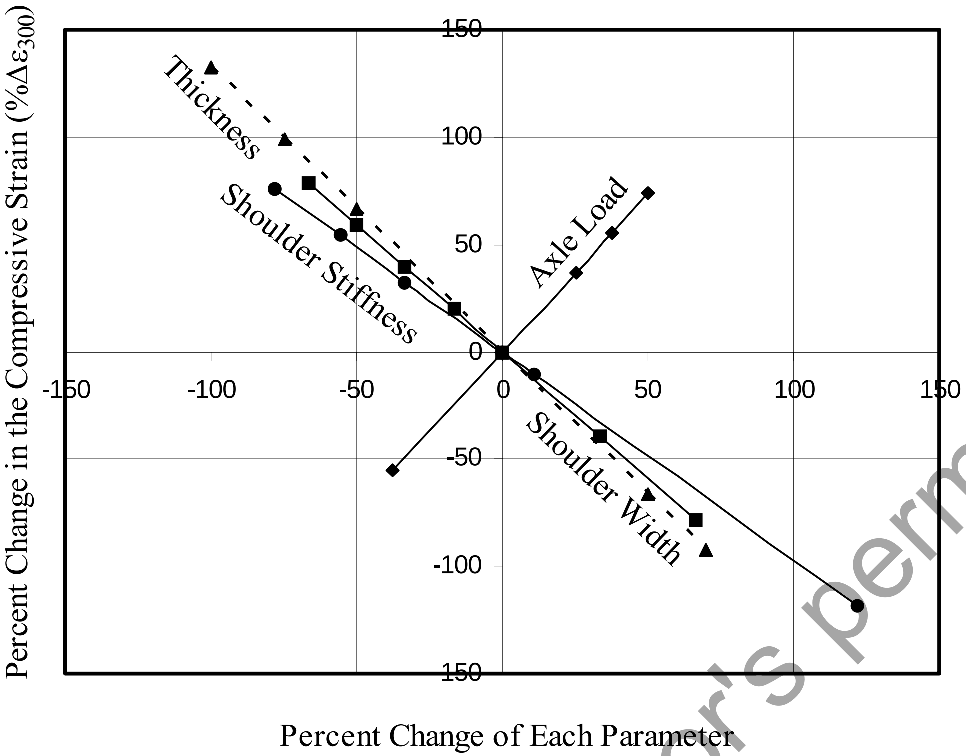

Figure 15 Sensitivity analysis of the significant factors affecting the compressive strain at the top of the subgrade (ε_{300})

Figures 16 to 18 show the pavement responses for three shoulder geometry and material conditions. The weak short shoulder has a 100 mm width, 300 mm thickness and 30 MPa stiffness. The medium shoulder has a 913 mm width, 300 mm thickness and 450 MPa stiffness. The relatively strong shoulder has a 913 mm width, 500 mm thickness, and 450 MPa stiffness. Figure 16 shows that for the same axle load and tyre pressure, the deflection under the outer wheel load for the weak shoulder is more than double that of the relatively strong shoulder and about 1.5 times the that of the medium shoulder. This clearly underscores the importance of the shoulder rigidity represented by its width, thickness, and resilient modulus on the pavement response.

Figures 17, 18 and 19 show that a weak short shoulder doesn't provide a good distribution of the load around the pavement edge and this causes the deflections, vertical compressive strains and compressive stresses to peak around the outer wheel on the top of the subgrade. This high concentration of deflections, stresses, and strains will lead to the edge failure. However, a relatively strong shoulder provides a good spread of the load therefore reducing deflections, stresses and strains on the top of the subgrade.

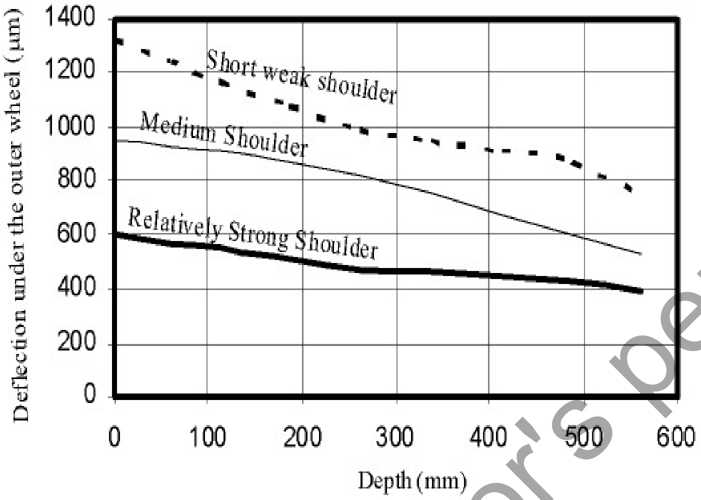

Figure 16 Comparison between the outer deflections for different shoulder conditions

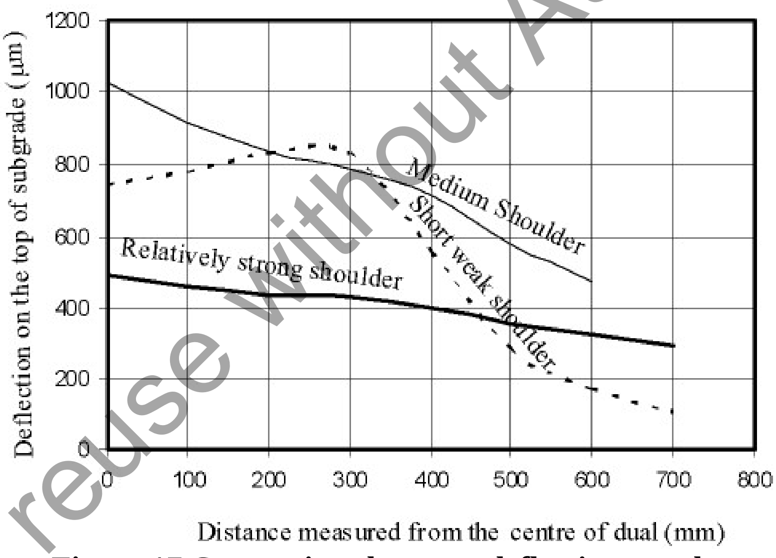

Figure 17 Comparison between deflections on the top of the subgrade for different shoulder conditions

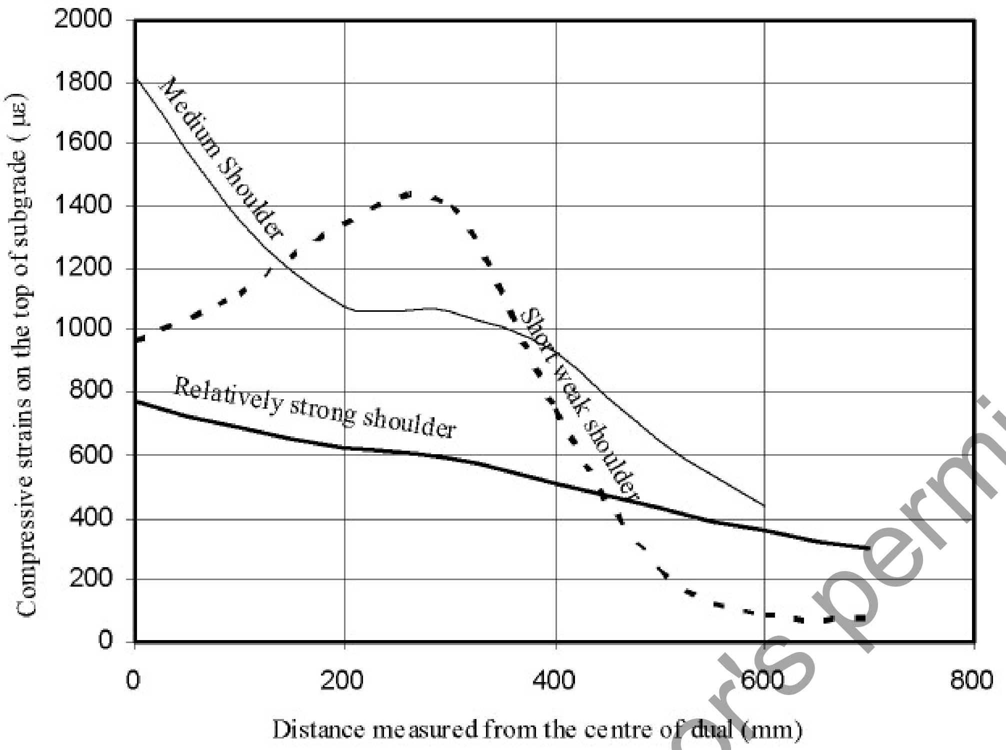

Figure 18 Comparison between the outer compressive strains on the top of the subgrade for different shoulder conditions

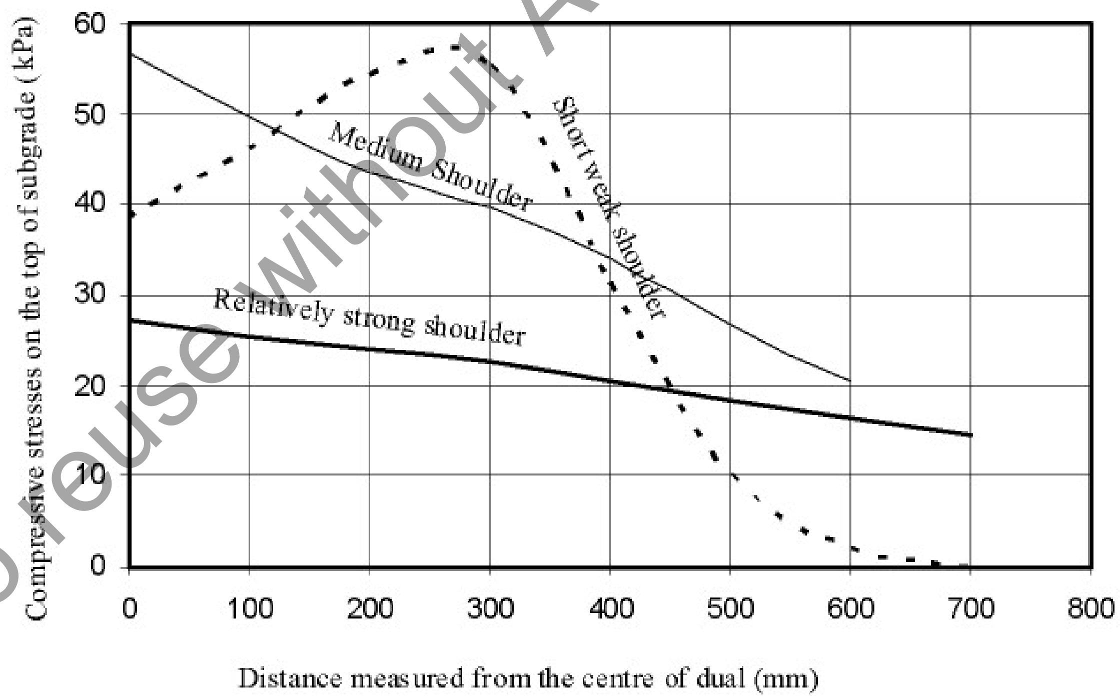

Figure 19 Comparison between the outer compressive stresses on the top of the subgrade for different shoulder conditions

Conclusions

This project is part of a research programme to develop low costs methods to strengthen pavement edges and shoulders to minimise the occurrence of edge break on narrow roads. The analysis that has been performed has highlighted the sensitivity of pavement failure to the lateral support offered by the shoulder

From the factorial design and finite element analysis, it is obvious that tyre pressure is insignificant when analyzing the pavement deflection and the compressive strain on the top of the subgrade. Axle load is the most significant factor affecting the edge damage of the pavement. Shoulder rigidity which is a function of the width, thickness and resilient modulus of the shoulder material has been shown to be a significant factor in the deflection and strain experienced by the pavement. Using a stiff shoulder will help reduce the concentration of stresses, strains on the top of the subgrade and will likely reduce the edge damage of the pavement.

The relationships given in this paper can be used by pavement designers to determine the shoulder rigidity requirements that will be required to ensure that the strain and deflection levels that occur under a pavement with a wide shoulder will also be obtained on pavements that need to be constructed or maintained in areas where topography limits the available total pavement width.

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Authors Autobiography

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Dr. Saleh has been working within the roading industry for the past 16 years. Mofreh has been a lecturer and senior lecturer in the Department of Civil Engineering, University of Canterbury, since his arrival in New Zealand in January 2001. During 2000, Mofreh developed several multimillion US dollars projects for the major maintenance highway division during his tenure with the California Department of Transportation (Caltrans). Prior to this Mofreh was directly involved in several research projects at Arizona State University, USA. Mofreh has published papers on his research in several prestigious referred journals. Dr. Saleh is a member of the following professional societies; American Society for Testing and Materials (ASTM), Association of Asphalt Paving Technologist (AAPT), American Society for Civil Engineers (ASCE) and REAAA. Dr. Saleh is a member of the editorial board of the international journal of pavement engineering.

John Patrick

John Patrick is the Pavements Research Manager at Opus International Consultants Central Laboratories Lower Hutt New Zealand. John has over 35 years' experience in roading investigations and research. He has been associated with a wide range of research into pavement materials including hot mix asphalt, granular basecourse, aggregates, and chipsealing and bitumen properties. He has also performed research into pavement performance and methods of measurement including roughness and skid resistance. John has been responsible for technical input into revisions to Transit New Zealand specifications and developing performance- based specifications for chipseals and hot mix asphalt. Practical experience has been gained during three years' employment with a roading contractor. He has co-authored the textbook Chipsealing in New Zealand..