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Evaluation of the Effect of Tire Loads with Different Contact Stress Patterns on Asphalt Rutting

W.J.vdM. Steyn

University of Pretoria, Civil Engineering, Lynnwood road, Hatfield, 0002, South Africa
PH (+27) 12 420 2171, FAX (+27) 12 362 5218, EMAIL wynand.steyn@up.ac.za

ABSTRACT: Road pavements are constructed to carry traffic which applies its load- to the pavement through the contact area between the tire and the pavement surface. Previously, the tire-pavement contact area and stresses were idealized, as appropriate instruments for quantification of these contact stresses were not available. The Stress-In-Motion (SIM) technology has made it possible to characterize these contact stresses at low speeds. In a recent Heavy Vehicle Simulator (HVS) test on various layers of Hot Mix Asphalt (HMA), the effects of non-uniform tire-pavement contact stresses were directly measured through application of two distinct types of tire-pavement contact stresses onto the HMA pavement. The rutting response of the pavement specifically showed the direct effects of these non-uniform contact stresses. In this paper the background to the tire-pavement contact stresses is discussed briefly, followed by details regarding the specific rut responses of five HVS tests where the pavement performance reflected the effects of the non-uniform tire loading conditions. Analysis of this data is presented together with discussions on the potential effects of this information on roads carrying real traffic and their rut development.

INTRODUCTION

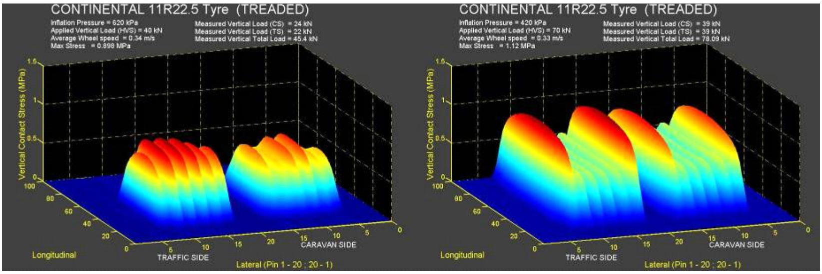
Road pavements are constructed to carry traffic which applies its load- to the pavement through the contact area between the tire and the pavement surface. Investigations around the effects of different types of loading on the response of pavements have been conducted for many years. Previously, the tire-pavement contact area and stresses were idealized, as appropriate instruments for quantification of these contact stresses were not available. The Stress-In-Motion (SIM) technology has made it possible for the three dimensional characterization of these contact stresses at low speeds (De Beer et al, 2006; 2008). However, the actual effects of different non-uniform tire-pavement contact stress patterns have not often been observed specifically in a controlled comparative study of pavement performance, although many analyses have shown that the non-uniform contact stresses should affect the response of the pavement structure, especially, near the surface.

In a recent Heavy Vehicle Simulator (HVS) test on various layers of Hot Mix Asphalt (HMA), the effects of non-uniform tire-pavement contact stresses were directly measured through application of two distinct types of tire-pavement contact stresses onto the asphalt pavement. The focus of this paper is to present and discuss the effects of specific applied tire-pavement contact stresses on a standard HMA to evaluate the extent of the effects during actual trafficking. Theory around HMA rutting is not discussed explicitly, as this is well covered in literature and not the focus of this paper.

BACKGROUND

The contact stresses developed between the tire of a vehicle and the surface of the pavement are complicated and dependent on various factors. These include the vehicle load, vehicle configuration, suspension type, tire material type, tire inflation pressure, tire construction, tread pattern, speed and moving action (i.e. acceleration, free-rolling or braking, cornering or straight). De Beer et al (2006, 2008) developed the Stress-In-Motion (SIM) technology that can be used to measure the tire-pavement contact stresses orthogonally while the tire rolls over the device. Various other devices can also be used to measure these stresses, but mostly only in the vertical direction (Morgan et al, 2008).

The tire-pavement contact stress typically show patterns similar to those shown in Figures 1a and 1b. De Beer et al (2006) used the terminology of m-shaped and n-shaped tire-pavement contact stresses, denoting tires that are typically overinflated (n-shaped – Figure 1a) and overloaded / underinflated (m-shaped – Figure 1b). These stress shapes have been observed under numerous truck tires (De Beer et al, 2008). Although various tests (mostly Accelerated Pavement Testing (APT)) have been conducted with different tire-pavement contact stresses (mainly due to changes in tire loading) (Hugo and Epps, 2004), the specific comparative response of the pavement surfacing to differing contact stresses has not yet been studied in depth.



a – n-shape b – m-shape

FIG.1 Typical n-shape (a) and m-shape (b) vertical maximum tire-pavement contact stresses.

It is well-known that rut development in a pavement is directly linked to and influenced by parameters such as the mix design, the supporting pavement structure, the loading conditions and the environmental conditions. Typical HMA material response relationships indicate a direct relationship between the stresses imposed on the pavement (as an input for the evaluation of rut development (NCHRP 1-37, 2004)) and the observed rut development. In this paper the mix design and environmental conditions are constants and the focus is on the effect that the maximum vertical contact stress has on the development of downward surface rut in the HMA surfacing.

EXPERIMENTATION

The HVS tests were conducted on road P159/1 west of Pretoria. The tests were part of the Gauteng Department of Public Roads, Transport and Works investigation into the rut development of HMA mixes (Steyn and Verhaeghe, 2006). Construction of the standard 40 mm thick HMA mix took place during October 2006. The original supporting pavement structure was constructed more than 20 years ago and consisted of 4 layers. The structural strength of the pavement was relatively high with an average elastic surface deflection (FWD-measured) of between 134 and 149 micron (Steyn and Fisher, 2008). A standard production HMA mix was used as an overlay for the tests. Selected properties of the HMA mix are summarized in Table 1.

Table 1. Selected properties of STD HMA mix.

Property	Value
Binder content [%]	5.0
Air voids in mix (constructed) [%]	6.4
Voids in mineral aggregate [%]	15
Voids filled with binder [%]	72
Indirect tensile strength [kPa]	1 187
Gyratory refusal voids (N=300) [%]	2.4

The HVS is an APT device that has been used extensively nationally and internationally for the controlled evaluation of pavement behavior under real loads (Du Plessis et al, 2006). The HVS is typically used to apply a controlled wheel load to a test section while the behavior of the pavement is monitored using dedicated instruments. The conditions under which the loads are applied are well controlled, and through the use of an environmental chamber the temperature of the pavement can be controlled (Steyn and Denneman, 2008). The test conditions used for the five tests discussed in this paper are summarized in Table 2. All tests were conducted using a dual set of radial 11R22.5 tires and a surface temperature of 60°C.

The main parameters monitored on these HVS sections were the surface rutting and surface profiles. It was measured using a laser profilometer (250 mm intervals across the 8 m test section). The data were summarized in terms of the average downward surface rut measured on the section at specific load application intervals. A number of test slots cut after the HVS tests confirmed that all the rut developed inside the HMA layers. All further analyses focus on the calculated average downward rut developed inside the HMA layer.

DATA ANALYSIS

The data analysis is focused on establishing the effects of the non-uniform vertical tire-pavement contact stresses on the rut profile development inside the HMA layers. In Figure 2 the general rut development against the number of load applications for the five sections are shown. The data focus on the average rut for the two wheel tracks of the channelised sections, and the average rut for the wandering sections. Thedata indicate the expected increasing trend of surface rut development with increasing number of load applications.

The similar response observed under the uni- and bi-directional trafficking (specifically those with similar load levels and both channelized - Sections 446A4 and 447A4) was confirmed by further HVS tests conducted on the same HMA not reported in this paper. It is perceived that this phenomenon is related to the relatively thin nature of the HMA (40 mm) and the relative fresh nature of the HMA when subjected to HVS loading (between 12 and 16 months after construction).

Table 2. Nominal HVS test methodology for five HVS tests discussed in this paper.

Test Number	Loading Conditions (Dual tyres)	Channelised/ wandering	Uni- / bi-directional	Total Repetitions
446A4	N-shape (60 kN, 800 kPa)	Channelised (no lateral wander of the test tires)	Bi	80 300
447A4	N-shape (60 kN, 800 kPa)		Uni	75 337
448A4	M-shape (60 kN, 420 kPa)		Bi	212 171
449A4	N-shape (60 kN, 800 kPa)	Wandering (50 mm x 10 step lateral wandering)	Bi	306 888
450A4	M-shape (60 kN, 420 kPa)		Uni	303 000

In Figure 3 the cross sections of the three channelized test sections towards the end of each of the HVS tests are shown. The- data show the effect of the vertical tire-pavement contact stress pattern on the rut development in the HMA surfacing.

Although the rut development for Sections 446A4 and 448A4 (N- and M-shape loads) shows similar rut rates towards the secondary stage of the test (constant rut increase) the difference in rut profile remained until the end of the specific tests, indicating that the effects of the contact stress patterns still influence the cross-sectional profile of the rut development. This is specifically evident on the edges of the rut cross profiles where the higher edge stresses (448A4) caused higher localized rut.

In Figure 4 the cross section profile of the two wandering test sections are shown. In these cases the tires wandered over the width of the section, distributing the location of the peak vertical contact stresses over the section. The different effects of the two contact stress conditions (n-shape and m-shape) are again visible in the surface rut development.

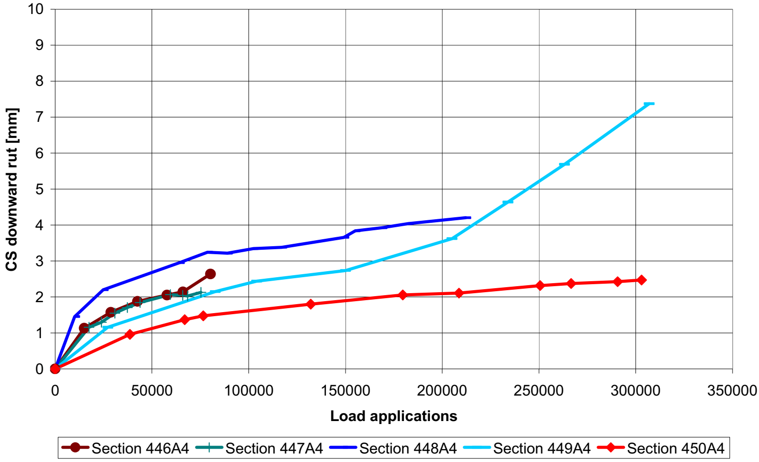


FIG. 2. Average downward rut development against number of load applications for five test sections.

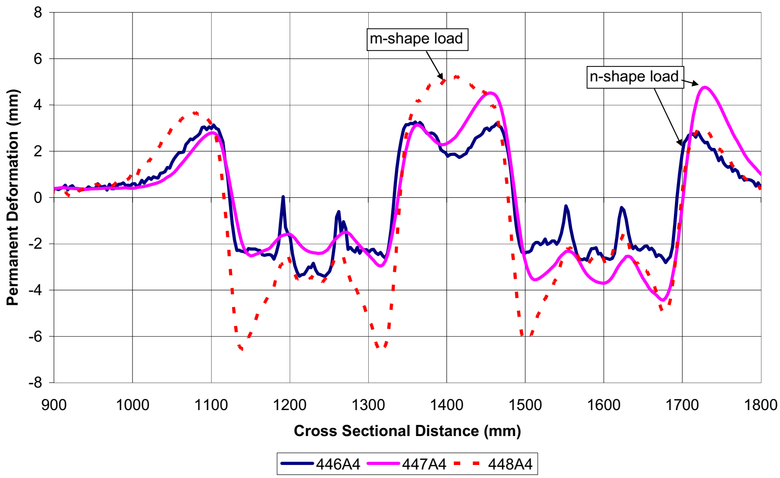


FIG. 3 Measured cross section rut profiles for three channelized test sections.

DISCUSSION

The data analyzed in this paper supported the hypothesis that the maximum vertical tire-pavement contact stresses directly influence the surface rut profile of a HMA surfacing. Figures 3 and 4 indicate that the rut profile under the various contact stress patterns differs. This leads to the observation that a similar effect would be visible on real pavements. With real traffic the tire loads are less channelized and therefore the ultimate effect may be less than that shown in this study. However, field observations performed during these tests has shown that trucks tend to follow a channelized pattern when traveling on straight sections of road, specifically when a level of surface rutting has started to develop. Further, the data indicate that the phenomenon is not only visible for channelized trafficking, but also for wandering traffic, although to a lesser degree.

In Figure 5 the ratio between the average downward rut and the maximum vertical contact stress for the various tests are shown (centre and edge of tire). The data indicate that all the ratios are within a band of between 3.3 and 5.3 mm/MPa. It does not appear as if the direction of trafficking affected these ratios (this is probably related to the relatively thin HMA being tested). The differences in the ratios are attributed to changes in the thickness of the thin asphalt layer over the width of the test section (a coefficient of variation of 9 per cent was measured on the test sections) as well as a possible difference in density of the thin asphalt layer over the width of the test section. Further evaluation of this is required, although it is logical that similar stresses on a weaker layer would cause higher rut development.

The question may be posed as to the distribution of specific contact stress patterns in a real traffic stream, as the contact stresses in the case of the specific tests discussed in this paper were all of a similar shape. Surveys conducted on highways in South Africa have indicated that the majority of steering axle tires in a typical traffic stream in South Africa show n-shaped contact stresses (De Beer, 2008). Previous studies by Steyn and Visser (2002) indicated that the road profile can give rise to different contact stress patterns along the length of the road, while spatial repeatability would tend to concentrate specific contact stress patterns in specific areas – thereby amplifying the effect in those specific areas.

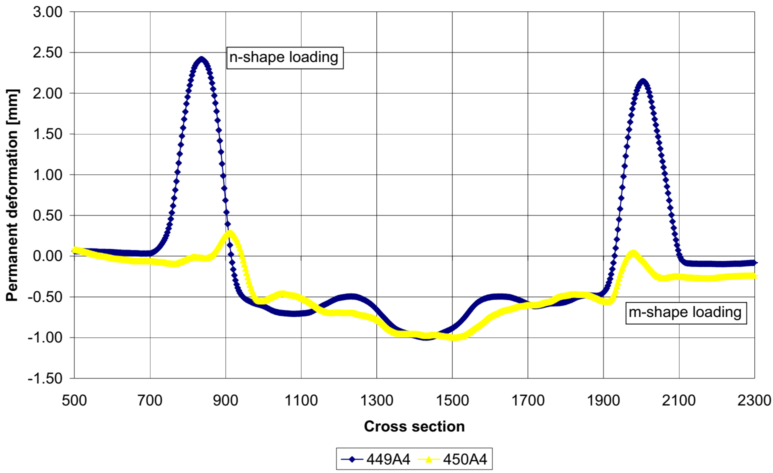


FIG 4. Observed cross section rut profiles for two wandering test sections (n-shaped contact stress (b) (uni-directional), m-shaped contact stress (b) (uni-directional)).

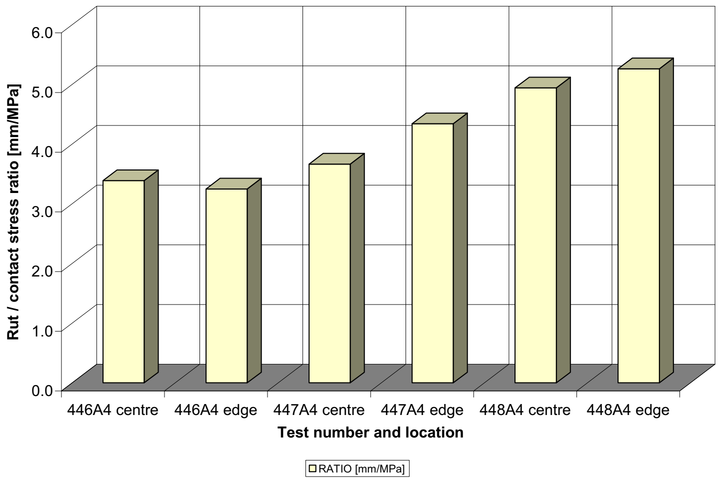


FIG 5. Summary of ratio between surface rut and maximum vertical contact stress.

CONCLUSIONS

Based on the information provided in this paper the following conclusions are drawn:

- The non-uniform vertical tire-pavement contact stresses have a direct and measurable influence on the downward surface rut development in the HMA mix evaluated;
- The ratios between maximum vertical tire-pavement contact stress and average downward surface rut in the HMA ranged between 3.3 and 5.3 mm/MPA, and is probably influenced by contact stress value, asphalt layer thickness and asphalt density;
- The uni- and bi-directional trafficking options provided similar responses for the test conducted on the specific HMA material, and
- The output of this study should be applicable to normal traffic where similar tire-pavement loading conditions were observed and may be used to explain the development of specific rut-related deterioration of thin HMA layers.

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