IMPACT OF ASPHALT CONCRETE TEMPERATURE AND TRAFFIC LOADING SPEED ON STRUCTURAL BEHAVIOR OF FLEXIBLE PAVEMENT

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ABSTRACT

Monitoring the temperature gradient of pavement structure layers and its effect on the structural behaviour helped to establish a fundamental understanding of the magnitude and impact of these variations on the pavement response to different loading conditions. The performance of pavements clearly reveals the need to properly measure the distribution of stresses and strains within road layers over a period of time taking into account the effect of extreme temperatures. The adverse effects of traffic speed during hot weather conditions on the structural behaviour of the flexible pavement are briefly discussed and possible recommendations to overcome these effects. Structural data including stresses and strains were collected under the action of external loads applied by a calibrated test trucks. To mimic the effect temperature extreme events on the flexible pavements, the study was carried out on flexible roads immediately after the construction at 51^{o} C (truck impact test) and 44^{o} C (truck creep test) and after one year at normal operating temperature (20^{o} C).

The field results showed unprecedented high stress and strain levels caused by low asphalt stiffness when the asphalt mat temperature is above a normal operating temperature. Traffic-induced stresses and strains transmitted through the asphalt concrete layer to unbound materials of the asphalt concrete are directly influenced by the stiffness. The impact test using a truck speed lower than 25 km/h resulted in a very high truck pressure impact. This study confirmed that most of pavement performance problems occurred at locations were buses frequently stopped and areas close to traffic signals. This finding highlighted the importance of traffic speed impact, extreme hot weather events and the interaction of both.

Key words: Temperature effect; flexible pavement; stiffness of asphalt concrete; structural behaviour;

INTRODUCTION

The performance of a pavement structure under traffic and/or environmental load depends to a large degree on the stress-strain relationships of the various pavement materials from which it is made. The response also depends on the intended use of these material layers and on the mechanism by which the load is transferred from one layer to another. In general, these are defined by the mechanistic properties of the road material. Furthermore, environmental factors such as temperature and moisture influence these properties and must be considered in the material model.

The behaviour of an asphalt concrete mixture as well as the binder, depends on temperature and load frequency and is reflected in its stiffness characteristics. Pavement modelling and design depend heavily on the temperature used to specify the performance grades for asphalt binders, load limits during spring season, and the thickness of the layer of frost-free base. Viscoelastic properties of asphalt materials are generally determined within the linear viscoelastic domain when the material is subjected to sinusoidal loading at different frequencies at small values of strain. However, when temperatures are above 40^{o} C, the mixtures can no longer be treated as linear viscoelastic. At low temperatures (below zero), the behaviour of asphalt concrete is considered to be a combination of both elastic and linear viscoelastic. This behaviour can be considered purely elastic and viscoelastic under measurements are obtained with low strain amplitude. The modulus values of asphalt concrete materials can rise during the cold winter months by a factor of 20 compared to its value during the hot summer months. The modulus values are dependent on the time of loading and temperature (Clyne *et al*., 2003).

The dynamic modulus reflects the stiffness of the mixture and its resistance to deformation at a designated frequency and temperature that has been implemented in the Mechanistic-Empirical Pavement Design Guide (M-EPDG/NCHRP, 2004). The American Association of State Highway and Transportation Officials provisional test standard (AASHTO TP62, 2003) is a stress-controlled version of the complex modulus test and focuses on capturing the visco-elastic response of AC materials. Traffic loading is simulated in the laboratory with a haver-sine cyclic load applied to the specimen and adjusted so that the specimen is subjected to an axial elastic strain. Each specimen should be tested for the 30 combinations of temperature and frequency starting with the lowest temperature and proceeding to the highest. Testing at a given temperature should begin with the highest frequency of loading and proceed to the lowest. Stresses and strains then can be calculated. The M-EPDG structural response model is based on conducting linear elastic analysis and hence, the phase angle is not being considered in the analysis. Creep compliance and tensile strength tests are considered to be the most promising for predicting the low-temperature performance of asphalt concrete mixtures.

Mechanical properties of asphalt materials, such as the modulus of elasticity "E", are often measured at room temperature (AASHTO design guide, 1993). It has been used to characterize pavement structures. This approach assumes that asphalt concretes exhibit a linear elastic response. However, most of the asphalt mixes used in pavement structures are nonlinear. Uzan, 1996; Perl *et al .,* 1983; Sides *et al.,* 1985; Kim and Daniel*,*1997; Wright and Zheng, 1994 and Lu and Wright, 1998, have shown that the asphalt concrete has four distinct responses; elastic, viscoelastic, visco-plastic and plastic behavior depending on loading and temperature. However, Di Benedetto and De La Roche, 1998 considered the behavior of asphalt concrete as complex visco-elasto-plastic, which can be considered purely elastic and viscoelastic at low strain amplitudes. At low temperatures, the asphalt concrete behavior is a combination of elastic and slight linear viscoelastic.

Temperature is a significant factor and it is not considered in the existing design guide (AASHTO design guide, 1993). It influences the performance of pavement, especially asphalt concrete (AC). AC mats may experience a wide range of thermal regimes during the different climatic seasons. It is well known that asphalt concretes become brittle subjected to temperatures lower than – 5^{o} C (Wright and Zheng, 1994). On the other hand, high temperatures cause flow and fluidity of asphalt cements which make asphalt concretes soft and prone to large permanent deformations in the form of rutting when subjected to stresses induced by applied traffic loads. These plastic deformations are mainly related to temperature and the number of loading applications (Wright and Zheng, 1994).

Tarefder and Zaman (2003), reported that the resilient modulus of asphalt concrete decreases with an increase in temperature by several orders of magnitude. However, these should not be interpreted as meaning that at higher temperatures traffic loads have a more detrimental effect to the fatigue failure of an actual pavement. In fact, it is at low temperatures, not at high temperatures, that an asphalt pavement is more susceptible to fatigue failure. Rather, asphalt concrete is more susceptible to plastic deformation or rutting at higher temperatures.

Characterization of pavement materials in the M-EPDG (NCHRP, 2004) level 1 involves an application of the dynamic modulus technique and creep compliance determinations for asphalt concrete. The M-EPDG also incorporated the Enhanced Integrated Climatic Model (EICM) to simulate changes in the behaviour and characteristics of pavement and subgrade materials according to the climatic conditions over the design period.

Traffic at low speeds that could be caused by traffic jam or bad weather on pavement performance was studied in the field to determine the impact of calibrated trucks on top of asphalt strain gauges, unbound pressure cells and unbound EMU coil gauges throughout the road structure layers.

As a tire rolls over the roadway, it repeatedly applies and removes a load. This induces a strain on the asphaltic concrete and strain and pressure on unbound materials. Typically, it is assumed that the asphaltic concrete and unbound materials behaviour is purely elastic and the strain that is induced is completely recovered. While this is true for the majority of the strain, some is not recovered and leads to plastic deformation and compaction of the asphaltic concrete. While the tire will apply the same loading on the asphaltic concrete when the speed of traffic is increased, it will spend less time in contact with the road. The result of less contact time with asphaltic concrete is less compaction, and therefore less rutting will occur (Maadani *et al*., 2015).

Based on the above discussion, it appears that investigating the influence of high temperature and speed of traffic on the pressure and strain transmitted through the asphalt concrete layer to the unbound materials road structure layers is of high importance.

This research addresses the influence of temperature and traffic speed on the distribution of stresses and strains within the pavement structure. High stresses and strains were registered when the road was opened to traffic (test truck operation).

The asphalt concrete temperature was still relatively high and the fresh mix exhibited a low modulus compared with that at normal road operating temperatures. The results were needed to support the development and importance of evaluating the sensitivity of M-EPDG with respect to different climatic conditions and to support of consideration of including the effect of temperature on the asphalt material stiffness.

EXPERIMENTAL WORK

A number of sensors, with different functions, were buried in the trench to capture the structural response of the pavement as well as the temperature changes within the road layers.

Variations in temperature conditions, which influence the structural response of foundation materials, were captured using thermocouples. Strains and permanent deformations were measured in different road layers. The road layers were also instrumented to capture stresses. The stresses and strains were measured under dynamic loading (calibrated truck). Figure 1, shows the distribution of all sensor types with different layers built in Los Angeles, CA. Sensors for measuring stress and strain under vehicular loading were positioned along the wheel path. The pavement structure as shown in Figure 1 is composed of an asphalt concrete surface of 230 mm, an aggregate granular base of 110 mm (CAB II), a select granular backfill material sub-base of 870 mm, and silty clay as sub-grade material. Annual Average Daily Traffic (AADT) was 2000.

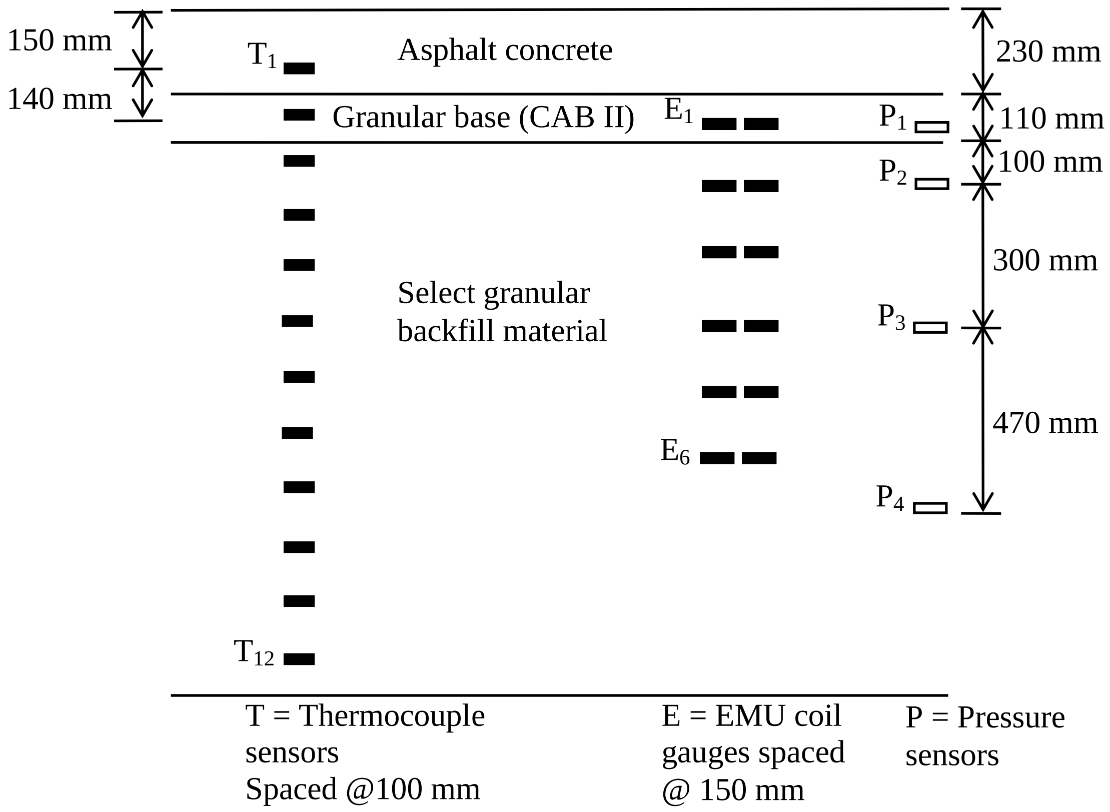

Figure 1: Vertical distribution of temperature and structural sensors

Impact of asphalt concrete temperature and loading speed on structural behaviour

Asphalt concrete temperature effect

A two axle test truck with axle loads of 57.83 and 83.18 kN respectively from front to back, was operated immediately after construction (asphalt mat temperature was 51° C), and at regular operating temperature (asphalt mat temperature was 20° C) at different speed over pressure cells located at four different depth levels (290, 390, 740 and 1210 mm) as shown previously in Figure 1. High levels of pressure, up to 290 kPa were measured at depth of 260 mm as shown in Figure 2, compared with the values (around 50 kPa) reported in the literature (Robin, M. A.; Wei, Z., 1997 and Gancalves *et al.*, 2003). The low asphalt concrete stiffness associated with high temperatures (above normal operating temperatures) reduces the material's ability to function properly as a surface layer responsible for distributing surface loads and minimizes the effectiveness of lower layers. The high pressures detected during the initial service life at the site are expected to affect the performance of the backfill layers below the asphalt concrete layer. Figure 2 shows the relationship of pressure impact at depth of 290 mm for a truck speed of 20 km/h at asphalt concrete temperatures of 51 and 20° C. Cooling the asphalt concrete from 51° C, (open to traffic) to 20° C (normal operating temperature) and asphalt concrete road aging (2 years) resulted in a 71 to 87 % decrease in the truck pressure impact.

The truck impact pressure gradient for a road structure layer at asphalt concrete temperatures of 51° C (representing open to traffic) and 20° C (representing both 2 years pavement aging and normal operating temperature) is shown in Figure 3. A drop in pressure of about 87 and 71 % occurred of the depth increased from 290 to 1170 mm, respectively. This drop is believed to be due to the temperature and densification of the backfill material under the action of general traffic.

Additionally, truck impact tests at the state of creep condition (0 km/h) were performed for both conditions, i.e. for open to traffic just after construction when the asphalt concrete temperature was about 44° C, and after 2 years of in-service road pavement at 20° C. The tests were carried out at a pressure cell depth of 290 mm which resulted in a very high truck pressure impact of 280 kPa compared to 170 KPa, in year 3 (Figure 4). Further analysis of the data in Figure 4, indicated that the creep impact after 2 years of construction was still very high. This finding was not reported in the literature associated with conventional road practices and it does not include a reference to field data or analytical simulations at such high levels of pressure as well as this type of test.

Figure 5 shows the pressure gradient at depths of 290, 470, 740 and 1210 mm at state of creep of 0 km/h speed (no overburden) throughout the road structure layer. The pressure gradient was measured for the open to traffic condition (at 44° C asphalt concrete temperature) and 2 years after the construction condition (aging and 20° C asphalt concrete temperature) and was found to decrease by 39 and 26 % at depths of 390 mm and 1160 mm, respectively.

This creep test mimics the effect of bus stoppages, general traffic impact at a light signal and more importantly traffic jam caused by any of climate events. Once again, this finding highlights the importance of considering the traffic creep impact and the role of this impact in the M-EPDG.

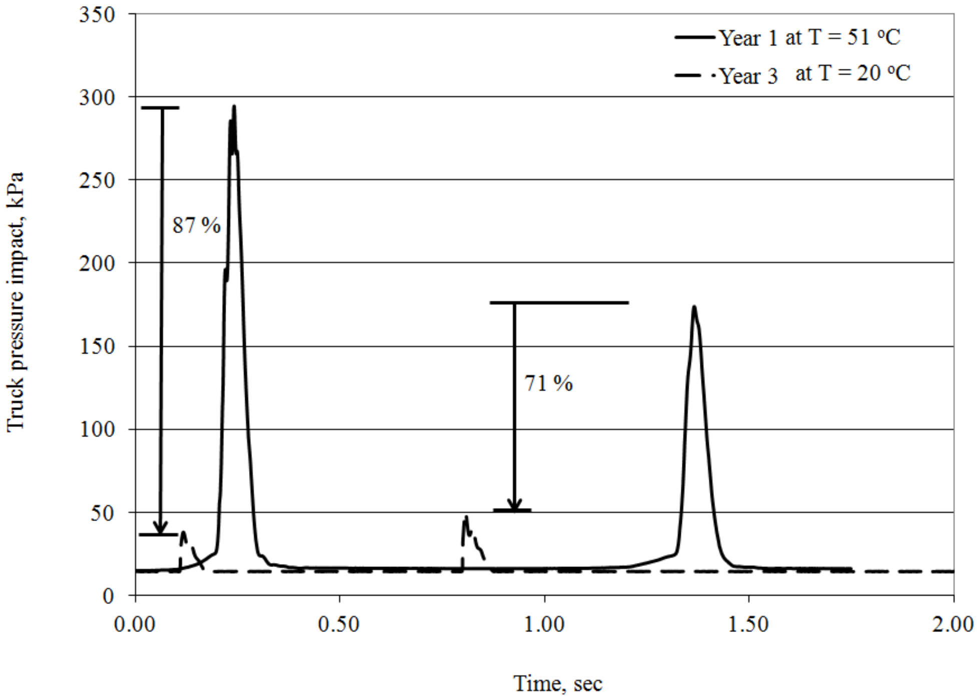

Figure 2: Effect of temperature on the top pressure cell at a depth of 290 mm

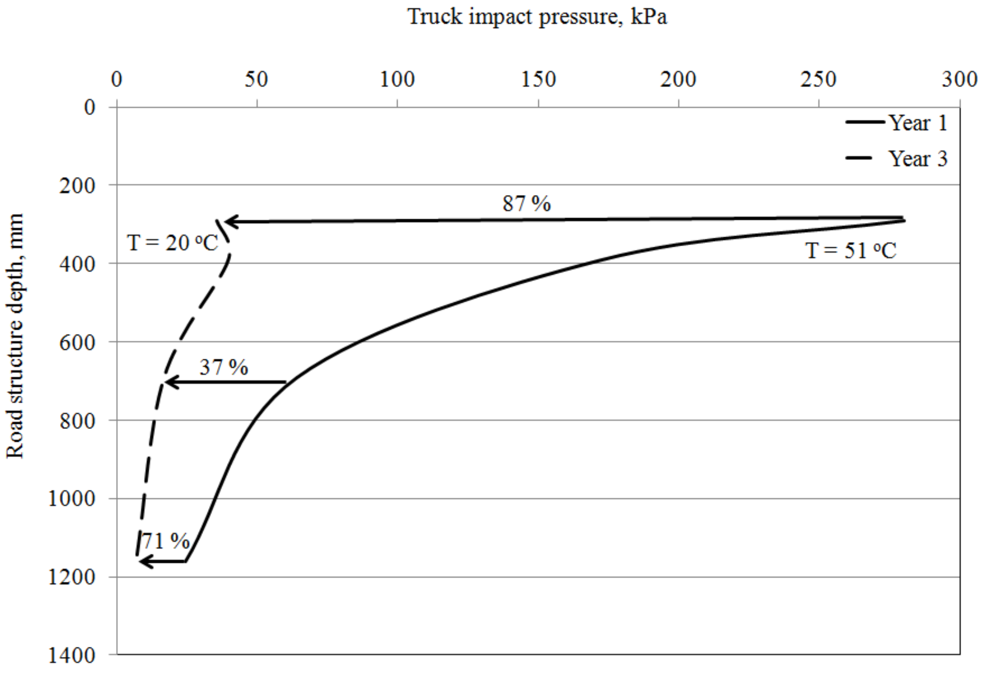

Figure 3: Effect of temperature on truck pressure impact profile

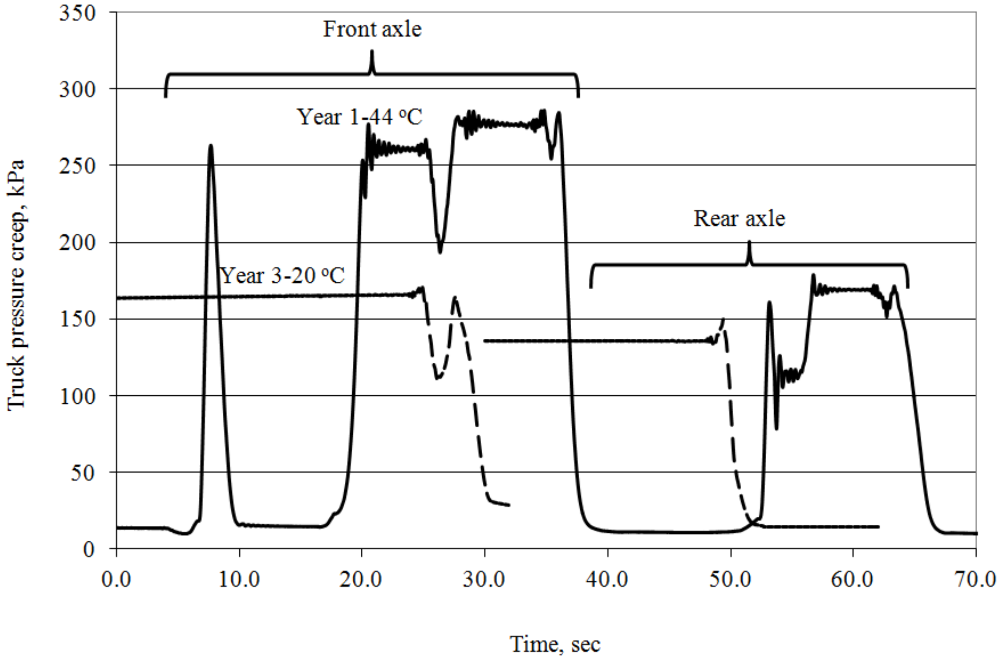

Figure 4: Temperature effect on truck pressure creep at a depth of 290 mm

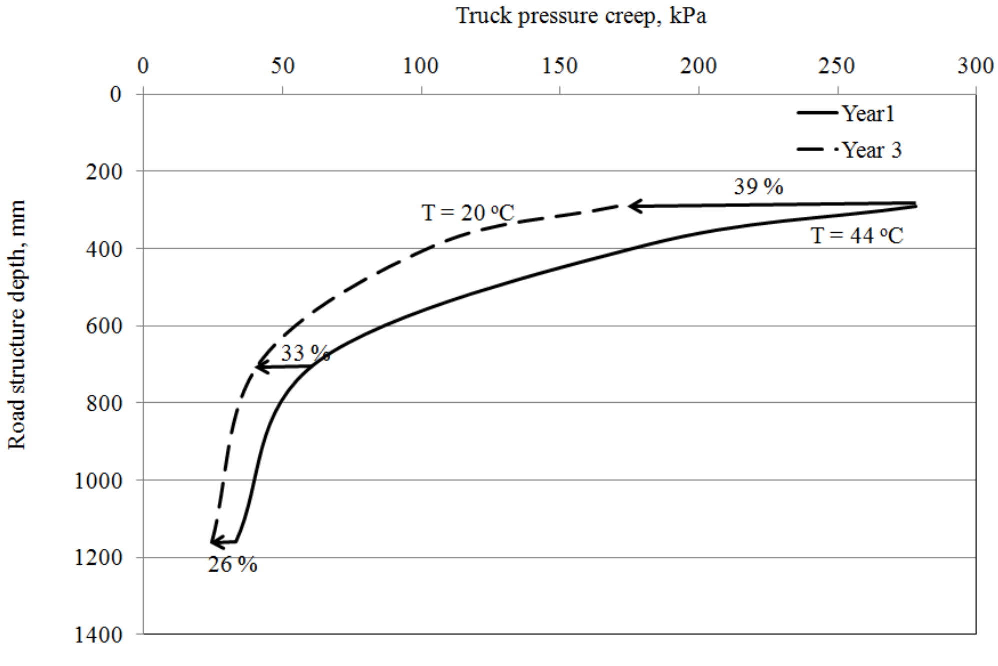

Figure 5: Temperature effect on truck pressure creep profile

Similar to the pressure signal, typical truck strain impact data recorded by the ε-Measuring Unit (EMU) soil strain measuring system, an induction coil technology

(Dawson, A.R., 1994) developed at Nottingham University which was later refined and enhanced (Dawson *et al*., 1999) at the Cold Regions Research and Engineering Laboratory (CRREL) of the US Army Corps of Engineers. The EMU measurements at a depth of 290 mm for unbound materials are shown in Figure 6. The truck strain impact revealed that when the road was opened to traffic while the asphalt concrete temperature is high (51° C), the road was susceptible to excessive permanent deformations (settlement and rutting) because of extreme high strains detected in the backfill layers under the action of a moving test truck. Further analysis of the data in Figure 6, determined that low stiffness of asphalt concrete at relatively high temperatures (51° C) was the major contributor to these high strains compared to the strains recorded after 1 year of construction and when the asphalt concrete temperature was 20° C (normal operating temperature). The drop in strain for both conditions was 92 %.

Figure 7 shows the strain gradient for the unbound materials pavement structure layers. The two strain profiles represent the truck strain impact at the early opening of the road when the asphalt temperature was 51° C after the road aged 1 year and where the asphalt temperature was 20° C. The latter dropped by about 92 % at a depth of 390 mm and 64 % at depth of 990 mm below the asphalt concrete surface. It is important to control the excessive deformation occurring as a result of prematurely loading a freshly constructed road.

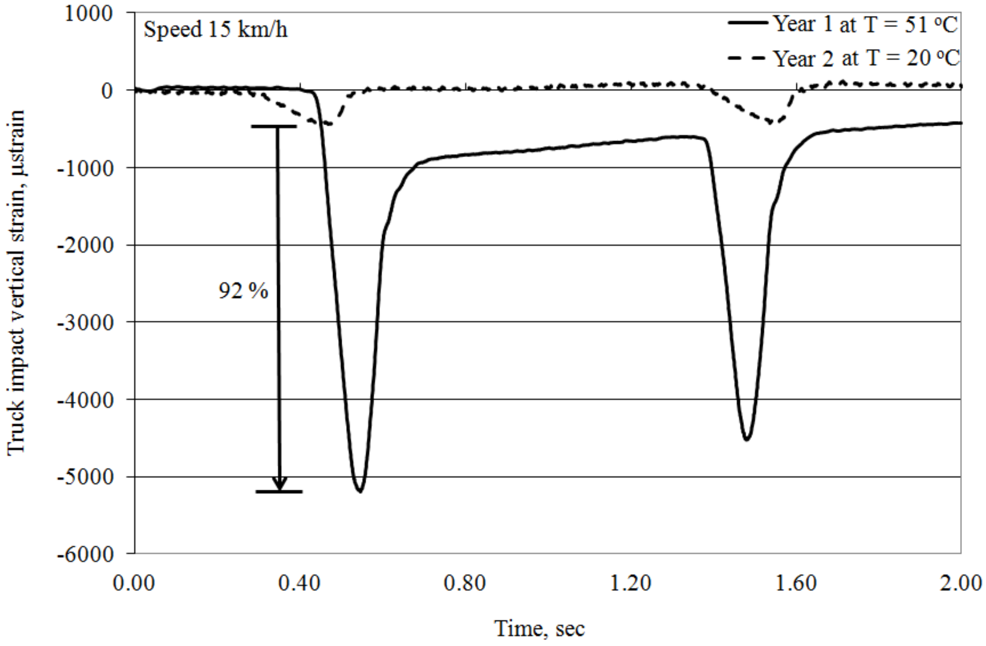

Figure 6: Temperature effect on the top EMU coil gauges at a depth of 290 mm

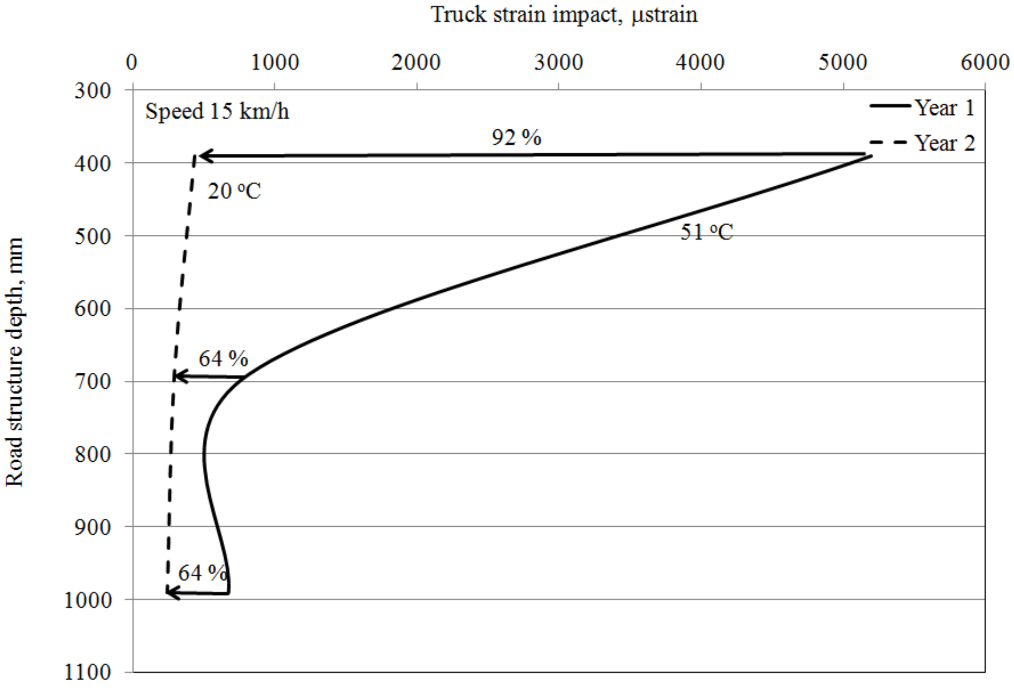

Figure 7: Effect of temperature on truck strain impact profile

Loading speed effect

The structural behaviour of asphalt concrete pavement is affected by the traffic speed effect. Traffic speed can vary from zero (Creep) to the road speed limit and that controlled by the traffic jam or bad weather resulted on different pavement distresses. The structural behaviour throughout the road structure at speed of 0, 5, 35, 75 and 100 km/h was studied to determine the impact of calibrated trucks on top of asphalt strain gauges, unbound pressure cells and unbound EMU coil gauges.

Figure 8 shows the relationship of pressure impact at a depth of 290 mm with truck speeds of 20 and 35 km/h. The speed increase of 75 % leads to a decrease in the pressure impact of 19 %. In the case of truck strain impact when the speed increased from 15 km/h to 35 km/h (a 133 % increase), it resulted in a strain decrease of 37 % as shown in Figure 9. Moreover, the pressure impact gradient throughout the depth for those two speeds was plotted in Figure 10. It is noted that the average drop in pressure is about 20% along the road structure layer when speed is increased by 75 %.

Typical truck impact pressures at different speeds on the top pressure cell are shown in Figure 11. A speed increase from 3 to 20 and 25 km/h resulted in a decrease of pressure by 39 and 43 %, respectively.

A creep truck impact study at a speed of 0 km/h was made and resulted in a very high truck pressure impact. Figure 12 shows the pure pressure gradient (no overburden) throughout the road structure layer at speed of 0, 3, 20 and 25 km/h. The maximum percentage of truck pressure impact decreased by 80 % as truck speed increased 0 to 25 km/h.

Most of the pavement performance problems occur at locations where buses stop close to a traffic signal, more problems expected will occur during extreme event weather that caused traffic jam. This finding highlights the importance of traffic speed. Further analysis of the results is plotted in Figure 13. It shows truck speed up to the range of 5 km/h has great impact on the asphalt road layer structure.

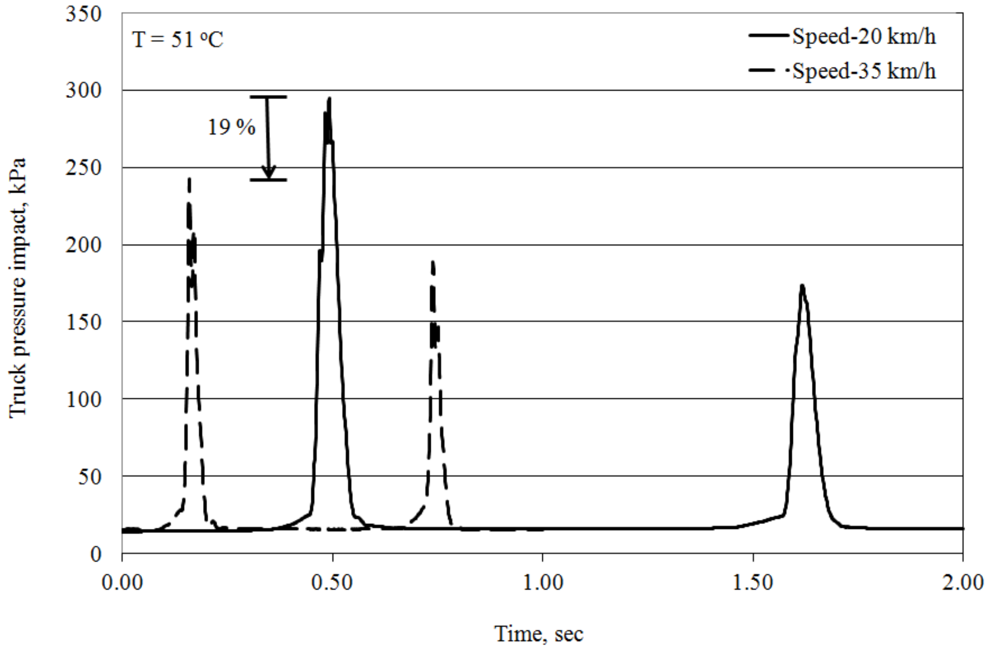

Figure 8: Effect of speed on the top pressure cell at a depth of 290 mm, year 1

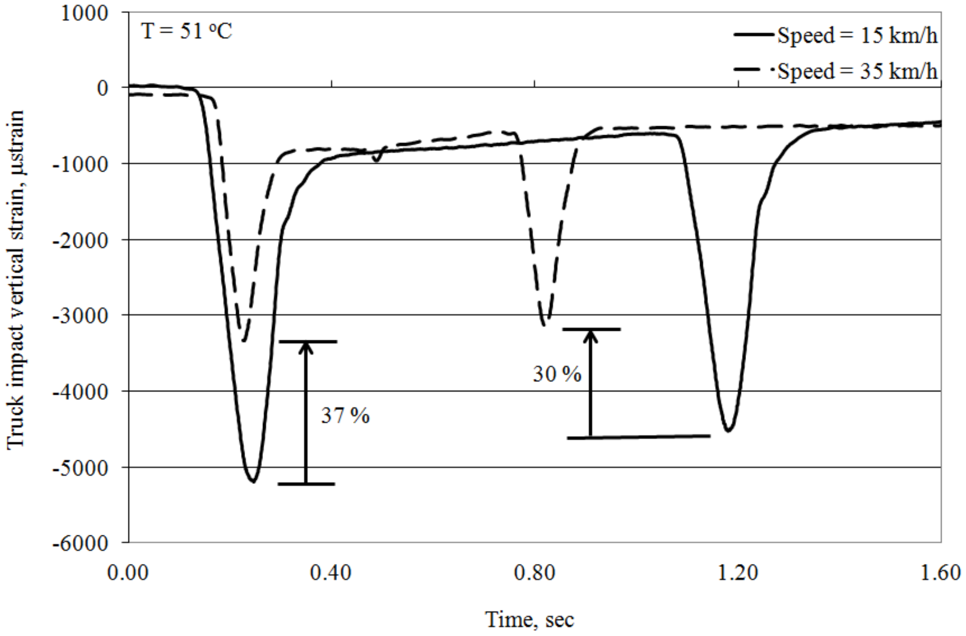

Figure 9: Speed effect on truck strain impact at a depth of 290 mm, year 1

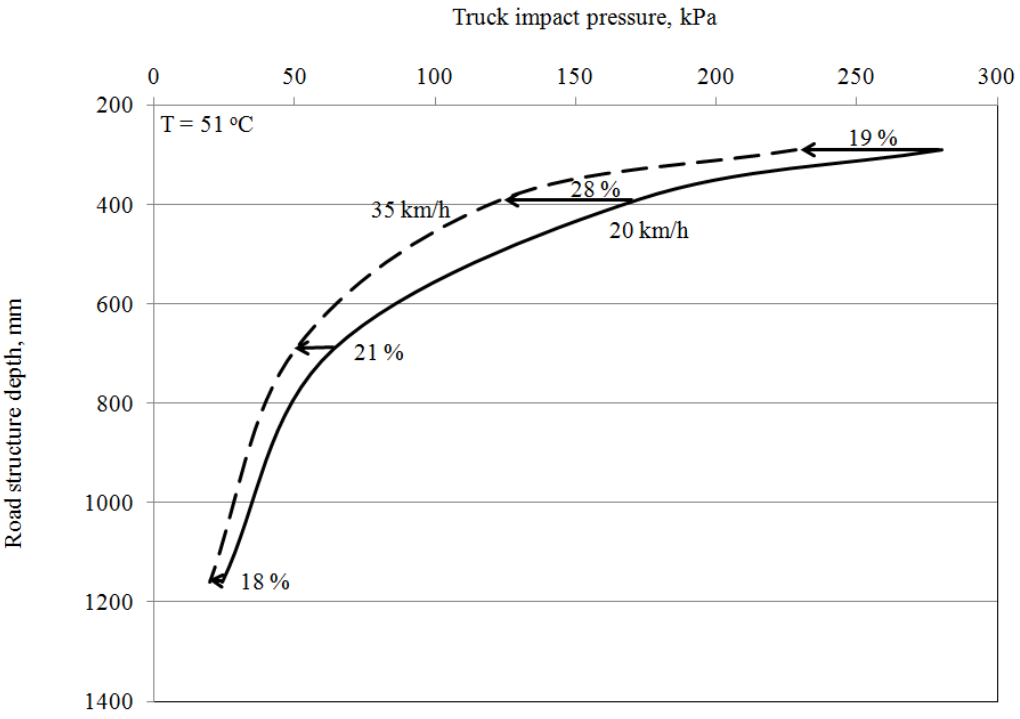

Figure 10: Effect of speed on pressure profile on year 1

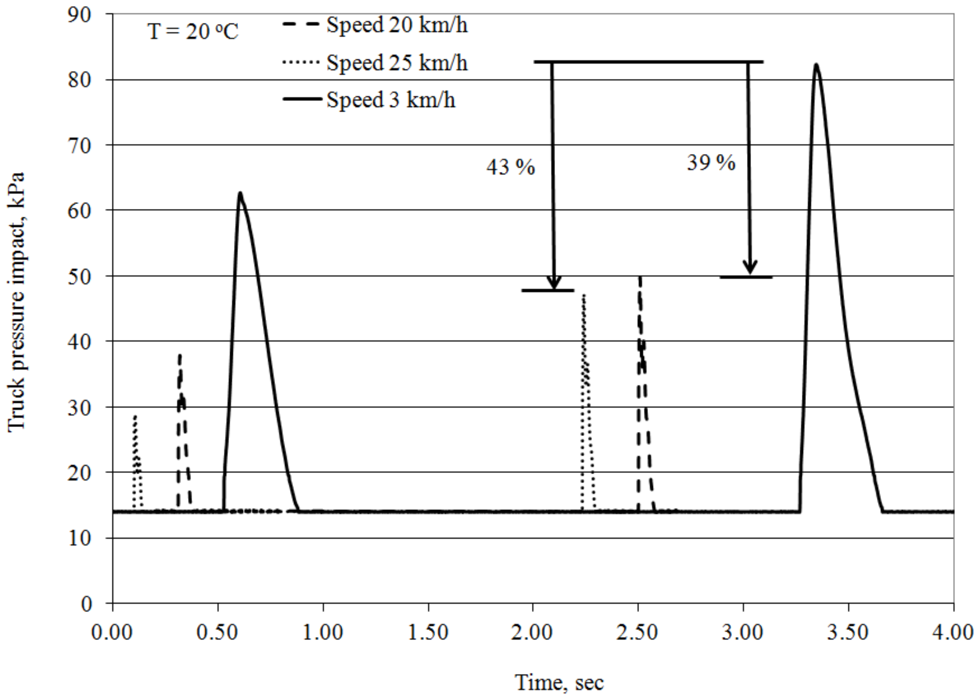

Figure 11: Effect of speed on the top pressure cell at depth 290 mm year 3

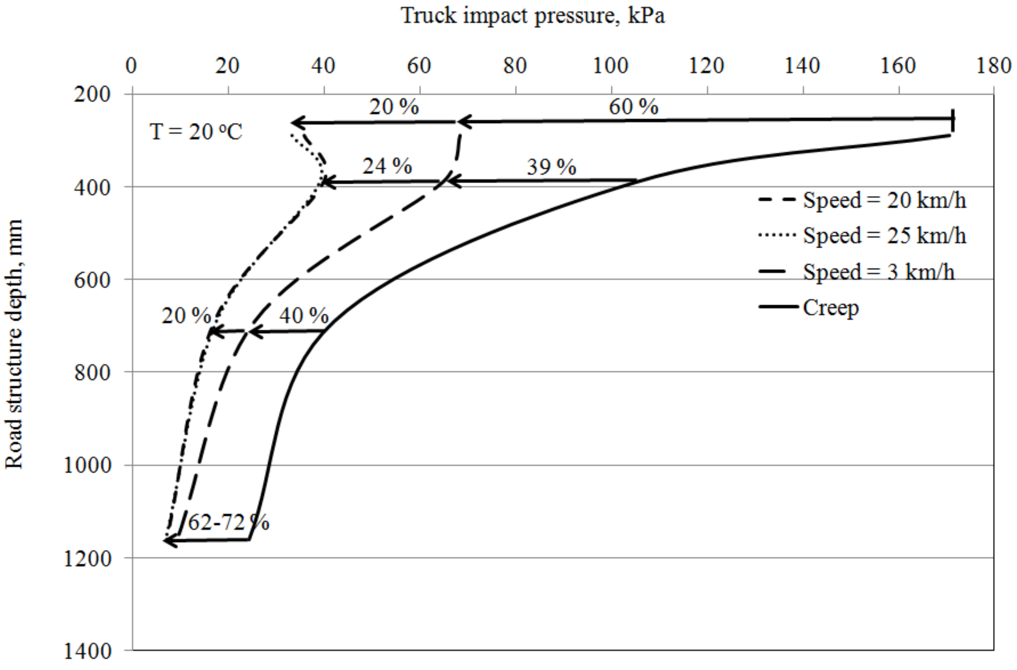

Figure 12: Effect of speed on the truck impact pressure profile year 3

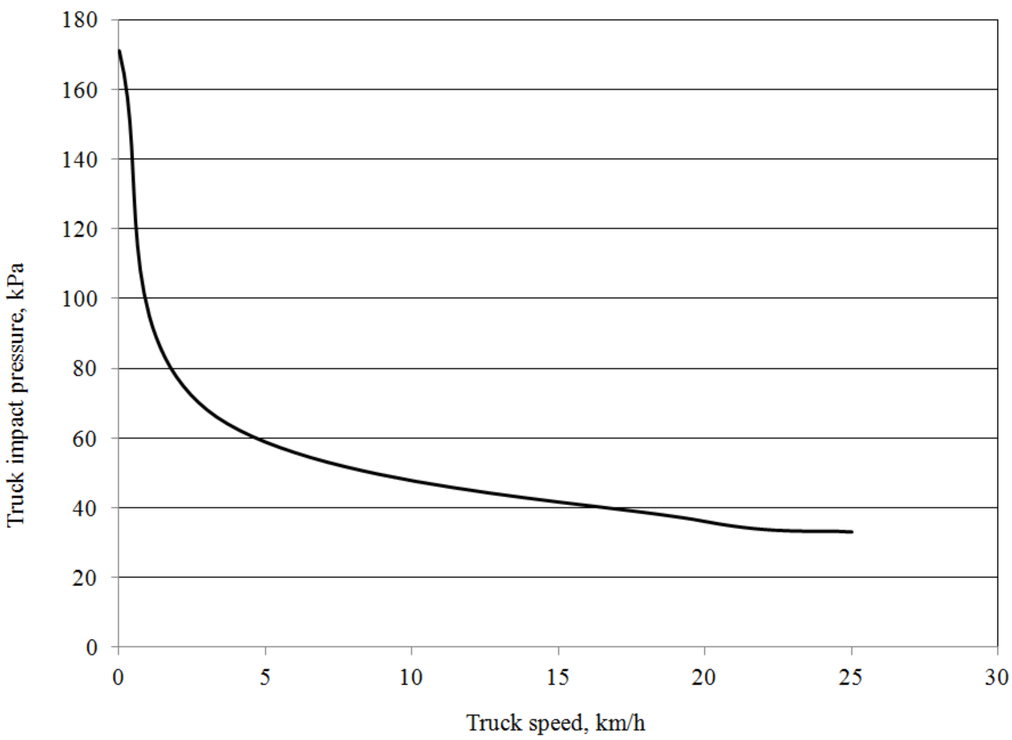

Figure 13: Truck impact pressure and speed profile at depth 290 mm year 3

CONCLUSIONS

Based on the results of the current study, the following conclusions are drawn:

- Traffic-induced stresses transmitted to the backfill layers beneath the asphalt concrete are directly influenced by the asphalt concrete stiffness. High temperatures result in low asphalt concrete stiffness and, hence, higher stresses are transmitted through the asphalt concrete layer to unbound materials in the road structure.
- The accumulation of excessive deformation during the low asphalt concrete stiffness state is associated with high temperature and can be prevented. Traffic-induced stresses transmitted to the backfill layers beneath the asphalt concrete are directly influenced by the asphalt concrete stiffness. High temperatures result in low asphalt concrete stiffness and hence, higher stresses are transmitted through the asphalt concrete layer to unbound materials of the road structure.
- Distresses of asphalt concrete roads such as rutting (bound and unbound materials) is expected to decrease with increasing the speed and it is in good agreement with the finding of the field work as dynamic strain caused by

calibrated truck impact dropped rapidly when the speed increased from 15 to 35 km/h. Similarly, the impact of calibrated truck pressure decreased when the speed increased from 3 to 25 km/h.

- The impact test at calibrated truck speeds of 0 (creep) and 25 km/h resulted in a very high truck pressure impact. This confirmed that most of the pavement performance problems occurred at locations with frequent bus stoppage and areas close to traffic signals. This finding highlighted the importance of traffic speed.
- Two speed effect categories were identified in this study: below and above 35 km/h. The lower category is considered the most critical in terms of the amount of damage that can be caused.

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