Measurement and Prediction of Forward Movement and Rutting in Pavements Under Repetitive Wheel Loads

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A three-dimensional mechano-lattice stress-strain analysis has been used to predict rutting and permanent forward displacement behavior of pavements subjected to 14 630 one-directional passes of a 226-kg (500-lb) loaded pneumatic tire under very well-controlled conditions. The two pavement sections tested consisted of crushed prospect dolerite with 10 percent clay, each placed in an indoor test track with different compactive efforts and moisture contents and a thin coating of bituminous materials. The favorable comparisons between these predictions and the measured values seem to support the mechano-lattice analysis as a pavement analysis tool.

I have been encouraged, particularly by C. L. Monismith, to compare predictions made with his mechano-lattice stress-strain analysis on pavement behavior with well-controlled practical tests. The accuracy of the mechano-lattice analysis as applied to the more complex problems of hysteretic friction has been amply verified (1-3). In this paper, the findings of the very precise repeated-rolling tests on the Sydney Test Track carried out by Sparks (4) are compared with mechano-lattice predictions. Such one-directional rolling tests of high precision are expensive and rare.

The theory of linearized elasticity has been used successfully to develop relatively rational flexible pavement design techniques. The Shell method is a good example. However, it has become apparent that a stress-strain analysis that more closely simulates pavement material behavior would allow more rigorous and reliable failure predictions. It is for this reason that I have introduced a version of the mechano-lattice analysis that simulates repeated rolling of elastoplastic materials (5-7).

SYDNEY TEST TRACK EXPERIMENTS

The Sydney Test Track was designed by Taylor in 1966 (8) with subsequent development from Sparks and Lee (9) to investigate the phenomenological aspects of flexible pavement behavior. It consists of a 25-cm (10-in) diameter loaded pneumatic tire repeatedly rolling in one direction along a test bed 4.87 m (24 ft) long by 0.91 m (3 ft) wide. Pavement structures of any thickness can be simulated by adjusting the level of the rigid base supports in each of the four 1.22-m (4-ft) long bays. The drawn rolling tire can be caused to execute lateral departures from the centerline according to any desired standard deviation.

The test sections were 15.24-cm (6-in) thick pavements compacted on a rigid foundation. The behavior of the pavements in bays 3 and 4 was simulated by the mechano-lattice analysis. These test sections consisted of crushed dolerite with 10 percent clay compacted with vibrating hammers to the dry densities, California bearing ratio (CBR) values, and moisture contents indicated in the table below (note, 1 kg/m^3 = 0.062 lb/ft^3):

			Optimum		
Bay	CBR (%)	Dry Density (kg/m^3)	Moisture Content (%)	Dry Density (kg/m^3)	(%)
3	80	6.9	6.5-6	7.0	7
4	35	6.1	5.5-5	6.7	8.5

The 227-kg (500-lb) loaded tire with a contact pressure of 690 kPa (100 psi) and a contact area of 32 cm^2 (5 in^2) was caused to perform the normal distribution of lateral departures as repeated rolling progressed, as shown in Figure 1 by the smooth curve.

The surfaces of the test pavements were thinly coated with bituminous material, and targets were fixed to various places on the surface to enable a vernier-driven microscope to measure the lateral, longitudinal, and vertical movements of the surface at various stages throughout the test.

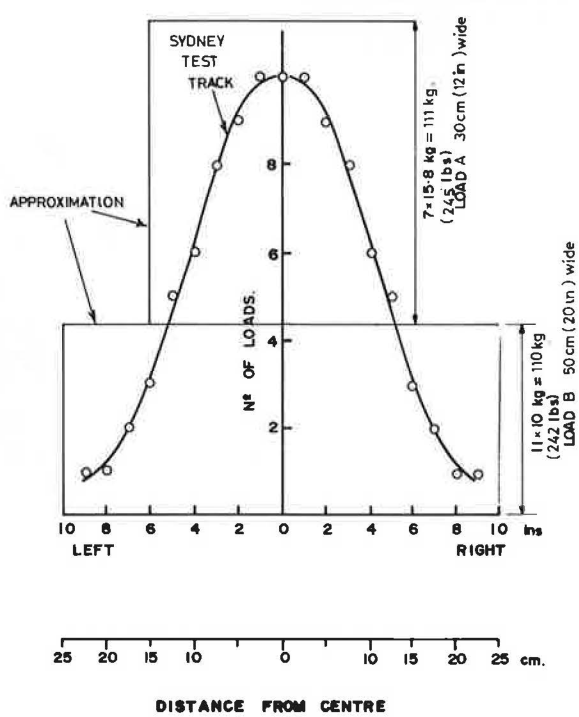
After the pavements were placed, two repeated-load bearing tests, each for five load repetitions, were carried out on each of the bays. These were used in this paper to determine the material properties. The results are shown in Figures 2 and 3. The rutting and permanent horizontal movement behavior was recorded throughout 14 630 one-directional passes of the loaded tire. All the information regarding these experiments was obtained from Sparks (4). Some of the same information is available elsewhere (9).

MECHANO-LATTICE ANALYSIS PREDICTION

The mechano-lattice stress-strain analysis, which

Figure 1. Lateral departures of wheel passes from centerline and approximation for mathematical prediction.

POSITION INS. FROM CENTRE	0	1L 1R	2L 2R	3L 3R	4L 4R	5L 5R	6L 6R	7L 7R	8L 8R	9L 9R
Nº OF LOADS	10	10	9	8	6	5	3	2	1	1



has been described elsewhere (1,5-7), is a type of mechanized finite-element analysis that was devised to simulate nonlinear and energy-absorbing materials, including elastoplastic materials.

Figure 4 shows how one of the bays in the Sydney Test Track experiment is simulated by an assembly of mechano-lattice units. One of the units is shown in the inset. The lattice unit simulates a cube of the elastoplastic road material. A unit consists of 24 elements, each of which has a larger loading to unloading compliance. This gives the simulated material the property of elastoplasticity, such that when one unit is loaded and unloaded, a residual deformation will result. When the units are connected (as shown in Figure 4) by frictionless joints at their corners, the stress-strain history of each element of each unit is taken into account as it, in simulation, moves toward, under, and away from the

Figure 2. Load deflection results for repeated-load bearing test on compacted but untrafficked material in bay 3.

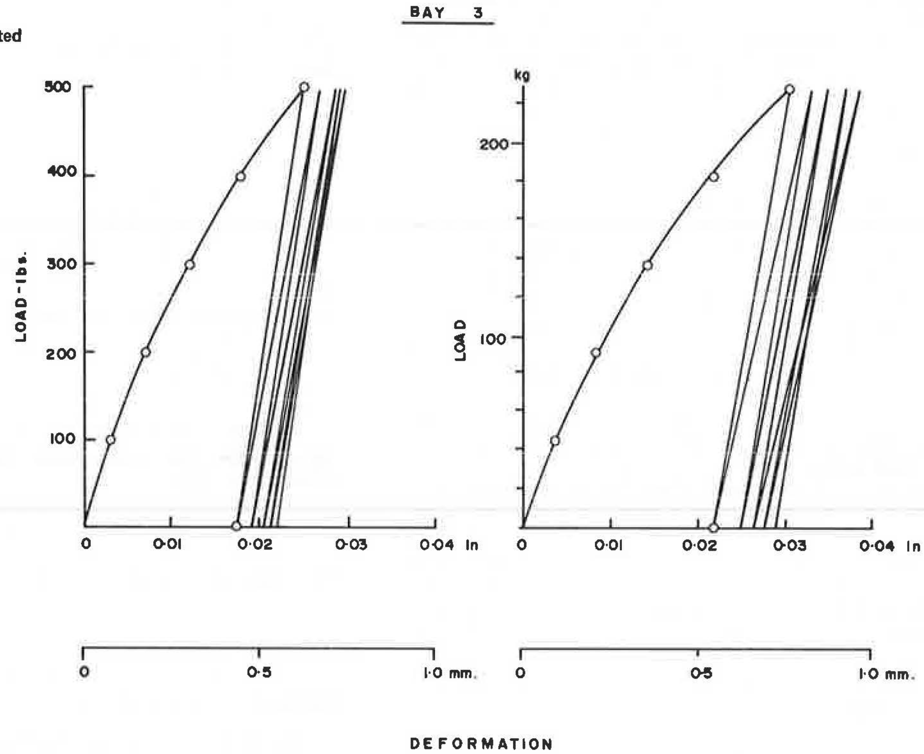


Figure 3. Load deflection results for repeated-load bearing tests on compacted but untrafficked material in bay 4.

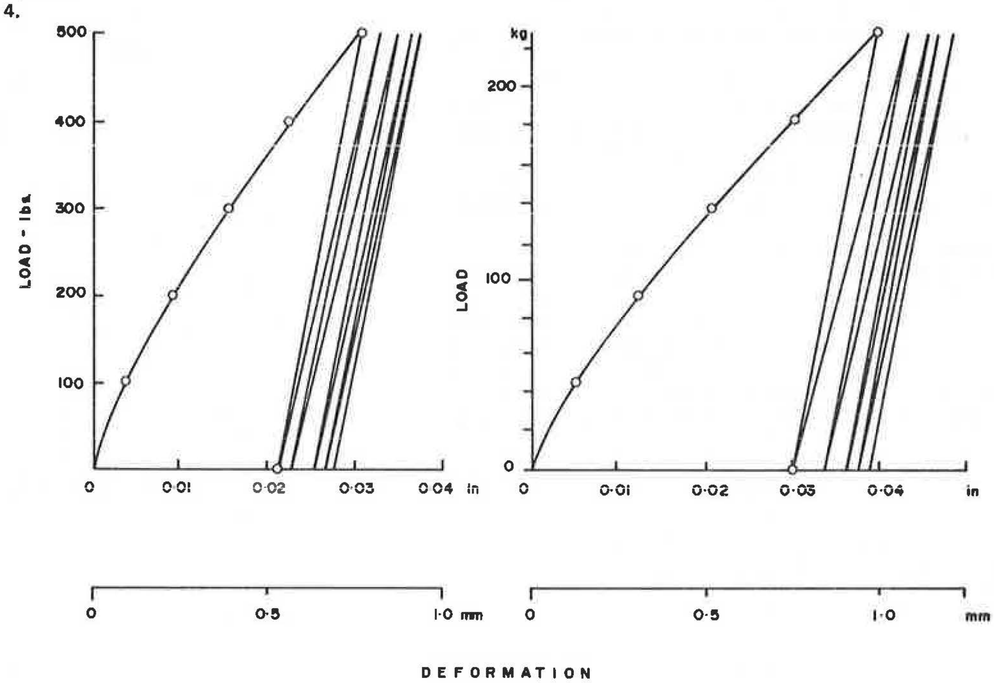
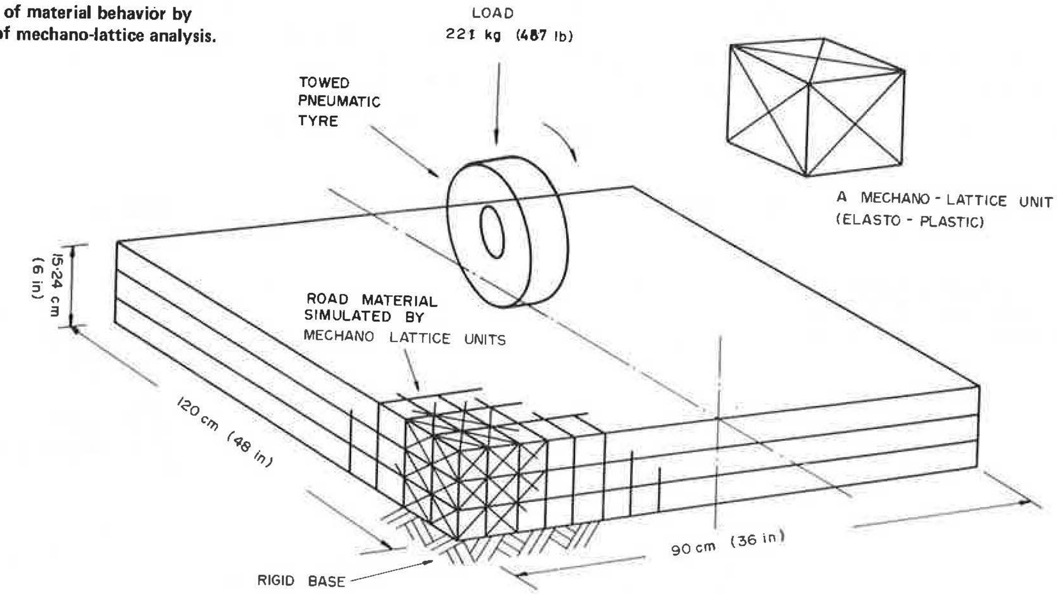


Figure 4. Simulation of material behavior by elastoplastic version of mechano-lattice analysis.



wheel load. The requirements of continuity and equilibrium are maintained in this rigorous method. The load in each diagonal and rectalinear element is determined by its length, stiffness, previous loading history, and whether its load is increasing or decreasing. The joints are moved in the direction of their unbalanced forces until equilibrium is achieved.

ROLLING RESISTANCE

To make the simulation realistic, it is necessary to take into account the fact that the test wheel is being drawn and not torque driven. Therefore, the rolling resistance will lead to a horizontal force that acts on the surface of the pavement in the direction of the wheel motion. It was assumed that such a force, which amounts to 10 percent of the normal load, should account for the rolling resistance emanating from both the road material and from the pneumatic tire. In order to show its differing effects on permanent forward movement, one case for a torque-driven wheel was also computed.

SIMULATING WHEEL LOADS

As mentioned earlier, the 5-cm (2-in) wide rolling wheel tracks sequentially about the centerline with a normal distribution. One hundred wheel passes gives one normally distributed coverage of 227-kg loads. This is possible to simulate on the computer, but it would be quite expensive. The compromise used was to simulate one-hundredth of the effect of one, 100 pass coverage by one pass of a symmetric 30-cm (12-in) wide, 111-kg (245-lb) load, called load A, plus one pass of a symmetric 50-cm (20-in) wide, 110-kg (242-lb) load, called load B, as shown in Figure 1. The contact pressures exerted by these two loads are 69 and 41 kPa (10 and 6 psi), respectively. The stress-strain behavior of the road material is elastoplastic, as shown in the inset of Figure 5, so this reduction in contact pressure by a factor of 10 will not alter the permanent deformational behavior. However, this would not be the case with an elastic perfectly plastic material or if the curved relations of the bearing tests (Figures 2 and 3) were used instead of the straight-lined assumption that appears in the inset of Figure 5 (as explained later). The above simplification would reduce resistance to rutting by a small amount due to the greater lateral shearing caused by the concentrated load of the narrow pneumatic tire compared with the wide contact region of the computer-simulated traveling load. The relatively high Poisson's ratio (0.40) would reduce this effect; however, in addition, the simulated load, being 3 percent lower than the test load, should cause, for example, a rutting underestimation of 3 percent.

REPEATED-BEARING TESTS

It is more usual to obtain the properties of a road material for life-prediction purposes by mechano-lattice analysis from repeated-load triaxial tests. However, the only information available is that of the bearing tests, the results of which are shown in Figures 2 and 3. These give surface deflection versus load for five load repetitions.

It is unfortunate that the repeated-bearing tests were not continued to a greater number of repetitions but, as can be seen in Figure 5, the sets of five points plot very nearly to parallel straight lines on the log-log plot of permanent strain versus load repetitions. There is no indication of the curvature that often, but not always, occurs as convex upward in repeated-load triaxial tests. It was therefore considered reasonable to extrapolate the straight lines to the 15 000 load repetitions necessary, as shown in Figure 5. For permanent deformation prediction purposes, the pairs of test results were averaged on the plot for 300, 800, 1800, 3800, 7300, and 14 630 wheel passes. It is necessary to the operation of the mechano-lattice analysis to transform this information to that that would emanate from a triaxial test on the same material. From the knowledge that the 227-kg loaded tire was applied to the 15.24-cm (6-in) thick pavement surface, the Young's modulus of the material in bay 3 (by using linear-elastic theory) was 70 MPa (9941 psi) and that in bay 4 was 60 MPa (8450 psi), as was the average material permanent strain equal to 0.21 of the surface deflection in centimeters (0.54 of the surface deflection in inches). The average vertical stress was calculated to be 280 kPa (40 psi). It was convenient to set the calculating unloading modulus at 105 MPa (15 000 psi). Thus, one load-unload of a simulated triaxial test would

leave a residual strain of 0.002 (see inset in Figure 5).

Thus to obtain a prediction of the rutting after n passes, one uses the following expression:

$(\epsilon_n/0.0020)$ x rut depth from one calculation pass of mechano-lattice analysis

where ϵ_n is the cumulative axial strain from the hypothetical repeated-load triaxial test as transformed from the bearing tests depicted in Figure 5. A similar expression was used for predicting forward movement.

DISCUSSION OF RESULTS

Rutting

Figures 6 and 7 show a comparison of rutting predic-

Figure 5. Extrapolation of bearing tests up to 15 000 load repetitions and load-unload hysteresis loop from a simulated triaxial test of material in bay 4.

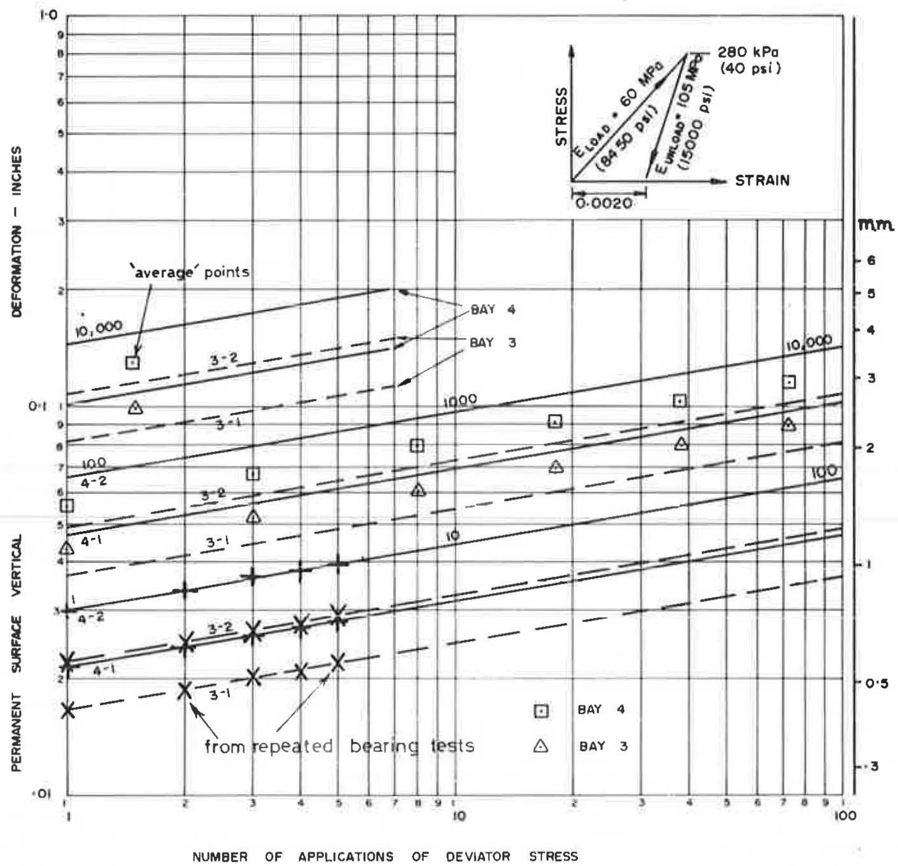
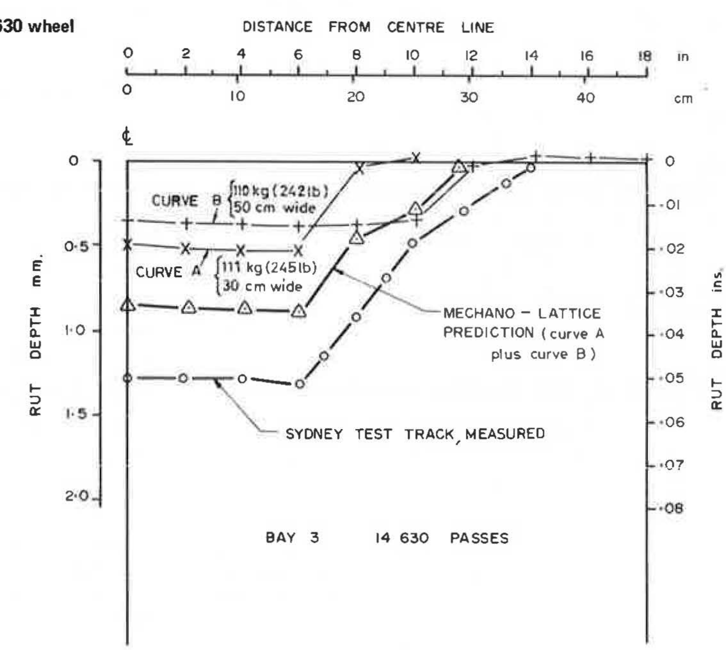


Figure 6. Measured and predicted rutting in bay 3 after 14 630 wheel passes.



tion with measurement after 14 630 passes of a 227-kg load in the central sections of bays 3 and 4, respectively. The individual effects of the 30-cm-wide, 111-kg load pass (curve A, Figure 6) and the 50-cm-wide, 110-kg load pass (curve B, Figure 6) are added to give the predicted rut shape shown. The prediction for bay 4 is very close. The comparison of rut prediction and measurement from 100 passes to 14 630 passes is shown in Figure 8. The trends are close--a fact that shows the close relation between the bearing tests and the rather lengthy repeated-rolling tests. It should be realized that the extrapolated bearing tests account for the natural decrease in plasticity with repeated loading. If the extrapolations of Figure 5 are correct, the plastic strain reduces from about $2x10^{-2}$ mm/mm per cycle down to $7x10^{-6}$ per cycle at 14 000 repetitions.

Forward Movement

The forward-movement prediction is not as successful as that of rutting, as shown in Figures 9 and 10. In bay 4, the material away from the centerline is moving in the opposite direction to the travel. The 10 percent imposed rolling resistance in the prediction is entirely responsible for the central forward movement. This can be observed in Figure 10 by comparing curve A_1 with A_2. Curve A_2 is the predicted horizontal movement of the surface at 14 630 passes without net rolling resistance (i.e., the wheel is torque driven) for the 30-cm-wide, 111-kg load.

Figure 7. Measured and predicted rutting in bay 4 after 14 630 wheel passes.

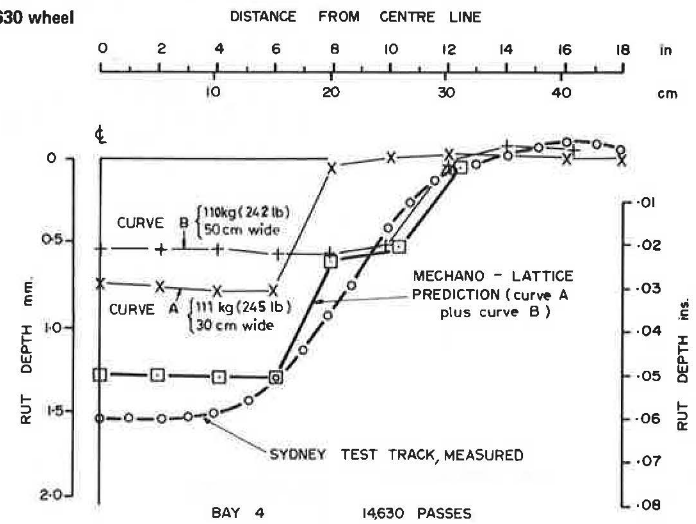


Figure 8. Measured and predicted rut invert depth over the range of 100 to 14 630 wheel passes for bays 3 and 4.

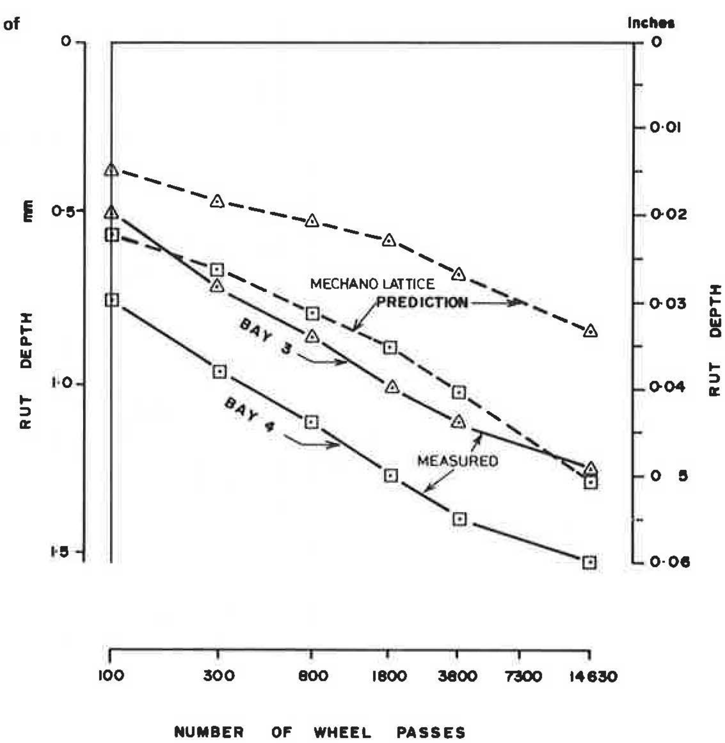


Figure 9. Measured and predicted forward surface movement of material in bay 3.

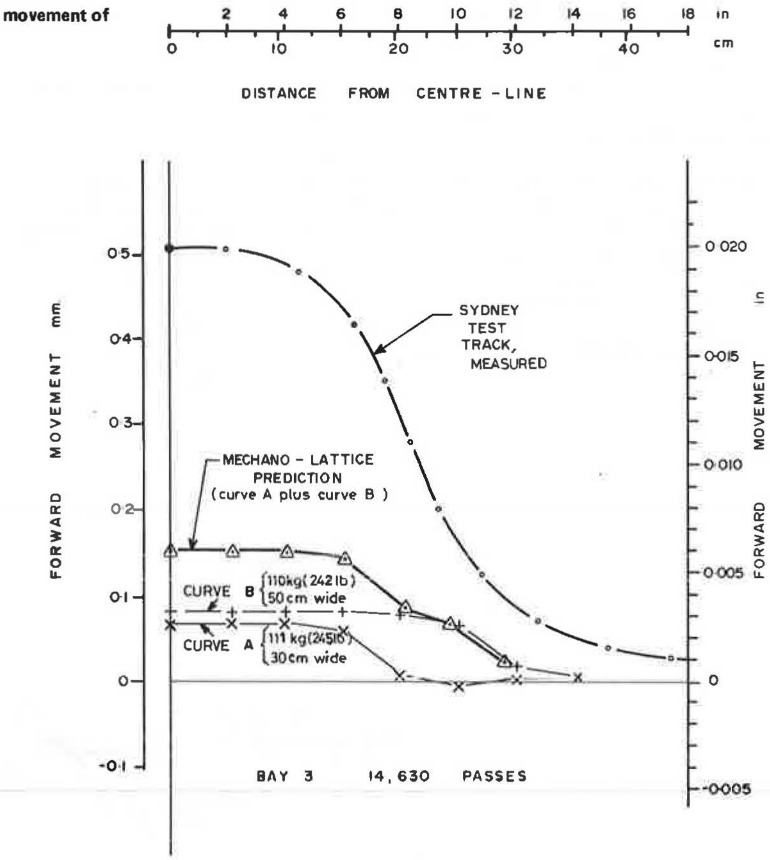


Figure 10. Measured and predicted forward surface movement of material in bay 4.

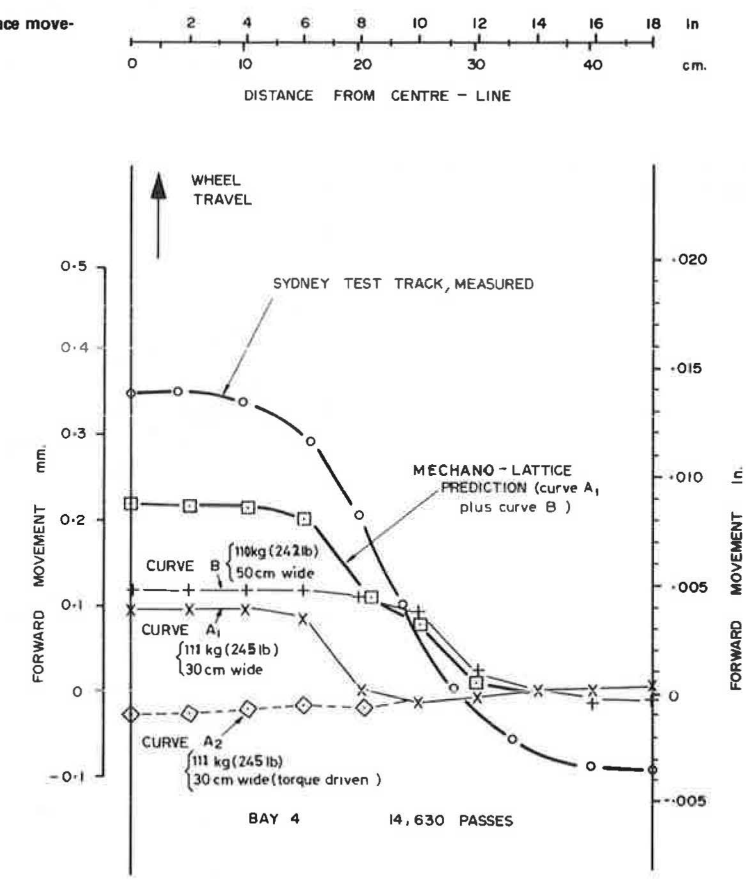


Figure 11. Measured and predicted forward surface movement over range of 100 to 14 630 wheel passes for bays 3 and 4.

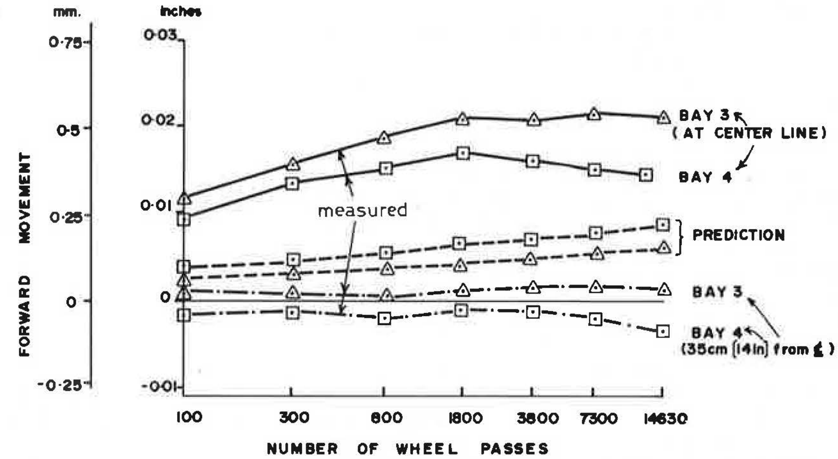
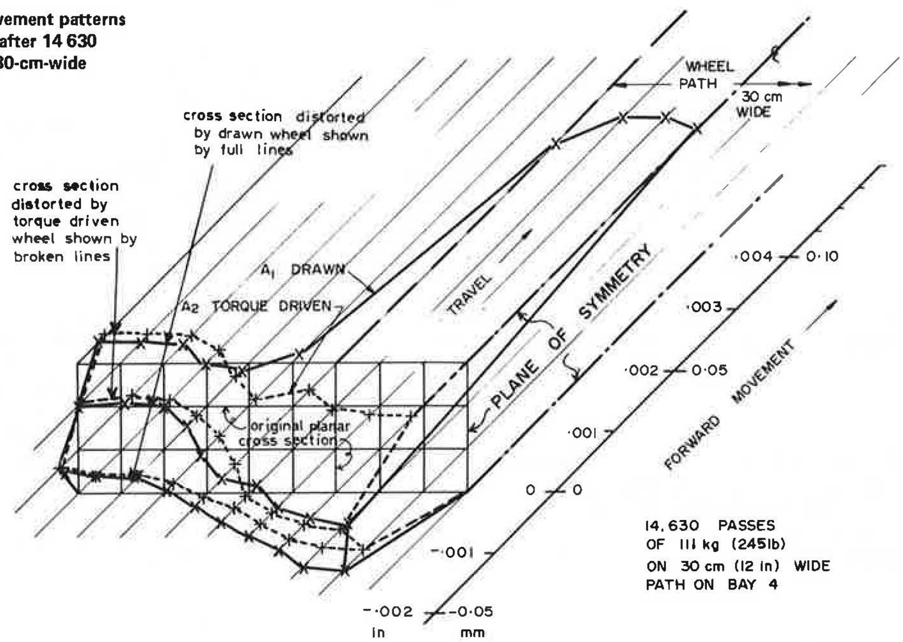


Figure 12. Predicted horizontal movement patterns for drawn and torque-driven wheels after 14 630 passes of 113-kg loaded wheel on a 30-cm-wide wheel path.



The horizontal movement of the surface trend for 100 to 14 630 passes is shown in Figure 11. Although the trends of the predictions are reasonably close to the measurement, the magnitude falls short of the measurement. A possible explanation for this can be given with reference to Figure 12. This figure shows the calculated horizontal movements of half an initially vertical cross-sectional plane after 14 630 passes of the symmetric 30-cm-wide, 111-kg load on bay 4. The full lines, curve A_1, indicate the movements associated with the tire that has a 10 percent rolling resistance (drawn). The broken lines, curve A_2, indicate the movements associated with a tire that has no net rolling resistance (torque driven). It is immediately apparent that the bulk of the material movement is opposed to the direction of wheel travel in both cases. It is only the surface material in contact with the wheel that is pushed forward in the case of the drawn wheel. The thinness of this predicted movement is limited by the coarseness of the mechano-lattice grid. If six layers of units were used instead of three in the prediction, it is obvious that a thinner layer would extend twice as far in the direction of wheel travel and thereby come closer to the actual performance.

Drawn and Torque Driven

Curves A_1 and A_2 show the difference between the effects of drawn (from the axle) and torque-driven wheels. Although deeper material will flow in the opposite direction to wheel travel, in both cases the drawn wheel will cause the material on the surface to move in the direction of travel. This was predicted and demonstrated on a miniature test in 1971 (5) in plane strain situations. This phenomenon also supports the practice of pavement engineers to have the forward wheel, on the first passes of a roller, torque driven. The trailing drawn wheel then moves the surface material forward while the torque-driven front wheel moves it backward, thereby preventing cracks from forming between the rollers and also preventing bow waves.

CONCLUSION

The prediction of rutting on a single layered pavement resting on a rigid foundation has been surprisingly accurate in view of the fact that only five load repetitions were used in the four material tests. However, if the straight-line extrapolation should instead have curved downward to some extent,

the calculated prediction would have fallen farther short of the measured values. These findings not only seem to support the validity of the elastoplastic material-simulating version of the mechano-lattice analysis, but also support the practical and theoretical work reported in 1971 (5). The dependence of horizontal flow on material properties indicates that nonhomogeniety in pavement materials can lead to lateral cracks and build up humps due to variable horizontal flow rate per wheel pass. It is believed that closer agreement of forward-movement prediction with practice would have been achieved had a finer mechano-lattice grid been used. I have analyzed many multilayered pavements by using the above method at a cost of $40/calculation pass ($1 Australian = $1.14 U.S.). This makes life predictions for as little as $160 possible.

The Sydney Test Track is being prepared for precise verification of mechano-lattice analysis of multilayered flexible pavements. However, some verification has already been achieved on real roads in less well-controlled conditions than the Sydney Test Track (7,10,11).

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