Fifth International Conference on Construction in the 21st Century (CITC-V)
“Collaboration and Integration in Engineering, Management and Technology”
May 20-22, 2009, Istanbul, Turkey

Performance Based Lab Tests to Predict Pavement Fatigue

Bernhard Hofko, Ronald Blab
Institute of Transportation, Chair of Road Construction, University of Technology Vienna, Austria
bhofko@istu.tuwien.ac.at, rblab@istu.tuwien.ac.at

Abstract

As roads are subjected to high traffic loads due to the strong growth in heavy vehicle traffic and new trends in the automotive and tyre industries, the traditional asphalt mix tests are often inadequate for a reliable prediction of the in-service performance of flexible road pavements. With the new generation of performance-based test methods (PBT) the complex thermo-rheological properties of bituminous bound materials such as asphalt concrete (AC) can be obtained. On the basis of PBT performance indicators like low-temperature cracking, high-temperature rutting and fatigue at intermediate temperatures are assessed. This paper presents the principle of the so-called 4-point-bending-beam (4-PBB) fatigue test as one PBT to predict pavement fatigue. Furthermore it is shown, how results from this test can be used in combination with computer-based simulations to quantify the effects of different tyre types and wheel configurations on pavement fatigue. In an ongoing research programme extensive 4-PBB-tests are carried out on different AC mixes for base layers at various temperatures and frequencies to obtain Woehler-curves. At the same time, computer-based linear elastic simulations are performed. These simulations are carried out on two different constructions, different tyre types (standard and wide base) and wheel configurations (tyre load and pressure). The strains on the bottom of the bituminous bound layers are taken from the simulations and used in combination with the Woehler-curves to evaluate the life-time in permissible load cycles for different tyre configurations.

Keywords

Performance-based test methods, Pavement fatigue, Numerical simulation, Wheel configuration

1. Introduction

For decades the characterisation of bituminous bound materials was carried out by a simple and easy method, the so called Marshall Mix Design. The method seeks to select the asphalt binder content at a desired density that satisfies minimum stability and range of flow values. Implemented during World War II by the U.S. Army the Marshall method, despite its shortcomings, was not so long ago the most widely used mix design method in the world (White, 1985).

As roads are more and more subjected to high traffic loads due to the strong growth in heavy vehicle traffic, new trends in the automobile and tyre industries, and higher maximum axle loads limits today, the traditional Marshall method is often inadequate for a reliable prediction of the engineering properties and in-service performance of so called flexible road pavements constructed of different hot mix asphalt (HMA) layers. The problem facing designers of flexible road pavements is the need to fully characterise the complex thermo-rheological properties of asphalt on the one hand while on the other hand also providing a realistic simulation of the traffic- and climate-induced stresses to which pavement structures are exposed over their design lives of 20 to 30 years. Since the mid 1990s efforts in pavement research have been focused on the setup and implementation of PBT for bituminous materials on the basis of effective mechanical characteristics. These methods are now implemented in European Standards and used for specifying the mix properties within an advanced type testing procedure required to meet customised quality standards for materials defined in tender documents as well as for mix design. As the new generation of pavement tests lead to mechanical parameters, like stiffness modulus, tensile strength etc., the results can be used for further analysis. One example for this is presented in this paper. In combination with data obtained from measurements with the stress-in-motion (SIM) system Vehicle-Road Surface Pressure Transducer Array (VRSPTA) (De Beer and Kannemeyer, 1998), results from pavement stiffness and fatigue tests are used for a simulation to predict and compare the life-time of different flexible road pavements with various tyre types and wheel configurations.

2. Performance-based Lab Tests

To describe the performance of HMAs entirely three indicators have to be taken into account. It is (1) the low-temperature cracking, (2) the pavement stiffness and fatigue at intermediate temperatures and (3) the permanent deformation at high temperatures (rutting). The 4-PBB-test used for stiffness and fatigue testing is the test method employed for the research presented in this paper and will be illustrated in the following section.

2.1 Pavement Stiffness and Fatigue at Intermediate Temperatures

Fatigue testing, where a repeated stress is applied on a test specimen, has been a major topic in pavement engineering in the last two decades. Presently a European Standard specifies the methods for characterising the fatigue of asphalt mixtures by alternative tests, including bending tests and direct and indirect tensile tests, but without imposing a particular type of testing device. Stiffness and fatigue testing is used to derive basically two material characteristics: the material’s stiffness, expressed by the variation of the complex asphalt modulus $E^*(T)$ as function of temperature and frequency, and the long-term fatigue behaviour, expressed by the number of load repetitions N_{perm}. The initial stiffness modulus $E^*(T)$ of the unloaded material can be determined on the basis of specimen geometry, load impulse and simultaneous measurement of the resulting strains by strain sensors. The stiffness is calculated from the quotient of the applied stress and the resulting strain, which is time-shifted by the corresponding phase angle (φ) as a result of the visco-eastic material behaviour of asphalt (Figure 1).

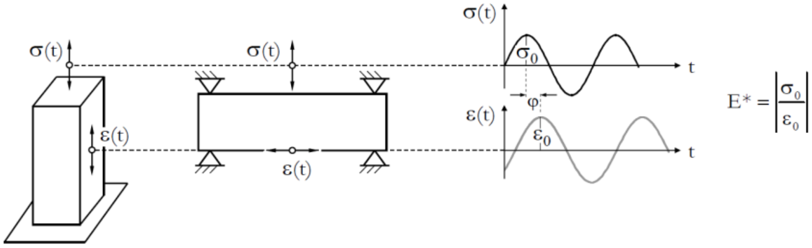

Figure 1: Stiffness modulus (E^*) and phase angle (φ) (Blab and Eberhardsteiner, 2006)

The traditional fatigue criterion of asphalt concrete is linked to the number of load-cycles giving half the initial stiffness. Usually a series of fatigue tests for one material is carried out at different levels of the horizontal strain ε at the bottom of the specimen. The number of permissible load-cycles $N_{perm}(\varepsilon)$ is determined for each of the fatigue tests. When the horizontal strains ε are plotted against N_{perm}, the so called Woehler-curve can be determined. An example is illustrated in Figure 4. The Woehler-curve gives important information for the derivation of fundamental relationships between mix composition and stiffness properties and serves as input for material and structure optimization.

For the 4-PBB a prismatic shaped specimen is used, which is symmetrically clamped on the load frame by two inner and two outer clamps, representing the four points. The specimen is subjected to four-point sinusoidal bending, which is realised by loading the two inner load points (inner clamps), in the vertical direction, perpendicular with regard to the longitudinal axis of the beam. The vertical position of the end-bearings (outer clamps) is fixed, thus provoking a constant moment, and hence, a constant strain between the two inner clamps. The strain applied to the specimen is small and thus keeping the test in the linear domain. (Figure 2).

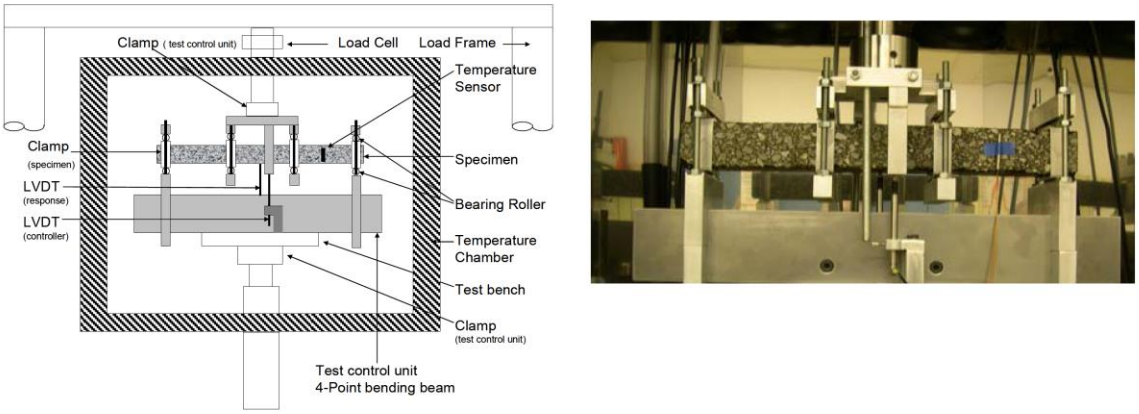

Figure 2: Layout of the 4-PBB equipment (Blab and Eberhardsteiner, 2006)

The following parameters are measured in regard of time: load, needed for the bending of the specimen, deflection and phase lag between these two signals. The complex modulus can be calculated from the stress-strain-relationship. As a result the change of the stiffness modulus over time or rather over the number of load applications is determined at different temperatures, frequencies and strain levels.

3. Life-time Prediction of Pavement Structures – Case Study

One way to benefit from PBT is to use the results together with load data to simulate a flexible road structure, compute the representative stresses and strains and determine the life-time of a pavement structure loaded by a certain tyre type with a given axle load and tyre pressure. Following this principle, the fatigue performance of different pavement structures, as well as the effect of different tyre types and pressures on pavement fatigue may be evaluated. An outline of the approach is given in Figure 3.

3.1 Materials and Tyre-Types

In the particular study two construction types with a layout given in Table 1 are compared. The “LK 3” represents an Austrian load class for roads designed for 0.4m to 1.3m ESAL (equivalent standard axle loads), whereas “LK S” stands for a load class of 10m to 25m ESAL. LK S is the highest load class in Austria used for highways and expressways. The wearing course for both structures is a 30 mm layer of SMA 11 with a 70/100 standard bitumen. This layer is built on a 100 mm AC 22 binder course with a 50/70 bitumen. This binder layer is only used for LK S. The lower bound base course is a 120 mm AC 32 30/50. Below these bituminous bound layers, there is a 200 mm unbound base course and a 300 mm unbound subbase.

To compare the influence of twin-tyre versus super-single configuration on the life-time of pavement structures, one radial tyre and one wide base tyre were chosen. The radial tyre is a 11R22.5 with an overall width of 279 mm (equivalent to 11 inches) and a rim diameter of 572 mm (equivalent to 22.5 inches). The wide base tyre is a 425/65R22.5 with an overall width of 425 mm and the same rim diameter as the radial tyre. Both tyre types are commonly used on commercial trucks.

Table 1: Compared pavement construction types

Construction Type	LK 3	LK S	Stiffness Modulus [MPa]
Wearing Course	30 mm SMA 11 70/100	30 mm SMA 11 70/100	4688
Binder course	---	100 mm AC 22 50/70	5825
Lower bound base course	120 mm AC 32 30/50	120 mm AC 32 30/50	7526
Unbound base course	200 mm	200 mm	2128
Unbound subbase	300 mm	300 mm	1120
Subgrade	1350 mm	1350 mm	560

3.2 Material Tests and Results

Stiffness tests were performed on the SMA 11, the AC 22 and the AC 32 at 20°C and 10 Hz which corresponds to a speed of 60 kph. The tests result in stiffness modulus for each of the materials. These moduli are used as input data for the material stiffness in the simulation. Table 1 shows the results of the stiffness tests. The values for the unbound layers were taken from former studies (Blab and Eberhardsteiner, 2006).

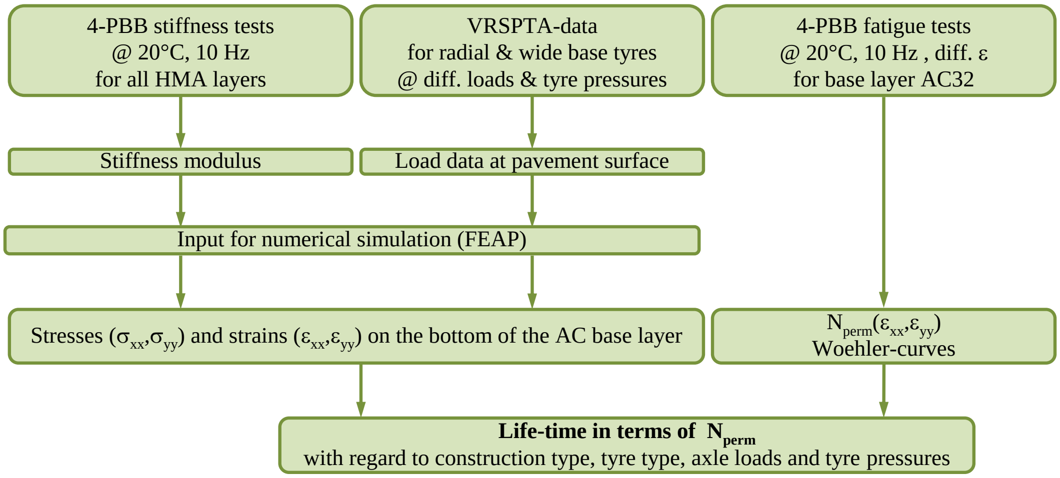

Figure 3: Principle of life-time prediction of pavement structures

4-PBB fatigue tests were carried out on the lower bound base layer AC 32 30/50 as the largest and therefore relevant strains will occur on the bottom of the bound AC layer. 15 single tests with horizontal strains on the bottom of the specimen ranging from 187 to 270 µm/m were performed. For each of the tests the number of permissible load cycles was calculated as the load cycle where half the initial stiffness occurs. The results are shown in Figure 4. The dashed line is a logarithmic regression and represents the Woehler-curve for the AC 32.

To apply realistic loading in the FE simulation, data from a stress-in-motion system called VRSPTA (Vehicle-Road Surface Pressure Transducer Array) was used. This system measures the tyre/road interface stresses under a moving pneumatic wheel load. It simultaneously records the vertical, transverse and longitudinal interface stresses. The VRSPTA consists of an array of calibrated strain-gauged steel pins fixed to a steel base-plate buried in the surface of the road. The strain outputs from these pins are scanned at a high rate while the wheel traverses the pins, giving an indication of the vertical, transverse and longitudinal loads acting on each pin with a screen width of 17 mm. By using this system you get the interaction stresses not of a static wheel but of the wheel load in motion which corresponds to the actual stresses under traffic (De Beer and Kannemeyer, 1998).

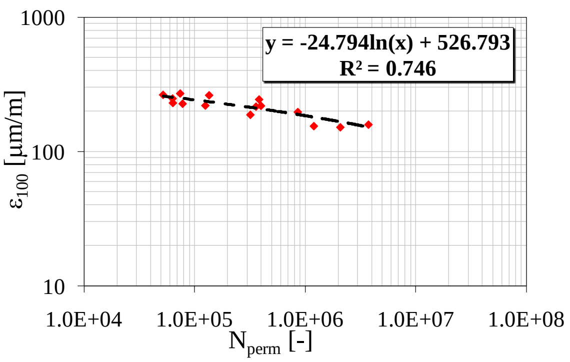

Figure 4: Result of the 4-PBB fatigue tests at AC 32 30/50 and Woehler-curve

For the two tyre types mentioned above there were data for 20 different load cases available, 11 measurements for the normal tyre 11R22.5 with a range for the loading from 25 kN to 54 kN and the pressure from 420 kPa to 820 kPa. 9 measurements were carried out for the super-single 425/65R22.5 ranging from 28 kN to 68 kN with a pressure from 500 to 1000 kPa. The results for such a stress-in-motion analysis are given in the form of coordinates for each of the pins and the force on the pin in Newton. Figure 5 gives an example for a result from a VRSPTA-measurement. On the left hand a super-single tyre at the lowest load level and tyre pressure is given, whereas on the right hand a standard radial tyre at the highest load level and tyre pressure is presented. As depicted in Figure 5 the super-single tyre does not distribute the loading very well, at least at this low load level and tyre pressure. There are concentrated areas of load in the centre of the contact area whereas the outer region shows marginal loading. The radial tyre at a high load level and tyre pressure shows a more balanced distribution. But it seems that the tyre pressure is too high for this load, as the outer regions of the contact area get the highest share of load.

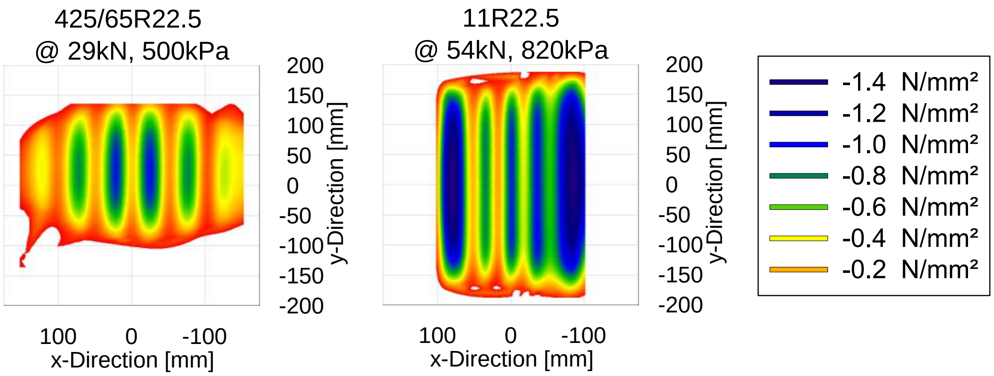

Figure 5: Example of VRSPTA-results for a super-single tyre (left) and a normal tyre (right)

3.3 Numerical Simulations

To actually compare different road structures, tyres, loads and pressures, simulations were carried out in a finite element method (FEM) software named FEAP (A Finite Element Analysis Program) (Taylor 2008). The 3d-mesh was generated especially fine at the contact area of the wheel and around this area in all three dimensions. For example, the wearing course with a z-dimension of 30 mm was divided into 5 layers, whereas the unbound subbase with a thickness of 300 mm was divided into only 2 layers. In x- and y-direction the mesh gets rougher with increasing distance to the area of loading. All in all the total dimensions of the mesh is 12 times the dimension of the contact area of the wheel in x- and y-direction. Boundary conditions are set to zero displacements at the border of the mesh in all three dimensions. The input parameters for the bituminous layers are set according to the results of the stiffness tests described in chapter 2.1. The moduli obtained from these tests were taken as input of the layer modulus. The Poisson’s ratio was assumed to be 0.35 for all materials. The load input was taken from the VRSPTA-measurements for each of the 20 load cases according to chapter 3.2.

The simulations were performed for the two construction types LK 3 and LK S each with the 20 load cases at 20°C and 10 Hz (60 kph). As the radial tyre is only used in twin-tyre configuration, two tyres of this type were situated on the mesh next to each other with a gap of 34 mm between them. The results of FEM-simulations are given in terms of stresses and strains for every element of the mesh. In this case the strains in x- and y-direction (ε_{xx}, ε_{yy}) on the bottom of the bound layers were computed. These strains are commonly held responsible for pavement fatigue at intermediate temperatures in terms of bottom-up cracking at repeated loading.

3.4 Results

Since the simulations performed within this study cover two different construction types, two tyre types and various loads and pressures, a broad field of conclusions can be drawn from the results. To compute the theoretical life-time of a certain pavement structure under a specific loading, the maximum range of strain $\Delta\varepsilon=\varepsilon_{max}-\varepsilon_{min}$ at the bottom of the bituminous bound layers in x- or y-direction of a passing load were extracted from the results of each simulation. This $\Delta\varepsilon$ is the relevant parameter for pavement fatigue, as it occurs at each load-cycle. By using the formula given in Figure 4 and reformulate it the following way

$$N_{perm} = \exp\left(\frac{\Delta\varepsilon - 526.793}{-24.794}\right)$$

the permissible number of load-cycles, i.e. the life-time, can be calculated for each construction type and load case.

3.4.1 Influence of construction type on pavement life-time

Two examples for the comparison of the construction types LK 3 and LK S are given in Figure 6. The results are presented for a section through the mesh at y=0. As stresses are easier to interpret than strains, the results are presented in terms of stress, whereas the life-time in permissible load-cycles is calculated with strains.

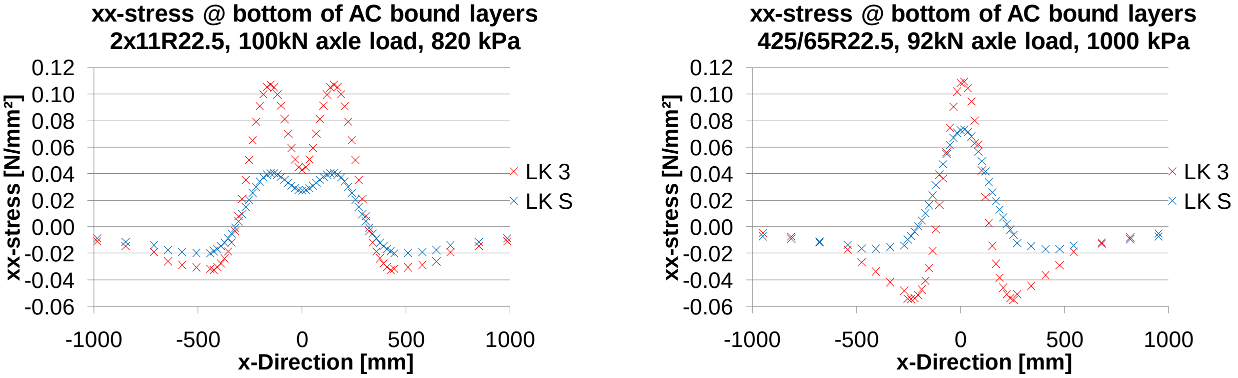

Figure 6: Comparison of xx-stress for LK 3 and LK S for twin-tyre configuration (left) and super-single configuration (right)

On the left hand of Figure 6 a twin-tyre configuration with 100 kN axle load and a tyre pressure of 820 kPa is shown for LK 3 (red) and LK S (blue). Clearly visible are the two tyres on the mesh as two maximums left and right of x=0 occur. The pavement structure at LK 3 is stressed about 2.8 times higher than LK S. The maximum stress in x-direction for LK 3 is 0.11 N/mm², whereas for LK S it is 0.04

N/mm². This fact is also reflected in the calculated life-time. 223m permissible load-cycles for LK 3 compared with 403m for LK S at an axle load of 100 kN.

The right diagram of Figure 6 shows the situation for a super-single tyre with 92 kN axle load and a pressure of 1000 kPa for LK 3 and LK S. Again, LK 3 shows higher stresses than LK S, 0.11 N/mm² compared to 0.07 N/mm². This fact gets even more obvious when looking at the numbers for the permissible load-cycles. LK 3 has a life-time 109m load-cycles, whereas LK S can bear nearly 4-times more load-cycles (396m).

3.4.2 Influence of tyre pressure on pavement life-time

Figure 7 compares different tyre pressures for the twin-tyre configuration (left) and the super-single configuration (right). It is clear, that a lower tyre pressure leads to a large contact area and thus smaller mean contact stresses. The left diagram shows the twin-tyre at an axle load of 184 kN and LK 3. Red represents xx-stresses for a pressure of 420 kPa, blue the situation for 820 kPa. The higher pressure leads to a maximum stress of 0.15 N/mm², whereas the 420 kPa tyre produces only 0.10 N/mm². If you take a look at the calculated life-time for the two tyre pressures, the pictures gets even more considerable. While a pavement structure loaded by twin-tyres with 420 kPa tyre pressure can carry 209m load-cycles, this number decreases to 73m load-cycles if the tyre pressure is raised by 400 kPa to 820 kPa.

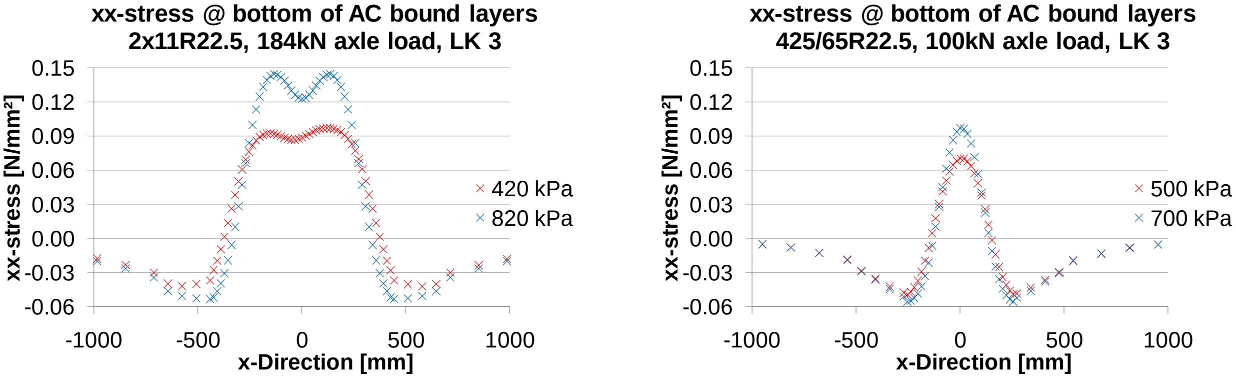

Figure 7: Comparison of xx-stress for different tyre pressures for twin-tyre configuration (left) and super-single configuration (right)

The same problem occurs when comparing the super-single configuration at 100 kN axle load with tyre pressures of 500 and 700 kPa. Maximum xx-stresses of 0.07 N/mm² for the lower tyre pressure compared to 0.10 N/mm² for the higher pressure. In terms of life-time, the 500 kPa tyre can bear 239m load cycles, the 700 kPa tyre only 154m. Both examples, the twin-tyre and super-single show that the tyre pressure has a crucial influence on the life-time of a road construction.

3.4.3 Influence of tyre type on pavement life-time

Another interesting matter is the comparison of tyre configuration at the same load level and tyre pressure. The analysis was carried out for an axle load of 115 kN which is the maximum permissible axle load in the European Union at the present. Figure 8 depicts the analysis for the LK 3 (total AC layer thickness d = 150 mm) on the left hand and LK S (total AC layer thickness d = 250 mm) on the right hand. In all cases, the super-single configuration leads to a higher demand for the road construction and thus a lower life-time. For LK 3 and low tyre pressures of 500 kPa, the twin-tyre shows to a permissible number of load-cycles of 208m versus 190m for the super-single. This means a difference of 18m or 9 %. The higher the tyre pressure gets, the larger the difference between the two tyre configurations is. At 800 kPa the diagram shows a life-time of 128m load-cycles versus 92m. The difference in this case has doubled compared to 500 kPa with 36m or 28%.

A road construction for LK S shows lower effects in respect to the two tyre configurations. Again, the higher the tyre pressure the larger is the difference. At 500 kPa the twin-tyre induces fatigue after 388m load cycles, whereas a super-singe can only pass 381m times. If the pressure of the tyres is increased to 800 kPa, the maximum number of load-cycles falls down to 330m for the twin-tyre versus 285m for the wide base tyre.

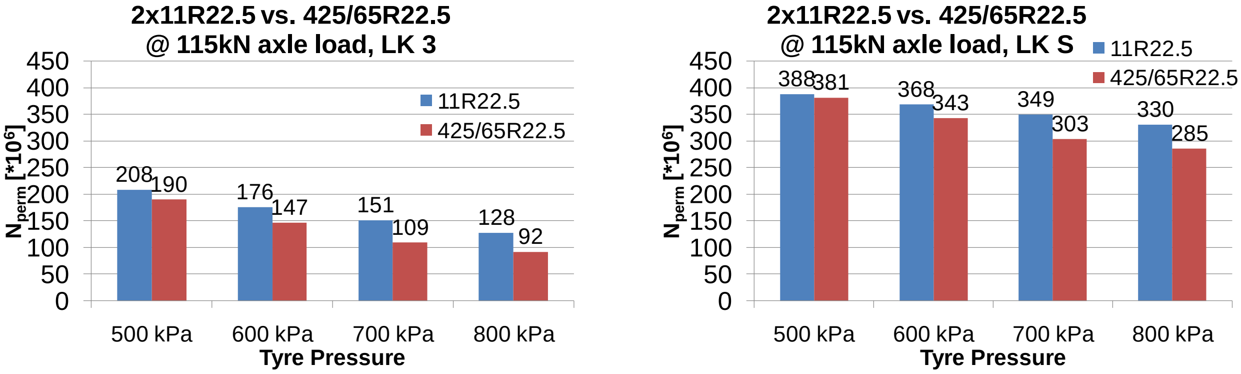

Figure 8: Twin-tyre (blue) vs. super-single (red) configuration at 115 kN axle load and different tyre pressures for LK 3 (left) and LK S (right)

Super-single tyres compared to normal twin-tyres generally mean higher wear for the road construction and thus shorter life-times. The influence of the tyre pressure is higher for super-single tyres. If the pressure is raised from 500 to 800 kPa, the life-time drops from 190m to 92m (-52 %) load cycles for LK 3 and from 381m to 285m (-25 %) for LK S if the truck uses super-single tyres. For the same situation with twin-tyres, the life-time declines from 208m to 128m (-38 %) for LK 3 and from 388m to 330m (-15 %). This also shows that the influence is lower for thicker pavement. High-level roads will not be affected as much from the use of super-single tyres instead of twin-tyres than low-level roads like urban and rural roads.

Besides that the study shows, that the actual problem is the correct tyre pressure because it has an even higher influence on the life-time of a road construction than the tyre type or any other parameter beside axle loads. A twin tyre used with a high pressure (800 kPa, 128m load-cycles) leads to a 33 % lower life-time than a super-single with a considerably lower pressure (500 kPa, 190m load-cycles). This is the case for a low-level road (LK 3). For a high-level road with LK S the difference in permissible load-cycles is still more than 13 %. Just now, when road cargo companies try to raise the tyre pressure of their trucks to a maximum to safe fuel and reduce their costs, not only axle weights but also tyre pressures should be limited and enforced.

4. References

Blab R. and Eberhardsteiner J. (2006). “Methods for the Optimization of Flexible Road Pavements”. *Mitteilungen des Instituts für Straßenbau und Straßenerhaltung*, Vol. 17.

De Beer M. and Kannemeyer L. (1998). “Latest Developments of Tyre/Pavement Surface Interface Stress Measurements – Draft Technical Note”. *TRB 1999 Presentation*, Session 440, Paper P99-3486.

Kennedy, T.W. and Huber, G.A. (1992). “The SHRP Final Products: Performance Based Specifications”. *7th International Conference on Asphalt Pavements, Proceedings*, Vol. 5.

Österreichische Forschungsgesellschaft Straße, Schiene, Verkehr (2008). „RVS 03.08.63 – Oberbau“.

Taylor R.L. (2008). “FEAP – A Finite Element Analysis Program”. *Department of Civil and Environment Engineering, University of California at Berkeley*.

White, T.D. (1985). “Marshall Procedures for Design and Quality Control of Asphalt Mixtures”. *Proceedings, Association of Asphalt Paving Technologists*, Vol. 54.