Behaviour of tyre reinforced unsealed pavement

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Keywords: unsealed road, pavement, reinforcement, recycled tyre, base, experimental test, finite element modelling

ABSTRACT

Recently, tyre-reinforced unsealed pavements had been constructed in a number of sites throughout Australia. The use of partially cut-up waste tyres within the base layer was expected to produce (i) less lateral movement of base aggregate; (ii) increase in modulus through confinement; (iii) improved vertical stress distribution on the subgrade due to increased base modulus or slab action and (iv) reduced shearing in the top of the subgrade. This paper presents the results of preliminary study to confirm these expectations through experimental testing and finite element analyses.

In the experimental testing, a box test was used to investigate the performance of a model unsealed pavement, reinforced with a tyre. Surface and subsurface measurements indicate that the tyre and base aggregate worked together and acted as a flexible foundation. Finite element analysis confirms that tyre reinforcements help reduce the subgrade vertical pressure which provides a lucrative alternate tyre reinforced pavements that can be constructed over soft subgrades.

1 INTRODUCTION

In Australia, a very limited quantity of waste tyres finds usage in transport/civil engineering related applications. Out of all the waste tyres generated every year, 49% end up in landfills, whilst only 3% are used in civil engineering related applications (Matthews 2005). One method of recycling that is currently showing potential for greater use of waste tyres is tyre-reinforced pavements. Tyre reinforced pavements use waste tyres that have one sidewall removed (Figure 1). These tyres (normally truck tyres) are filled with compacted free draining aggregate, with a nominal diameter of 75 – 100 mm. The tyres provide confinement of the aggregate, allowing the aggregate to develop adequate stiffness. The tyre units are placed in a honeycomb pattern on a layer of geofabric, which is placed on the ground after it has been cleared of organic matters (CRC Construction Innovation, 2006). Tyre reinforced pavements could possibly negate the need to have a thick layer of base course material and large embankments when constructing pavements in areas of poor subgrade strength.

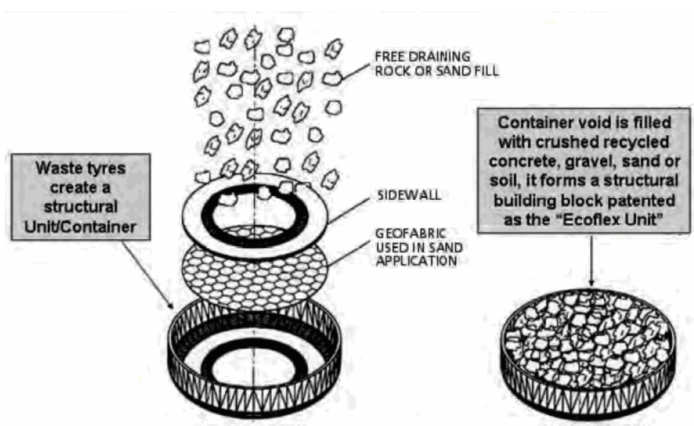

Figure 1: Schematic of tyre reinforced pavement (CRC Construction Innovation, 2006).

2 EXPERIMENTAL METHOD

A box test was set up to investigate the performance of a scaled-down model of unsealed pavement reinforced with a tyre. Figure 2 shows the experimental test rig that was used for a series of experiments. This set up consisted of a tyre unit, made of a 550mm diameter car tyre filled with a Class 3 aggregate and placed on a compacted subgrade. A loading platen of 191 mm in diameter was utilised. The subgrade was prepared by compacting a loam in a steel box (which had removable sides) in six layers, with the first layer being 100mm deep and each of the other five layers 20mm deep. The 20mm layers were placed in alternating colours (each alternate layer was coloured black using a dye). This allowed the settlement behaviour of the soil layers to be observed after testing. The California Bearing Ratio (CBR) of the subgrade was determined to be approximately 5% using a dynamic cone penetrometer test.

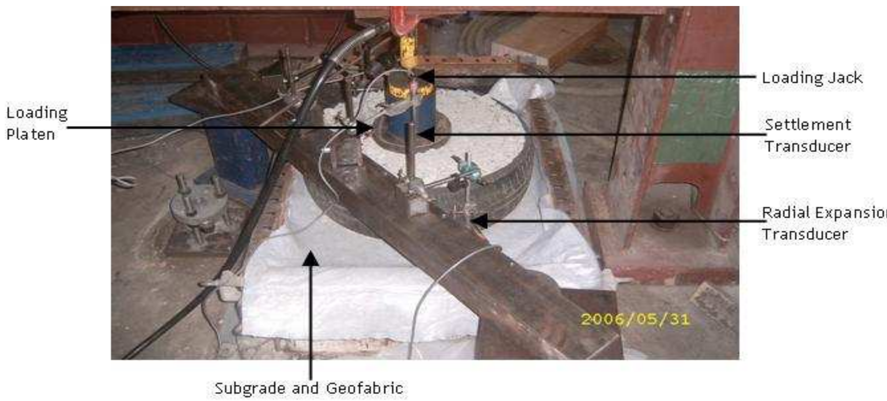

Figure 2: Experimental setup of box test

The test involved pushing the loading platen with a jack until a maximum pressure of 750 kPa was reached. Displacement transducers were placed on the platen to measure settlement of the infill material at the centre of the tyre and on the tread of the tyre to measure its radial expansion. After loading, one wall of the box was removed and the soil was carefully excavated in order to establish the pattern of the subgrade settlement. The results of the experiment showed that negligible settlement occurred in the subgrade and the average surface settlement of the infill aggregate in the tyre was 2.75 mm. The average radial expansion of the tyre was 0.2 mm.

3 NUMERICAL MODELLING

In order to develop a greater understanding of the behaviour of tyre-reinforced pavements, a finite element model was developed and calibrated against the experimental results. A Finite Element Analysis (FEA) allowed for further and more extensive testing to be done without the time and costs associated with laboratory testing. In order to create this model the various components of the experiment (subgrade, tyre, infill aggregate) needed to be represented in the FEA. For simplicity, in this preliminary study only elastic material properties were used. Since it was believed that the use of geofabric had negligible effect on the results of the experiment, it was not considered in the numerical model.

3.1 3-D Model

A 3-D model simulating the experimental test was set up as shown in Figure 3 using SOLIDWORKS, which consisted of a base block (dimensions 1100 x 590 x 220 mm) to represent the soil, and a cylinder that was used to represent the tyre. The geometry used to create the tyre was obtained by measuring the average dimensions of the tyre (550mm outer diameter with a width of 150mm). The sidewall had a thickness of 7mm in the middle, with the edge containing the steel bead to be 11mm, with an inside radius of 165mm. The tread thickness of the tyre was 11mm. The aggregate within the tyre was modelled similar to the soil block using elastic material properties. The dimension of the aggregate was made so that it would fit inside the tyre. The tyre, containing the aggregate block, was placed on top of the soil block and both components were left unrestrained to reflect the boundary conditions in the laboratory.

3.2 Finite Element Modelling

Traditionally, if the complex behaviour of the tyre was required to be modelled with greater accuracy, several authors such as Tonuk et al. (2001) and Holscher et al. (2004) recommended the use of a Mooney-Rivlin two parameter hyperelastic model, to accurately model the non-linear stress-strain characteristics of the rubber. Therefore, to simplify the model, an alternative tyre model suggested by Tonuk et al. (2001) was used with a linear elastic approximation in ANSYS Workbench™. Tonuk et al. suggested that a tyre could be idealised using two major components, the tread, and the sidewall with each component having different elastic material properties. In the same paper, these authors suggested an elastic modulus of 14 MPa for the tread, and 5.5 MPa for the sidewall to represent the stiffness of a passenger car tyre. It was also suggested that the tyre should be nearly incompressible, and this could be achieved using a Poison's ratio of 0.45 for both components. The material properties for the components of the model before calibration are summarised in Table 1.

Table 1: Material properties of FE model components prior to calibration

Component	Elastic Modulus	Poisson's Ratio
Tyre Tread	14 MPa	0.45
Tyre Sidewall	5.5 MPa	0.45
Infill Material	150 MPa	0.35
Soil Block	50 MPa	0.30

The model had had one of five contacts, bonded, rough, frictional, no separation and frictionless assigned to the surfaces in contact with each other depending on how the surfaces were expected to behave. This is shown in Table 2.

Table 2: Contact definition matrix

	Tyre Tread	Tyre Sidewall	Infill Material	Soil Block
Tyre Tread	---	Bonded	Frictional	No Contact
Tyre Sidewall	Bonded	---	Frictional	Rough
Infill Material	Frictional	Frictional	---	Frictional
Soil Block	No Contact	Rough	Frictional	---

The final assembly was imported into ANSYS Workbench and a structural FEA was performed. The FE and post-processing models are shown in Figure 3.

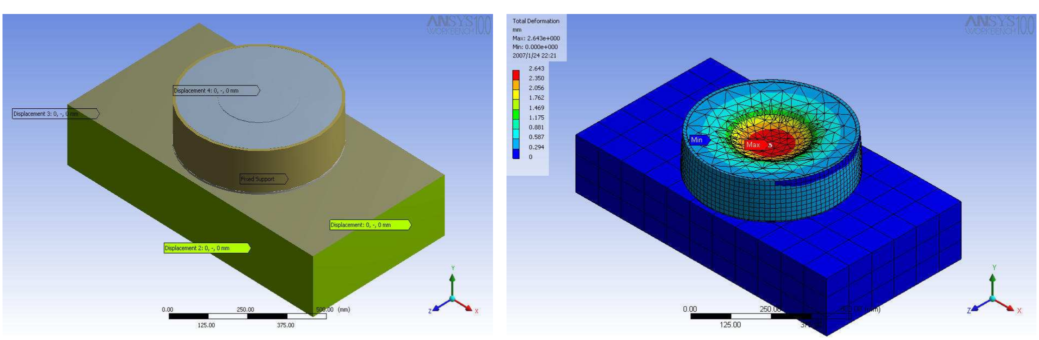

Figure 3: FE Model (left) and post processed model (right)

The model was calibrated so that the results reflected the results from the experiment. This was done by adjusting the material properties of the numerical model such that the results as obtained from the experiment (the surface deflection of the infill aggregate was 2.64 mm and the expansion of the tyre was 0.2 mm) could be closely matched by the numerical model. This was achieved when the modulus of the road base material was set at 50 MPa and that of the subgrade assigned to 45 MPa. The authors believe the aggregate in the tyre was weaker than expected (100-150 MPa expected strength), because it was a poor quality material and it was not adequately compacted (compaction done by hand using a rubber mallet because of difficulties associated with compaction inside the tyre).

3.3 Numerical Model Performance Assessment

In order to assess the effect of the inclusion of tyres, numerical analyses were carried out with and without tyre inclusion. The results from both FEA are shown in Table 3.

Table 3: Results from FEA with and without tyre reinforcement

Along Tyre Centreline	Without Tyre	With Tyre
Surface deflection	2.68 mm	2.64 mm
Subgrade deflection	1.20 mm	1.15 mm
Subgrade pressure	466 kPa	82 kPa

It is seen that the most significant effect of tyre inclusion is the 82% reduction in the pressure applied to the subgrade. Thus, it can be concluded that the tyre works effectively as a footing and has a significant positive impact on the pavement response. However, further analysis will be required to assess how this result may be influenced by changes in material properties or loading conditions.

4 SENSITIVITY ANALYSIS

4.1 Aggregate Stiffness

Sensitivity analyses were performed to assess the impact changing the aggregate properties would have on the results. While all other material properties were kept constant, a new tyre infill aggregate was used for the FEA. The Class 1 Rhyolite aggregate (modified compaction) was chosen and represented by a three parameter non-linear model as shown in Equation 1 (Nataatmadja 1994):

$$(M_r\ \sigma_1)/\theta = A + B\ q_r + C\ q_r \qquad (1)$$

M_r Resilient modulus (kPa)
q_r Repeated deviator stress (kPa)
θ Sum of the principal stresses (kPa)
σ_1 Vertical stress (kPa)
For rhyolite (modified compaction): A = 26,800; B = 633; C = –0.68

The use of a non-linear model to represent the resilient modulus of infill aggregate was an improvement on the linear elastic model described earlier. The effect of the new material on the results is shown in Table 4.

Table 4: Sensitivity analysis results – Effect of aggregate variation

Along Tyre Centreline	Class 3 Aggregate	Rhyolite
Surface deflection	2.64 mm	1.09 mm
Subgrade deflection	1.15 mm	0.835 mm
Subgrade pressure	82 kPa	55 kPa

The effect of using a well-compacted and stiff aggregate to fill the tyres is apparent as it results in less surface and subgrade deformation and causes a significant decrease in subgrade pressure.

4.2 Tyre Size and Stiffness Variation

The next step in the sensitivity analysis was to assess the impact of changing the size and stiffness of the tyre on the subgrade's deflections and pressures (along the tyre's centreline). To achieve this, a truck tyre (983mm diameter) was chosen for the model. Truck tyres have much thicker walls compared to a car tyre and its elastic modulus is higher. According to Nakashima et al. (1993), the elastic modulus of this particular type of tyre when fully inflated is about 35 MPa. They also found that varying the elastic modulus of the tread and sidewall did not make a large difference to tyre deflections. Hence, in the present study, both the sidewall and tread moduli were kept at 35 MPa. In addition, it was decided to analyse a model with a tyre modulus of 17.5 MPa as well to see how sensitive the results were to tyre modulus variation. Rhyolite (represented by Three-Parameter model) was used as the tyre infill aggregate for both conditions. Table 5 shows the results of the analyses.

Table 5: Sensitivity analysis results – Effect of tyre size and stiffness variation

Conditions	Surface Deflection	Subgrade Deflection	Subgrade Pressure
No tyre	1.287 mm	0.875 mm	80 kPa
Car tyre	1.09 mm	0.835 mm	55 kPa
17.5 MPa truck tyre	1.44 mm	1.01 mm	11.9 kPa
35 MPa truck tyre	1.46 mm	1.03 mm	12 kPa

Table 5 indicates that the tyre modulus has very little impact on the results. The results from the 35 MPa tyre are almost identical to those obtained using a modulus of 17.5 MPa. It is also seen that the subgrade pressures under these truck tyres are much smaller than those produced by the other two cases. This appears to support the conclusion that the tyres behave as similar to shallow foundations in distributing the load to the subgrade.

The deflections obtained from truck tyres are greater than the other two cases. It was suggested that the presence of tyres would produce additional deflection at the surface, as the tyres are more compressible than the aggregate. In this case, due to their dimensions, the two truck tyres also produced greater subgrade deflection values than the car tyre. It would appear that the use of larger tyres causes a decrease in subgrade vertical pressure but an increase in surface and subgrade deflections.

4.3 Multiple Tyre Analyses

These additional analyses were aimed to study the behaviour of multiple tyres when loaded at different locations. The analyses were also used to assess the effects of tyre modulus variation. The setup of the model is shown in Figure 4, along with the loading positions.

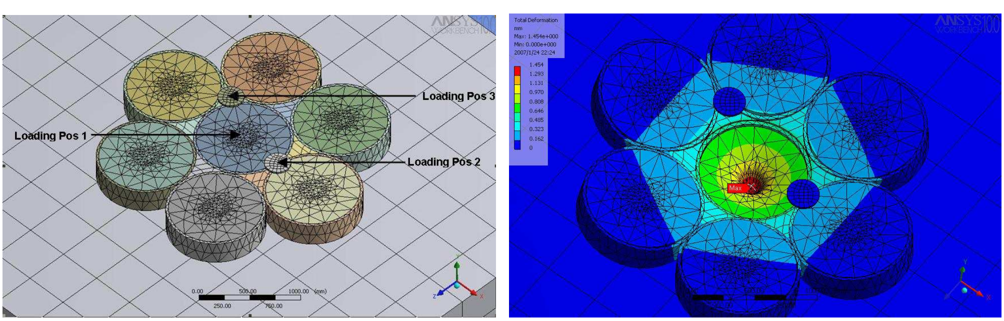

Figure 4: Setup of multiple tyre finite element models (pre and post analysis shown)

Results shown in Table 6 indicate that the surface deflections increase as the number of tyres directly under the loading area increases. In contrast with the results from single tyre, it is seen that stiffer tyres have lower surface deflections. The subgrade pressure appears to follow a similar pattern to the surface deflection. The subgrade deflections however show small decrease even though the surface deflection and subgrade pressure is increasing.

The other key measure of the performance of the multiple tyre models is the pressure that is applied to the subgrade. Table 6 shows that the subgrade pressures are very low, when compared to the initial applied pressure of 750 kPa. In addition, the pressures that result from the multiple tyre models are far less than those obtained from the single tyre models.

From these results, it can be concluded the tyres behave as flexible foundations and hence a larger tyre will ensure a better load distribution. The multiple tyre analyses appear to support this proposition, as the interlocking of the aggregate and friction between the tyres would result in the applied load being distributed over a larger area than what would be possible with a single truck tyre.

Table 6: Sensitivity analysis results – Multiple tyre analysis

Configurations	Max Surface Deflection	Max Subgrade Deflection	Max Subgrade Pressure
17.5 MPa Multi Tyre - Loading Position1	1.454 mm	0.920 mm	3.64 kPa
17.5 MPa Multi Tyre - Loading Position 2	1.56 mm	0.950 mm	4.08 kPa
17.5 MPa Multi Tyre - Loading Position 3	2.263 mm	0.920 mm	4.75 kPa
35 MPa Multi Tyre - Loading Position 1	1.397 mm	0.907 mm	1.68 kPa
35 MPa Multi Tyre - Loading Position 2	1.47 mm	0.860 mm	1.78 kPa
35 MPa Multi Tyre - Loading Position 3	1.826 mm	0.81 mm	1.86 kPa

5 CONCLUSIONS

In summary, the results of the FEA reveal that tyre reinforcement helps reduce the subgrade vertical pressure, thus allows pavements to be constructed over soft subgrades. It would appear that the larger the tyre, the lower the pressure that will be transferred to the subgrade.

The presence of the tyres generally causes greater surface deflections. This effect is more pronounced when the loading is applied directly over the tyres. In addition, it has been shown that the stiffer tyre will produce less deflections and subgrade pressures.

The results reported herein have been obtained from a preliminary study. Further numerical work will be conducted involving non-linear composite materials. Materials will be represented as anisotropic where appropriate. Both static and dynamic analyses will be carried out to simulate the effects of vehicles moving over the pavement. In addition, additional tests will be conducted in the laboratory to validate the results from the finite element modelling.

ACKNOWLEDGEMENTS

The authors acknowledge Professor D. Thambiratnam and Mr. M. Darestani for their advice in finite element modelling. Thanks are also extended to Mr. M. Barry and the QUT high performance computer team for the assistance in running the finite element models. The second author thanks Prof. I. Towhata of the University of Tokyo for providing the facilities to work on this paper.

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