Effect of wide specialty tires on flexible pavement damage

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1 Introduction

For many pavement analysis applications, the effect of heavy vehicles on pavement response is often modelled using typical tires configurations and dimensions associated with typical and most common heavy vehicles encountered on the road network. Most of the pavement damage models were also developed using these typical loading conditions. However, many specialty heavy vehicles use the pavement network across each Canadian Province. Among these vehicles, agricultural equipment are frequently encountered on the rural network. Liquid manure spreaders are among the typical specialty agricultural vehicles. These vehicles are often equipped with wide specialty tires, specially designed to reduce soil compaction under vehicle loading. Therefore, these vehicles and tires are engineered to circulate on loose soil where no pavement structures are encountered. These tires are wide single tires, most often mounted on multiple axle, and designed to operate at low inflation pressures. They also have a particular tire tread and therefore particular surface contact with the pavement surface.

Through the mechanistic analysis of flexible pavement structures, the damage mechanisms due to heavy vehicle loading are commonly associated with two pavement response. Figure 1 shows a three layer system submitted to dual tires loading. The system is defined by the layer's moduli (E*:complex modulus; Er: resilient modulus), thickness h and poisson ratio μ. As shown in Figure 1, the first response, the elastic tensile strain developing at the bottom of the asphalt concrete layer (ε_x or ε_y), is associated with bottom-up fatigue cracking. The other pavement response, the elastic vertical strain at the top of the subgrade soil (ε_z), is associated with structural rutting of the pavement structure.

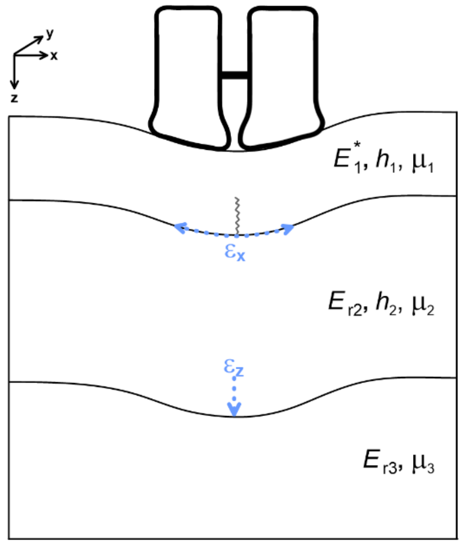

Figure 1. Tensile strain at the bottom of asphalt concrete and vertical strain at the top of the subgrade

A preliminary theoretical analysis performed at the Ministry of Transportation of Quebec [1], which was based on cumulative seasonal damage using linear elastic analysis of multilayer systems, concluded that the main damage mechanism involved when a pavement structure is submitted to wide specialty tires loading such as the ones used on farm vehicles is structural rutting. The bottom-up fatigue phenomenon of asphalt concrete layer would not be the dominating damage mechanism involved in that case. The conclusion obtained by this theoretical analysis was that wide specialty tires may cause slightly more damage to flexible pavements regarding the structural rutting criteria. This paper presents an experimental verification and validation of the preliminary work performed on the effect of wide specialty tires used on agricultural equipment on pavement performance.

2 Materials and methods

In order to perform an experimental study of the effect of wide specialty tires on pavement performance, an indoor test facility was used at Laval University (Figure 2). The facility consists of a laboratory equipped with a 2 m wide, 2 m deep and 6 m long test pit. A typical pavement structure, representative of Quebec's rural road network was built inside the test pit. The pavement structure consist of a silty sand subgrade (1200 mm), granular subbase (450 mm), granular base (200 mm) and asphalt concrete (100 mm) (Figure 3). Figure 4 presents the grain-size distribution of the pavement materials compacted in the test pit. Throughout the construction process, the flexible pavement structure was instrumented to measure important pavement response and condition parameters, such as strains in all pavement layers, stress in unbound layers, moisture condition in unbound layers and the temperature profile. As the main objective of this study is to perform an experimental study of pavement response under agricultural equipment tire loading, the tested pavement structure was heavily instrumented to monitor the response at various critical positions in the layered system. Figure 5 presents the sensors used to monitor pavement response in terms of stress and strain. In soil and unbound layers, the vertical stress (σ_z) and vertical strain (ε_z) were measured at the layer mid-depth or 75 mm below the top of the layer (subgrade). The transversal strain (ε_x) and longitudinal strain (ε_y) were measured at the bottom of the asphalt concrete layer using the technique previously discussed through research project performed at Laval University [2,3], which consists of retrofitting instrumented asphalt concrete cores in the layer. The strain sensors are all instrumented with optic fibre strain gages and the stress sensors are electrical pressure cells. Figure 6 shows and example of pavement response at the subbase level under wheel loading. The reported stress and strain values throughout this paper are the average values of five distinct and valid wheel passages over the sensors. Based on the previous experience with these sensors, a valid passage is defined by the tire being directly over the sensors in the transversal (x) direction ± 20 mm (Figure 3). The tests were performed at a speed of about 2 km/h due to the specific limitations of indoor testing conditions.

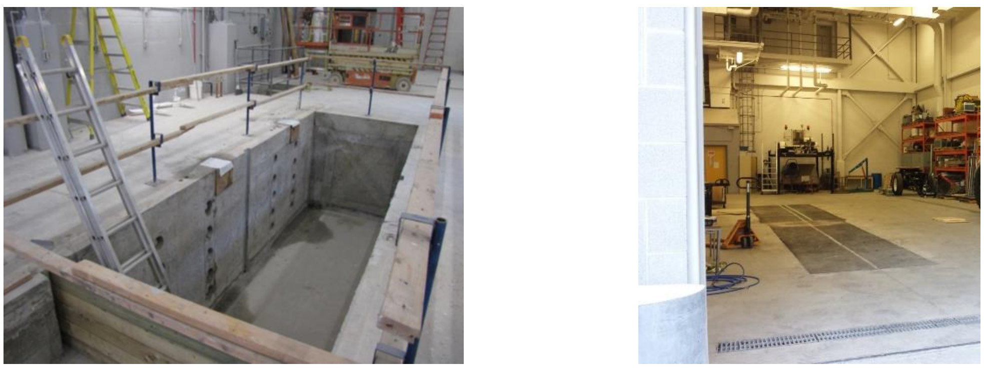

Figure 2. Indoor test facility – Left : empty test pit; Right : Paved flexible pavement structure

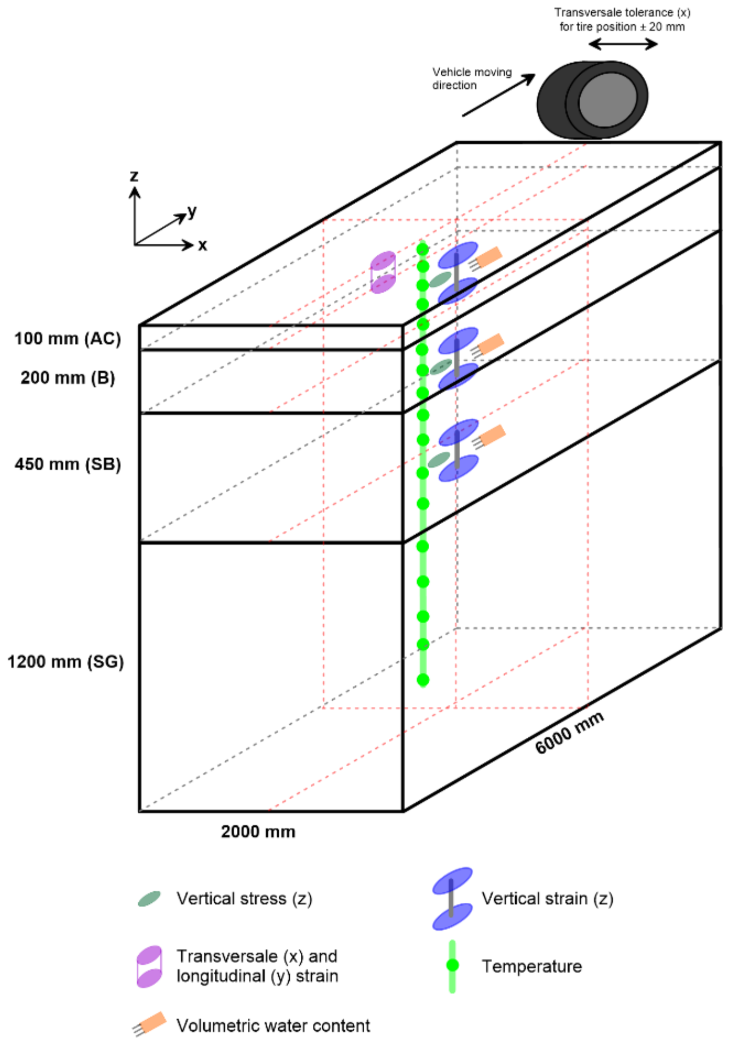

Figure 3. Tested pavement structure

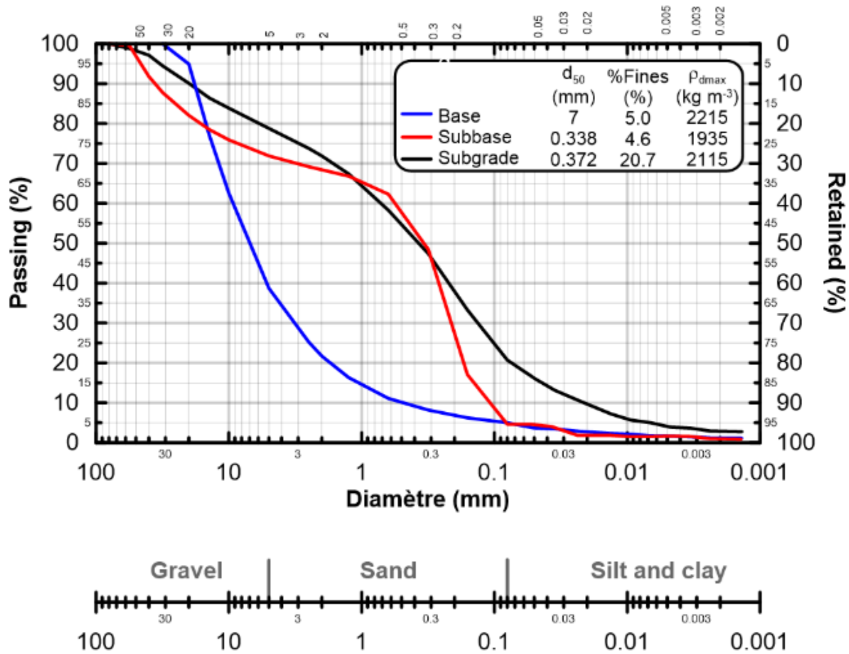

Figure 4. Tested materials grain-size distributions

Figure 5. Mechanical response sensors – Left : Vertical stress σ_z in soil and unbound layers; Center : Vertical strain ε_z in soil and unbound layers; Right : Transversal ε_x and longitudinal ε_y strain at the bottom of asphalt concrete

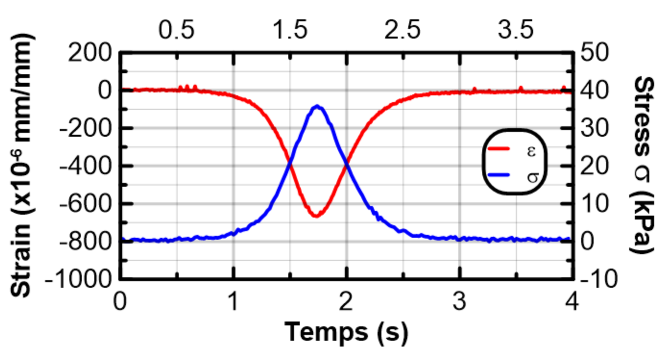

Figure 6. Example of vertical stress and vertical strain signal - Subbase

A total of 26 cases were studied for various tire types, inflation pressure and axle loads. Table 1 summarizes the tests performed in the project. Typical truck tires (11R22.5, mounted in dual configuration) were tested for relative comparison purposes. Six different tire types used on agricultural equipment were tested. Conventional tires (bias tires) (28L26 and 850/50-30.5) and radial tires (850/50R30.5 and 750/65R26) were selected for the study. The radial tires selected are considered as flexible radial tires, these tires being characterized by a high capacity to create large and uniformly distributed surface contact with the soil when loaded. As the legal load for single axle is 10 000 kg in Quebec, the proposed test matrix considers loading conditions in that range, going from 4000 kg to 5500 kg (half-axle load). The inflation pressures considered were selected based on manufacturer recommendations and practical considerations.

Table 1. Tests matrix

Tire		**Inflation pressure (psi)**			
Brand	**Dimensions**	**4000 kg**	**4500 kg**	**5000 kg**	**5500 kg**
BF Goodrich	11R22.5	100	100	100	100
BKT	28L26	30	30	30	
BKT	28L26	20	20	20	20
BKT	850/50-30.5	30	30	30	
BKT	850/50-30.5		20		
Nokian	850/50R30.5		15	15	15
Michelin	850/50R30.5		15	15	15
Michelin	750/65R26		15	15	
BKT	850/50R30.5		15	15	15

The tires were mounted on a single axle farm trailer with a 1.22 m x 2.44 m platform which was used to pile concrete blocks (Figure 7). The trailer was pulled by a standard farm tractor. The half-axle weight was measured using a 10 000 kg wheel scale. Prior performing loading of the tested pavement structure, loaded tire prints were taken using white cardboard and black paint, as presented in Figure 8. The tire print results were analyzed for gross and net surface contact.

Figure 7. Left - Farm trailer used; Center – Loading with concrete blocks; Right – Half-axle weight measurement

4000 kg	4500 kg	5000 kg
		
Gross surface area = 2087 cm² Net surface area = 1287 cm²	Gross surface area = 2493 cm² Net surface area = 1557 cm²	Gross surface area = 3276 cm² Net surface area = 2000 cm²

Figure 8. Example of loaded tire print measurements (850/50-30.5)

3 Results and analysis

The tests were performed in July 2014 in the indoor laboratory of the department of civil engineering of Laval University. During the tests, the temperature and water content in the pavement structure did not vary significantly and will not be discussed in this paper. The tire print on the pavement surface of specialty tires are summarized relative to the reference tires using the relative surface contact stress σ_0. The σ_0 value was calculated using

[1] $$\sigma_0 = \frac{W \times g}{A}$$

in which W is the weight on the half-axle (kg), g is the gravitational acceleration (9.81 m/s^2) and A is the area of the tire print on the surface (gross or net) (m^2). The relative σ_0 value is obtained using

[2] $$Relative\ \sigma_0 = \frac{\sigma_0\ farm\ tire\ (weight\ X)}{\sigma_0\ reference\ tire\ (weight\ X)}$$

The reference values obtained for the 11R22.5 are 370, 417, 514 and 522 kPa for the gross contact stress, while they are 496, 573, 791 and 803 kPa for the net contact stress. These values were calculated for the dual tires combined. As expected, a significant decrease is observed for the farm tires, quantified with a relative σ_0 value lower than 1, regarding the contact stress at the pavement surface (Figure 9). The specialty tires tested are significantly wider than standard dual truck tires and are designed to perform a low inflation pressure, allowing to cover a much wider ground surface when loaded. It can also be noted that the relative σ_0 is lower for the flexible radial tires than for the conventional tires, emphasizing the difference in design of both tire structure. For the cases where an inflation pressure reduction from 30 psi to 20 psi was tested, an average decrease of the relative σ_0 value of approximately 30% was observed, which is associated with a supplementary increase of the surface contact due to tire pressure decrease.

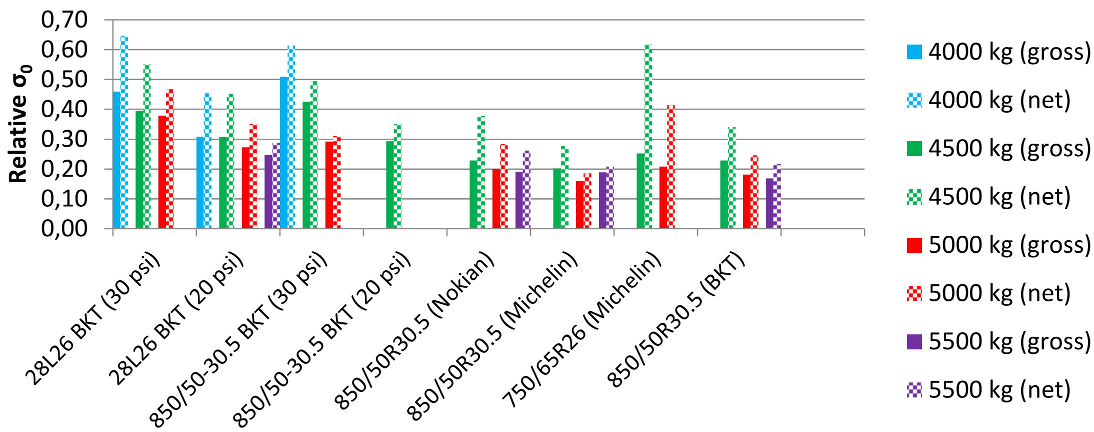

Figure 9. Relative values of surface contact stress for each tire and load considered

Table 2 presents the stress and strain values measured for each of the loading conditions tested for this study. As previously pointed out, the results presented in this Table are average values of five distinct valid passages on the pavement structure. The reported values are the maximum stress or strain experienced at a specific level in the pavement structure for each loading condition (Figure 6). A close observation of the provided data in Table 2 reveals that most of the stress and strain values measured for the wide specialty tires are lower than the ones measured for the reference tires for the same half-axle load. All the cases were this observation is not valid are associated with conventional tires, most of the time these data being very close but higher than the ones obtained for the reference tires 11R22.5.

Figure 10 and Figure 11 presents the collected stress and strain data as a function of half-axle load for each investigated depth in the pavement structure. For each figure, the data collected for the reference tires are presented in red lines and symbols. Regarding fatigue behavior of the surfacing layer (here commented using the maximum amplitude tensile strain, ε_y^{AC}), it is observed that strains either decrease with load increase, especially for lower values of loads, or stay approximately unchanged. This particular behavior is explained by the important increase of surface contact radius with the increase of load. Nevertheless, for each of the other pavement response parameters, an increase of strain and stress is generally noticed when the half-axle load is increased. In addition, as previously pointed out, a close observation of the data presented in Figure 10 and Figure 11 reveals that for most of the response parameters, the data collected for radial flexible tires are generally lower than the ones collected for the reference tires, as the lines associated with radial tires are easily differentiated from the red lines. For the conventional farm tires, the pavement responses often superposed, or are in a close range, with the data collected for the reference 11R22.5 dual truck tires. In terms of critical strains associated with pavement performance, the elastic compressive strains at the top of the subgrade soil are closer to the strains experienced for the reference dual truck tires. Therefore, the main damage mechanism involved when farm tires and dual truck tires are compared appears to be the structural rutting based on the experimental results collected.

Table 2. Strain and stress results obtained for each loading condition

Brand	Dimensions	Load (kg)	Inflation pressure (psi)	Strain (ε) Asphalt Concrete ε_x^{AC} (μ mm/mm)	Asphalt Concrete ε_y^{AC} (μ mm/mm)	Base ε_z^{B} (μ mm/mm)	Subbase ε_z^{SB} (μ mm/mm)	Subgrade ε_z^{SG} (μ mm/mm)	Stress (σ) Base σ_z^{B} (kPa)	Subbase σ_z^{SB} (kPa)	Subgrade σ_z^{SG} (kPa)
BF Goodrich	11R22.5	4000	100	113.7	317.5	-1261.6	-1123.8	-668.6	207.5	36.2	20.3
		4500	100	98.5	336.9	-1454.3	-1268.6	-743.1	225.9	41.5	22.8
		5000	100	87.6	361.6	-1714.1	-1477.0	-835.2	245.0	47.6	27.1
		5500	100	103.6	345.5	-1689.4	-1493.9	-864.1	252.5	49.4	27.7
BKT	28L26	4000	30	86.6	152.0	-1380.8	-1228.3	-710.5	239.8	41.2	21.6
		4500	30	89.5	131.0	-554.1	-1123.1	-717.5	179.9	41.1	23.0
		5000	30	83.0	118.2	-1010.5	-1298.3	-817.5	214.9	47.3	26.1
		4000	20	50.6	130.5	-1011.4	-1099.9	-682.7	207.6	38.4	*
		4500	20	44.0	108.6	-1240.4	-1237.4	-744.4	235.9	50.5	23.6
		5000	20	45.2	98.7	-1226.7	-1264.2	-806.0	223.0	46.2	28.1
		5500	20	46.7	90.7	-1447.8	-1302.2	-863.8	247.0	49.9	29.8
BKT	850/50-30.5	4000	30	58.3	239.5	-1109.5	-1090.4	-659.4	217.7	39.0	21.3
		4500	30	54.3	223.4	-1378.3	-1197.4	-749.0	229.0	43.1	23.9
		5000	30	57.8	195.0	-1385.8	-1270.1	-809.9	241.5	46.9	26.2
		4500	20	31.4	170.8	-1078.1	-1135.3	-721.4	214.9	40.2	23.5
Nokian	850/50R30.5	4500	15	18.8	75.5	-966.1	-1064.3	-695.8	198.0	36.6	22.4
		5000	15	23.7	59.9	-866.2	-1104.4	-733.4	196.6	38.4	23.9
		5500	15	41.0	83.0	-732.7	-1091.8	-751.8	186.6	39.8	26.0
Michelin	850/50R30.5	4500	15	17.8	98.1	-852.7	-1082.3	-718.4	192.2	37.3	22.7
		5000	15	16.1	95.4	-860.2	-1129.2	-753.5	194.7	40.0	24.6
		5500	15	*	108.3	*	*	*	184.7	38.9	25.9
Michelin	750/65R26	4500	15	28.4	77.6	-655.2	-994.9	-663.6	178.3	34.9	21.9
		5000	15	29.8	73.4	-773.4	-1064.0	-725.3	183.4	37.3	23.7
BKT	850/50R30.5	4500	15	15.1	102.0	-706.9	-1000.5	-672.9	179.6	34.5	21.9
		5000	15	18.9	92.7	-721.3	-1061.6	-728.2	183.5	36.9	23.8
		5500	15	18.3	76.2	-1050.6	-1131.4	-770.2	190.5	39.6	25.8

*Equipment issues caused unreliable data

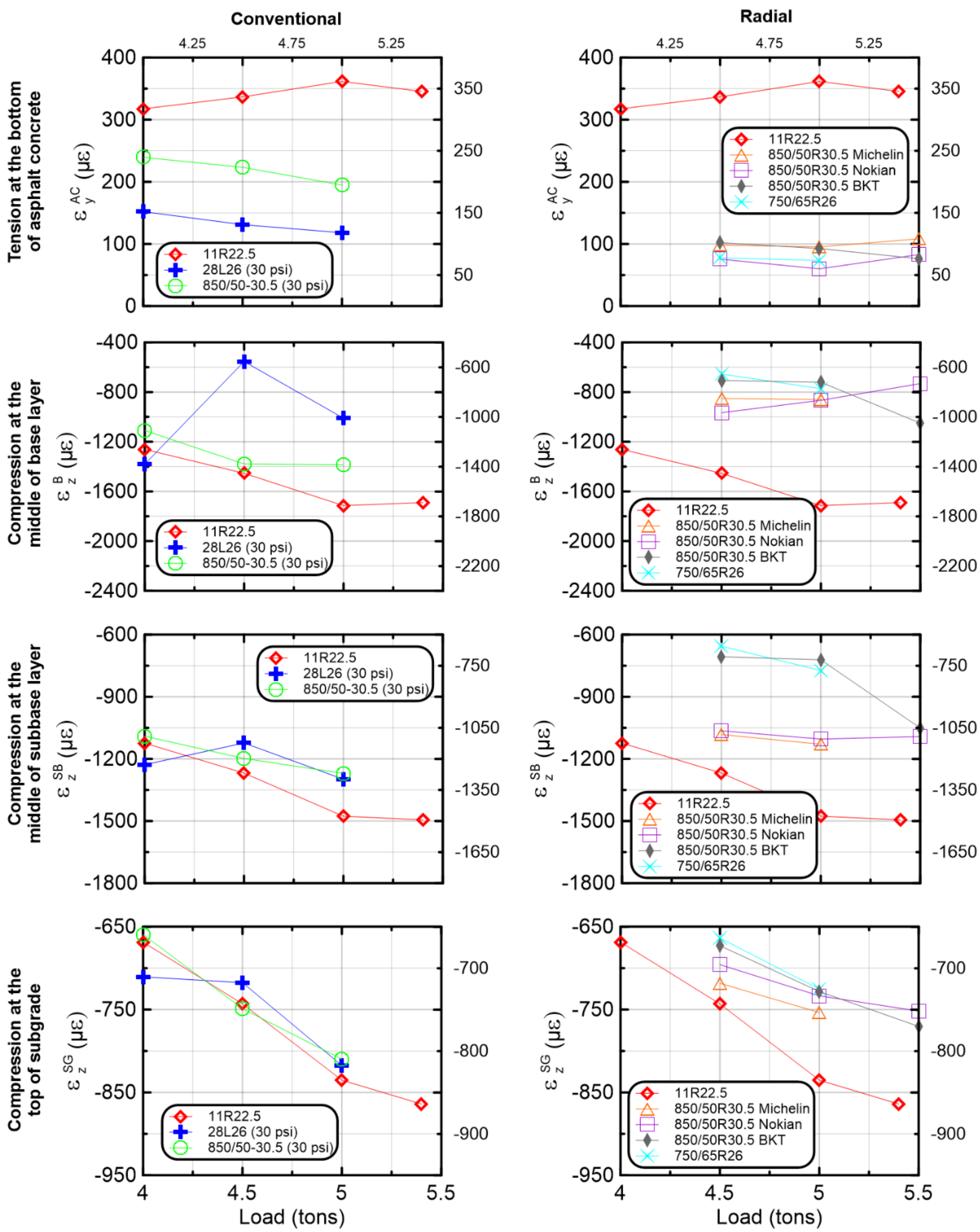

Figure 10. Strain data as a function of half-axle load for conventional and radial tires

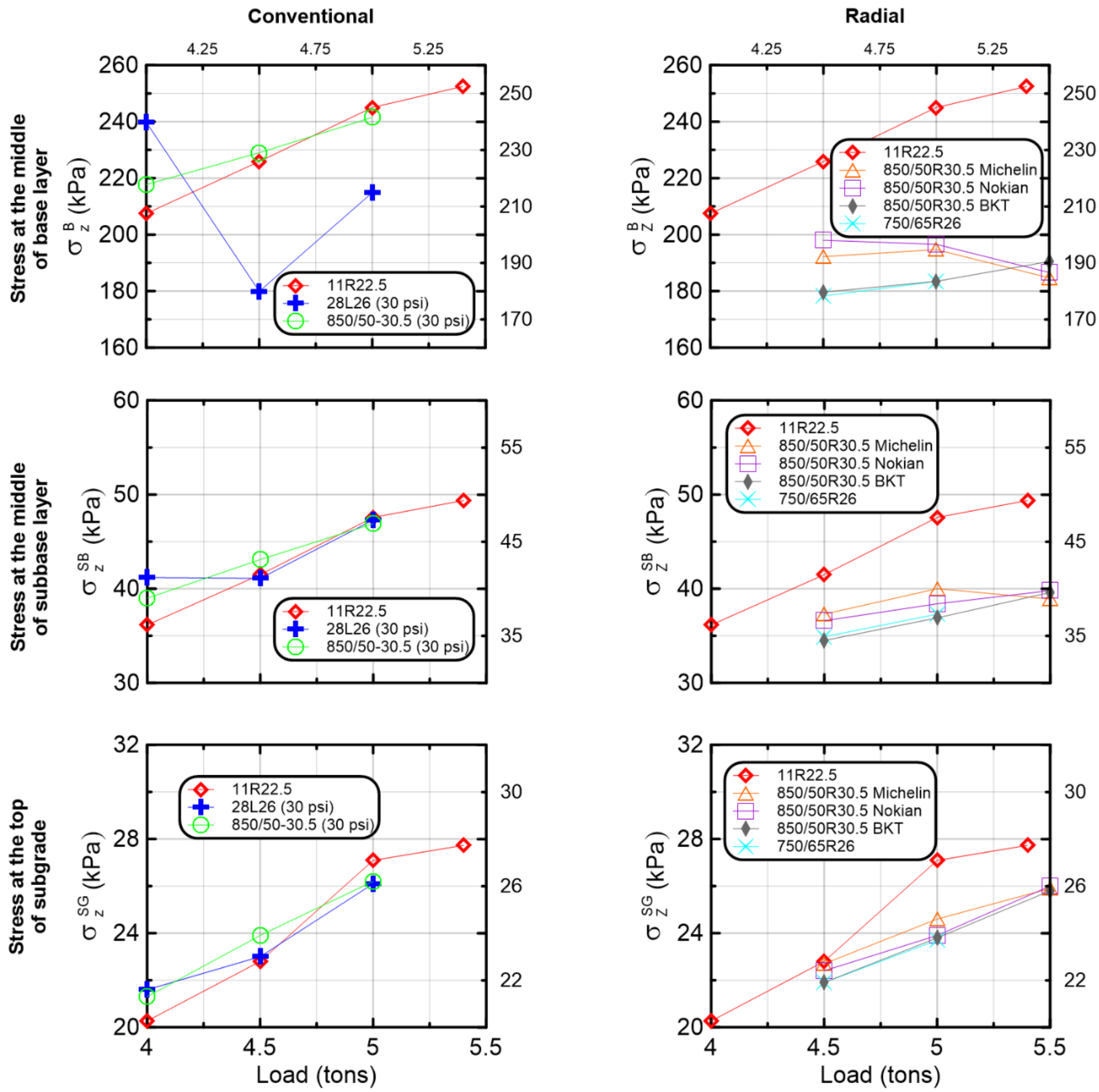

Figure 11. Stress data as a function of half-axle load for conventional and radial tires

The obtained results and the difference of pavement response between reference tires and wide specialty tires can also be pointed out when the results are presented as relative values to the reference tires (Figure 12). The results presented in this figure are relative values calculated using

[3] $$Relative\ strain = \frac{\varepsilon\ farm\ tire\ (weight\ X)}{\varepsilon\ reference\ tire\ (weight\ X)}$$

The use of this relative calculation allows to perform a direct comparison, in terms of strain experienced at various level in the pavement structure, between the farm specialty tires and the reference dual truck tires. This comparison is made for the legal load limit for half-axle (5000 kg), considering a single axle configuration. This reveals that the strain ratio is very low near the pavement surface, and that this ratio gradually increase towards a ratio of 1 with the increase of depth. A relative strain of 1 would mean, based on classical pavement engineering criteria, that both tire types would cause the same damage to the pavement. Therefore, for each wheel pass, when the relative strain value is closer to unity, the damage experienced under farm tires is getting similar to the one experienced for dual truck tires. The analysis of this figure reveals that fatigue cracking is likely not an issue for pavement performance, with relative values from 0.17 to 0.53, but that structural rutting may be the governing performance factor. For conventional farm tires, the relative strain at 5000 kg at the top of the subgrade soil is in the range of 0.975. For radial flexible tires, the relative strain is significantly different at an average value of 0.88. This difference in pavement response is attributed to the significant differences in the surface contact characteristics between conventional and flexible radial farm tires.

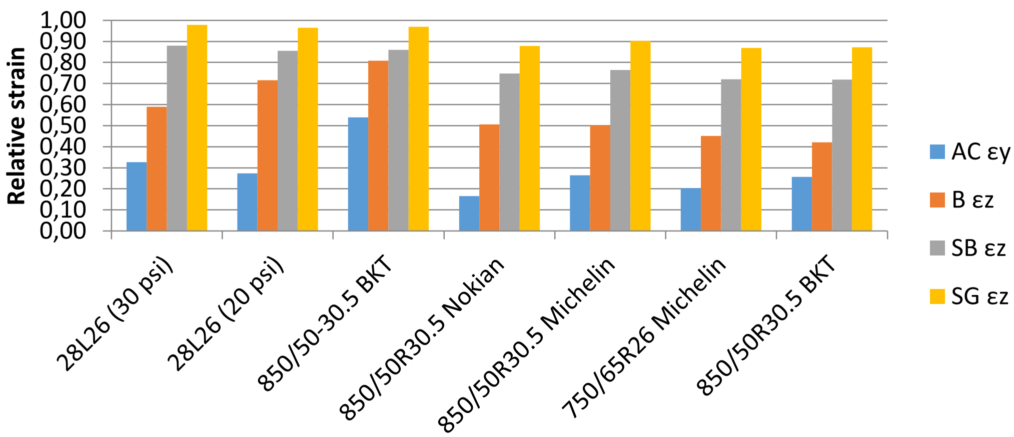

Figure 12. Relative strain for 5000 kg

As the strains experienced in the pavement structure were found to be generally equal or slightly lower than reference dual truck tires when farm tires are used, an investigation was performed to determine analytically the theoretical load to apply on wide specialty tires to obtain the same damage than reference dual truck tires at the legal load. In order to perform this theoretical analysis, best fit linear trend were used for the governing damage mechanism, which is the elastic compressive strain at the top of the subgrade layer. An analysis factor, called the limit load factor (*LLF*), was used to perform this analysis. It is obtained using

[4] $$LLF = \frac{L}{L_{Ref}}$$

in which L is the load needed to be applied on farm specialty tires in order to obtain the same vertical strain at the top of the subgrade soil experienced with the reference dual truck tires loaded at 5000 kg (half-axle) (ε_{z-ref}^{SG}). First, the specific pavement response for the reference tires is obtained using linear trend for the 11R22.5 tires (Figure 13), using 5 tons as the abscissa input (L_{ref}). The equation used is in the form of

[5] $$\varepsilon_{z-ref}^{SG} = m_{ref} \times L_{ref} + b_{ref}$$

in which m_{ref} and b_{ref} are regression parameters for the reference tires. Afterwards, using similar trend lines obtained for farm tires, such as the one presented in Figure 13 for 850/50R30.5, the value of L can be obtained. It is calculated from

[6] $$L = \frac{\varepsilon_{z-ref}^{SG} - b}{m}$$

in which m and b are regression coefficients for farm tires.

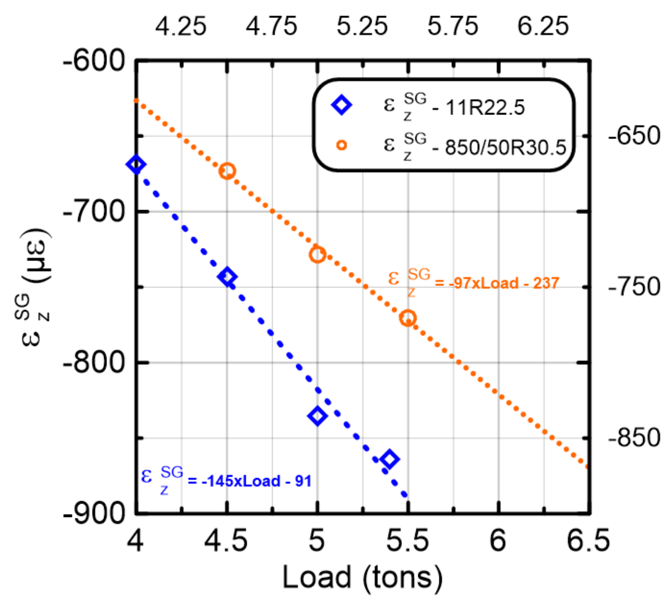

Figure 13. Example of linear trends used to obtain LLF

The results obtained from this calculation approach allows determining a relative increase of axle load in order to induce a damage of the same magnitude than the one experienced for reference dual truck tires (Figure 14) when farm specialty tires are used. This analysis revealed that, for wide farm tires, half-axle loads of up to 1.3 times the legal load for single axle induce the same damage than reference dual truck tires. An average value of 1.21 is found for radial flexible tires, which show a significant difference on the pavement response when compared to conventional wide farm tires. As a matter of fact, for conventional wide farm tires, the obtained *LLF* values of approximately 1 mean that these tires have essentially the same effect on the elastic compressive strain at the top of the subgrade in comparison with the selected reference tires (11R22.5). Therefore, their *LLF* value of 1 to 1.02 imply that the same axle load has to be applied in order to induce to same damage.

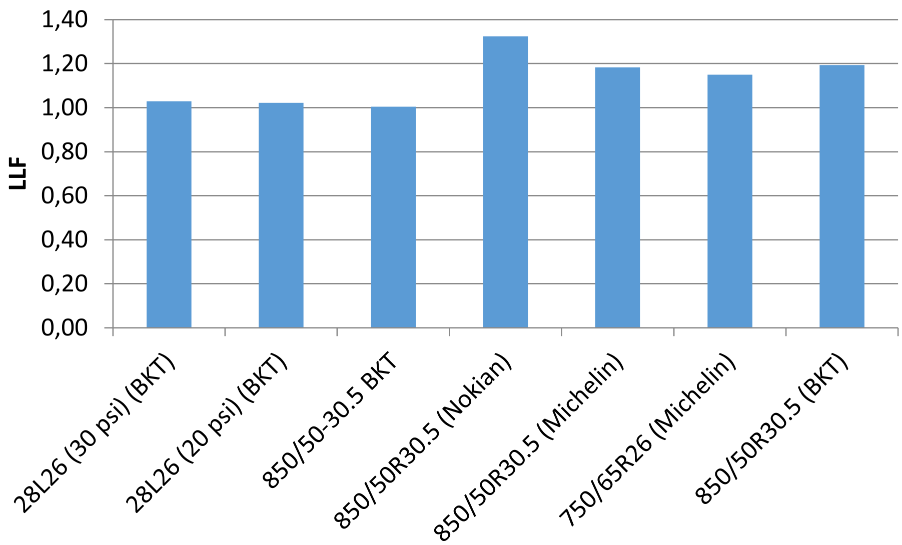

Figure 14. Load limit factor determined for a reference half-axle load of 5000 kg

The results presented on the basis of the laboratory experimental study are generally in good agreement with the theoretical preliminary analysis performed by the Ministry of Transportation of Quebec, as this preliminary analysis was performed on conventional farm tires. The preliminary analysis performed reveals that conventional wide farm tires cause strains to flexible pavements in the same range, but slightly higher, than reference dual truck tires. Therefore, the preliminary analysis concluded that wide specialty tires are slightly more damaging to flexible pavement structures. On the other hand, no flexible radial tires were considered in the preliminary study. The radial tires selected for the experimental study are flexible radial tires, characterized by their capacity to develop high surface contact area when loaded and uniform low soil contact pressures. These tires showed a significant effect on pavement response in comparison with conventional farm tires. The typical results highlighted in this study reveal a decrease of stress and strain when these tires are used in comparison with conventional farm tires. This effect can be in part attributed to the significant decrease in surface contact stress at the tire-asphalt concrete interface.

4 Conclusion

An experimental laboratory study was undertaken at Laval University to test the effect of wide specialty farm tires on pavement performance in comparison with reference tires used in the trucking and transportation industry. An indoor test pit was used to build a typical flexible pavement representative of Quebec's rural road network. The pavement structure was instrumented to monitor vertical stress and strain in the soil and unbound layers, as well as longitudinal and transversal tensile strains at the bottom of the asphalt concrete layer. The selected test matrix involved performing pavement response test for 26 case studies, varying in terms of various axle loads, tire pressures and by wide specialty tires brand, dimension and design. The pavement structure was loaded with single axle farm trailer moving at a speed of approximately 2 km/h. The pavement response results obtained allowed concluding the governing damage parameter is the elastic compressive strain at the top of the subgrade soil, which is associated with the structural rutting of the flexible pavement structure. The tensile strain at the bottom of the asphalt concrete layer was shown to be much lower than the reference dual truck tires (11R22.5) for the same axle load, and did not change significantly with the increase of axle load (within the range tested in this study). A significant difference in pavement response was observed depending if conventional wide farm tires (bias tires) or flexible radial tires were used to load the pavement structure. While, for the governing damage parameter, the conventional farm tires induce strain equal or slightly lower than the reference tires for the same axle load, the flexible radial tires induce strains that are significantly lower. This difference on the pavement response was in part interpreted as the effect of surface contact stress, which was measured lower for flexible radial farm tires.

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