Construction and Building Materials 89 (2015) 60–66

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Combining performance based lab tests and finite element modeling to predict life-time of bituminous bound pavements

Bernhard Hofko

Vienna University of Technology, Institute of Transportation, Research Center for Road Engineering, Austria

HIGHLIGHTS

- Combining data from stress in motion and 4-PBB tests with finite element simulation.
- Using data of dynamic measurements from actual tires instead of static data.
- Comparing impact of super-single and twin tires on fatigue of European pavements.
- Super-single tires mean higher stresses for pavements and thus shorter life-times.
- The influence of the tire pressure is stronger for super-single tires.

ARTICLE INFO

Article history:
Received 24 October 2014
Received in revised form 10 March 2015
Accepted 22 April 2015

Keywords:
Hot mix asphalt
Four point bending test
Finite element simulation
Wheel configuration
Tire pressure

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 tire industries, the traditional asphalt mix tests are often inadequate for a reliable prediction of the in-service performance of flexible road pavements. With performance-based test methods (PBT) at hand, the thermo-rheological properties of hot mix asphalt can be obtained. This paper presents results of a research project where 4-point bending beam (4-PBB)-tests are carried out on different AC mixes for base layers at various temperatures and frequencies to obtain stiffness and fatigue behavior. At the same time, linear elastic finite element simulations are performed with input data for the materials different from the 4-PBB. These simulations are carried out on two different pavement structures, different tire types (twin-tires and wide base super-single tires) and wheel configurations (tire load and pressure). Loading data for the tires are obtained from stress-in-motion measurements using the Vehicle–Road Surface Pressure Transducer Array (VRSPTA). The strain at the bottom of the bituminous bound layers are taken from the simulations and used in combination with the fatigue functions to evaluate the life-time in permissible load cycles for different tire configurations. The main findings are that super-single tires lead to significantly lower pavement life-times than the standard twin-tire configuration and that the relative difference increases with decreasing thickness of the pavement structure. Also, the tire pressure has a strong impact on the pavement life-time; an increase in tire pressure by 60% decreases the life-time by 25–52% (super-single) and 15–38% (twin-tire) respectively.

1. Introduction

For decades the characterization of bituminous bound materials was carried out by a simple and easy method, the so called Marshall Mix Design [15,23,8]. 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 up to the recent past the most widely used mix design method in the world [25].

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 tire industries, and higher maximum axle loads limits today, the traditional Marshall method developed in the 1930s does not take into account the mentioned developments and is thus often inadequate for a reliable prediction of the engineering properties and in-service performance of bituminous bound pavements. The problem facing designers of flexible road pavements is the need to fully characterize the complex thermo-rheological properties of asphalt mixes 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

---

E-mail address: bernhard.hofko@tuwien.ac.at

http://dx.doi.org/10.1016/j.conbuildmat.2015.04.036

exposed over their design lives. Since the mid 1990s efforts in pavement research have been focused on the setup and implementation of performance based tests (PBT) for bituminous materials on the basis of mechanical characteristics [13,9,16,26,20,3]. These methods are now implemented in European Standards and used for specifying the mix properties within an advanced type testing procedure required to meet customized 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) [4], results from stiffness and fatigue tests are used for a simulation to predict and compare the life-time of different pavement structures with various tire types and wheel configurations [18].

2. Performance-based lab tests

To describe the structural performance of HMAs, three main indicators have to be taken into account: (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 point bending beam test (4-PBB) 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 of asphalt mixes has been a major topic in pavement engineering in the last three decades [14,21,7,19,12,24]. Presently, a European Standard specifies the methods for characterizing the fatigue behavior of asphalt mixes 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 dynamic modulus $|E^*|$ as function of temperature and frequency, and the long-term fatigue behavior, expressed by the number of permissible load repetitions N_{perm}. The initial dynamic modulus $|E^*|_{\mathrm{init}}$ of the undamaged material can be determined on the basis of specimen geometry, load impulse and simultaneous measurement of the resulting strains by displacement sensors. The modulus 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 viscoelastic material behavior of asphalt [5].

The traditional fatigue criterion of asphalt mixes is linked to the number of load-cycles resulting in reduction of modulus to half its initial value. Usually, a series of fatigue tests for one material is carried out at different levels of the horizontal strain levels ε on the bottom of the specimen. The number of permissible load-cycles $N_{\mathrm{perm}}(\varepsilon)$ 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 Fig. 3. The Woehler-curve gives 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 realized 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 resulting in 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 (Fig. 1).

The dynamic modulus can be calculated from the stress–strain-relationship. As a result, the change of the modulus over the number of load cycles 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 pavement structure, compute the representative stresses and strains and determine the life-time of the respective pavement loaded by a certain tire type with a given axle load and tire pressure. Following this principle, the fatigue performance of different pavement structures, as well as the effect of

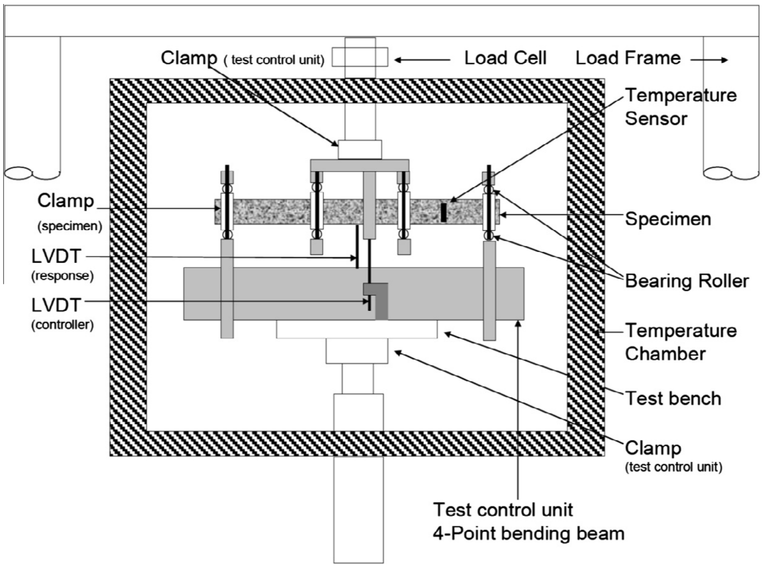

Fig. 1. Layout of the 4-PBB equipment.

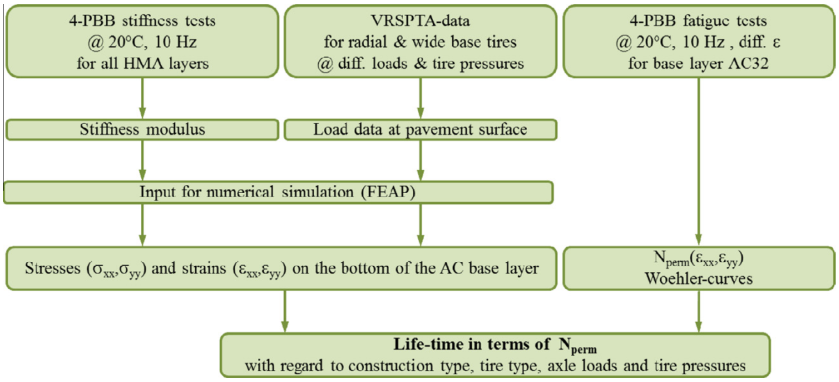

Fig. 2. Principle of life-time prediction of pavement structures.

Table 1
Compared pavement structure types.

Construction type	LK 3	LK S	Modulus [MPa]
Wearing course	30 mm SMA 11 70/100	30 mm SMA 11 70/100	4690[a]
Binder course	–	100 mm AC 22 50/70	5830[a]
Base course	120 mm AC 32 30/50	120 mm AC 32 30/50	7530[a]
Unbound base course	200 mm	200 mm	2130[b]
Unbound subbase	300 mm	300 mm	1120[b]
Subgrade	1350 mm	1350 mm	560[b]

[a] Dynamic modulus $|E^*|$ from 4PBB stiffness tests at 20 °C and 10 Hz.
[b] Deformation modulus E_{v2} according to DIN 18134 [6].

different tire types and pressures on pavement fatigue may be evaluated. An outline of the approach is given in Fig. 2.

3.1. Materials and tire-types

In the particular study two types of pavements structures with a layout given in Table 1 are compared. The "LK 3" represents a load class for roads designed for 0.4–1.3 m Esal (equivalent standard axle loads), whereas "LK S" stands for a load class of 10–25 m Esal. The wearing course for both structures is a 30 mm layer of SMA 11 with a 70/100 (pen-graded) bitumen. This layer is built upon a 100 mm AC 22 binder course with a 50/70 (pen-graded) bitumen. This binder layer is only used for LK S. The base course is a 120 mm AC 32 30/50 (pen-graded) bitumen. 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-tire versus super-single configuration on the life-time of pavement structures, one radial tire and one wide base tire were chosen. The radial tire is a 11R22.5 with an overall width of 279 mm (equivalent to 11 in.) and a rim diameter of 572 mm (equivalent to 22.5 in.). The wide base tire is a 425/65R22.5 with an overall width of 425 mm and the same rim diameter as the radial tire. Both tire types are commonly used on commercial trucks.

3.2. Material tests and results

Stiffness tests were performed on the SMA 11, the AC 22 and the AC 32 using a 4-PBB device at 20 °C and 10 Hz which corresponds to a speed of 60 km/h. The tests result in dynamic 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 [2].

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 layers. 15 single tests with horizontal strains ε_{100} on the bottom of the specimen ranging from 180 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 Fig. 3. The dashed line is a logarithmic regression and represents the Woehler-curve for the AC 32.

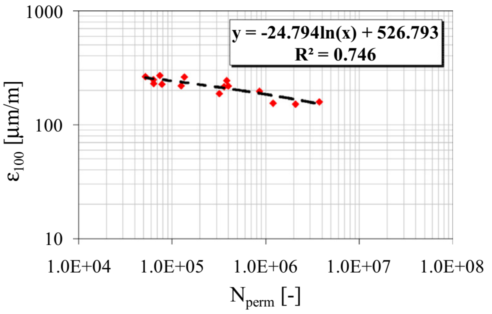

Fig. 3. Result of the 4-PBB fatigue tests at AC 32 30/50 and Woehler-curve.

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 tire/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 employing this system actual interaction stresses under wheels in motion are obtained rather stresses from static wheel measurements [4].

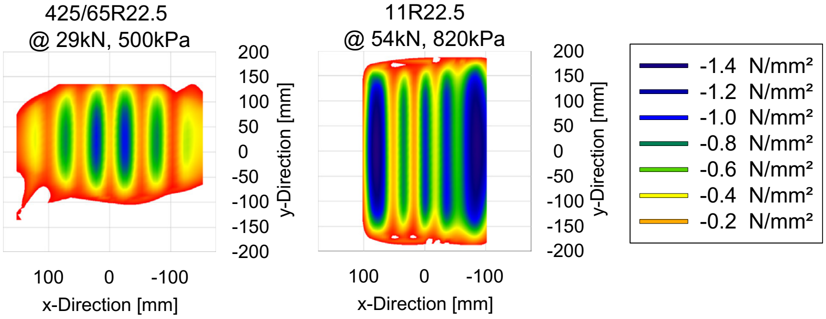

Fig. 4. Example of VRSPTA-results for a super-single tire (left) and a normal tire (right).

For the two tire types mentioned above data for 20 different load cases are available, 11 measurements for the normal tire 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 kPa 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. Fig. 4 gives an example for a result from a VRSPTA-measurement. On the left diagram in Fig. 4 a super-single tire at the lowest load level and tire pressure is given, whereas on the right diagram a standard radial tire at the highest load level and tire pressure is presented. As depicted in Fig. 4 the super-single tire does not distribute the loading very well, at least at this low load level and tire pressure. There are concentrated areas of load in the center of the contact area whereas the outer region shows marginal loading. The radial tire at a high load level and tire pressure shows a more balanced distribution. Still, it seems that the tire pressure is too high for this load, as the outer regions of the contact area get the highest share of load.

3.3. Numerical simulations

To actually compare different road structures, tires, loads and pressures, linear elastic simulations were carried out in a finite element method (FEM) software named FEAP (A Finite Element Analysis Program) [22]. 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. An example of the mesh is given in Fig. 5.

The input parameters for the bituminous layers are set according to the results of the stiffness tests described in Section 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 Section 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 km/h). As the radial tire is only used in twin-tire configuration, two tires 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 [17,10,11,1].

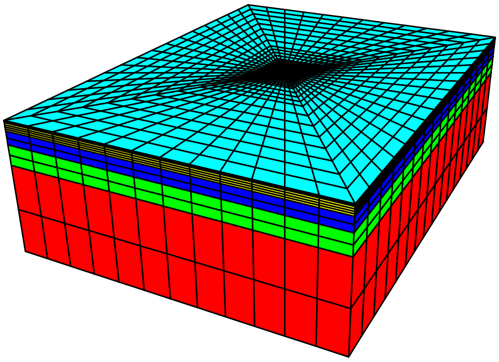

Fig. 5. Example of FE mesh.

3.4. Results

Since the simulations performed within this study cover two different construction types, two tire 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. The x-direction is transversal to the wheel path, the y-direction in direction of the wheel path. The z-direction is perpendicular to the plane created by x- and y-direction. This $\Delta\varepsilon$ is the relevant parameter for pavement fatigue, as it occurs at each load-cycle. By using the formula given in Fig. 3 and reformulating it the following way

$$N_{\text{perm}} = \exp\left(\frac{\Delta\varepsilon - 526.793}{-24.794}\right) \qquad (1)$$

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 Fig. 6. The results are presented for a cross 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.

The left diagram in Fig. 6 shows results of a twin-tire configuration with 100 kN axle load and a tire pressure of 820 kPa for LK 3 (red) and LK S (blue). Clearly visible are the two tires on the mesh

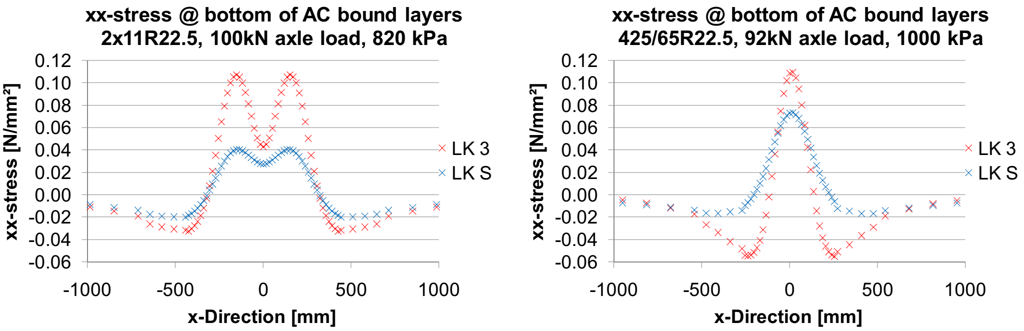

Fig. 6. Comparison of xx-stress for LK 3 and LK S for twin-tire configuration (left) and super-single configuration (right). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

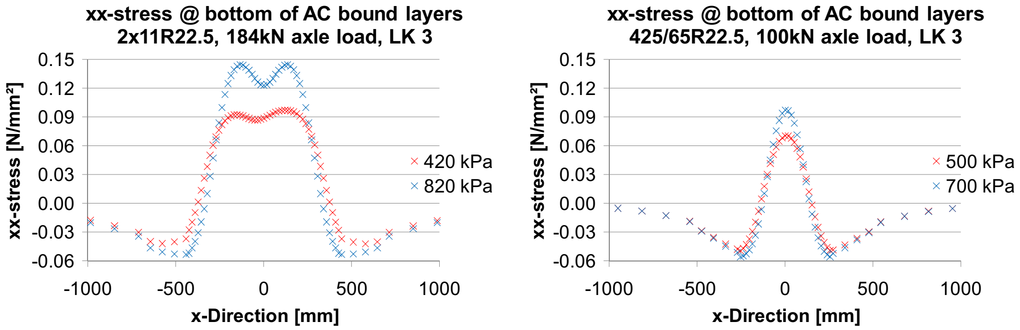

Fig. 7. Comparison of xx-stress for different tire pressures for twin-tire configuration (left) and super-single configuration (right).

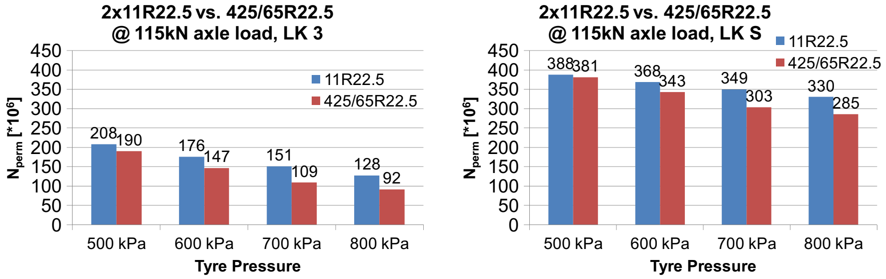

Fig. 8. Twin-tire (blue) vs. super-single (red) configuration at 115 kN axle load and different tire pressures for LK 3 (left) and LK S (right). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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/mm^2, whereas for LK S it is 0.04 N/mm^2. This fact is also reflected in the calculated life-time. 223 m permissible load-cycles for LK 3 compared with 403 m for LK S at an axle load of 100 kN.

The right diagram of Fig. 6 shows the situation for a super-single tire 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/mm^2 compared to 0.07 N/mm^2. This fact gets even more obvious when looking at the numbers for the permissible load-cycles. LK 3 has a life-time 109 m load-cycles, whereas LK S can bear nearly 4-times more load-cycles (396 m).

3.4.2. Influence of tire pressure on pavement life-time

Fig. 7 compares different tire pressures for the twin-tire configuration (left) and the super-single configuration (right). It is clear, that a lower tire pressure leads to a large contact area and thus smaller mean contact stresses. The left diagram shows the twin-tire 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/mm^2, whereas the 420 kPa tire produces only 0.10 N/mm^2.

If the calculated life-time for the two tire pressures is taken into consideration, the pictures gets even more considerable. While a pavement structure loaded by twin-tires with 420 kPa tire pressure can carry 209 m load-cycles, this number decreases to 73 m load-cycles if the tire pressure is raised by 400–820 kPa. This means a 65% reduction in pavement life-time due to doubling the tire pressure. The same problem occurs when comparing the super-single configuration at 100 kN axle load with tire pressures of 500 and 700 kPa. Maximum xx-stresses of 0.07 N/mm^2 for the lower tire pressure compared to 0.10 N/mm^2 for the higher pressure. In terms of life-time, the 500 kPa tire can bear 239 m load cycles, the 700 kPa tire only 154 m. The pavement life-time drops by 36% when the tire pressure is increased by 40%.

3.4.3. Influence of tire type on pavement life-time

Another interesting matter is the comparison of tire configuration at the same load level and tire 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. Fig. 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 tire pressures of 500 kPa, the twin-tire results in a permissible number of load-cycles of 208 m versus 190 m for the super-single. This means a difference of 18 m or 9%. The higher the tire pressure gets, the larger the difference between the two tire configurations is. At 800 kPa the diagram shows a life-time of 128 m load-cycles versus 92 m. The difference in this case has doubled compared to 500 kPa with 36 m or 28%.

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

4. Summary and conclusions

This paper brings together performance based lab testing of asphalt mixes in terms of stiffness and fatigue tests on a 4-PBB device and finite element modeling to predict pavement life-times of different pavement structures, loaded by different tire types (twin-tires and super-single tires) under various axle loads and tire pressures. Two pavement structures are considered: a typical structure for lower volume roads consisting of wearing and base course with a total asphalt mix layer thickness of 150 mm (LK 3) and a structure for high volume roads consisting of wearing, binder and base course with a total thickness of 250 mm (LK S). Stiffness tests were carried out on all three mixes to obtain dynamic modulus as an input parameter for the simulations. Fatigue tests were carried out on the base course to obtain the fatigue function. Loading data for the twin-tire and super-single tire were obtained from stress-in-motion measurements using the Vehicle–Road Surface Pressure Transducer Array (VRSPTA). Maximum strain amplitudes on bottom of the bound layers derived from the simulation were used to calculate the pavement life-time using the fatigue function from 4-PBB fatigue tests of the bituminous bound base course. The following conclusions can be drawn:

- Super-single tires compared to twin-tires generally mean higher stresses for the road construction and thus shorter life-times. The influence of the tire pressure is higher for super-single tires. If the pressure is raised from 500 to 800 kPa, the life-time drops from 190 m to 92 m (−52%) load cycles for LK 3 and from 381 m to 285 m (−25%) for LK S if the truck uses super-single tires. For the same situation with twin-tires, the life-time declines from 208 m to 128 m (−38%) for LK 3 and from 388 m to 330 m (−15%). This also shows that the influence is lower for stronger pavement structures. High-level roads would not be affected as much from the use of super-single tires instead of twin-tires than low-level roads like urban and rural roads.
- The results also indicate that the actual problem is the correct tire pressure since it has an even higher influence on the life-time of a road construction than the tire type or any other parameter beside axle loads. A twin tire used with a high pressure (800 kPa, 128 m load-cycles) leads to a 33% lower life-time than a super-single with a considerably lower pressure (500 kPa, 190 m 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%. Keeping the results in mind, it becomes obvious that not only axle weights but also tire pressures should be limited and enforced to ensure durable road infrastructures for the decades to come. However, an optimum tire pressure have to be found taking into consideration that lower tire pressures generally lead to a higher rolling resistance, and thus higher energy consumption. Also, surface wear tends to be increased by lower tire pressures.

References

[1] Ambassa Z, Allou F, Petit C, Eko RM. Fatigue life prediction of an asphalt pavement subjected to multiple axle loadings with viscoelastic FEM. Constr Build Mater 2013;43:443–52.
[2] Blab R, Eberhardsteiner J. Methods for the optimization of flexible road pavements. Austria: Vienna University of Technology; 2006.
[3] Blab R, Hofko B. Performance based tests to characterize HMA – the European perspective. In: 1st IRF Asia regional congress. Bali, Indonesia; 2014 [November 17–19].
[4] De Beer M, Fisher C, Jooste FJ. Determination of pneumatic tyre/pavement interface contact stresses under moving loads and some effects on pavements with thin asphalt surfacing layers. In: Proceedings of the 8th international conference on asphalt pavements; 1997. p. 10–4.
[5] Di Benedetto H, Partl MN, Francken L, De La Roche Saint Andre C. Stiffness testing for bituminous mixtures. Mater Struct 2001;34:66–70.
[6] DIN. DIN 18134: soil – testing procedures and testing equipment – plate load test. Berlin, Germany; 2012.
[7] Dondi G, Tataranni P, Pettinari M, Sangiorgi C, Simone A, Vignali V. Crumb rubber in cold recycled bituminous mixes: comparison between traditional crumb rubber and cryogenic crumb rubber. Constr Build Mater 2014;68:370–5.
[8] Gul WA, Guler M. Rutting susceptibility of asphalt concrete with recycled concrete aggregate using revised Marshall procedure. Constr Build Mater 2014;55:341–9.
[9] Hertlein BH, Davis AG. Performance-based and condition-based NDT for predicting maintenance needs of concrete highways and airport pavements. Proc SPIE 1996;2945:273–81.
[10] Hu X, Hu S, Walubita LF, Sun L. Investigation of fatigue cracking: bottom-up or top-down. In: Pavement cracking: mechanisms, modeling, detection, testing and case histories; 2008. p. 333–44.
[11] Hu XD, Walubita LF. Modelling tensile strain response in asphalt pavements bottom-up and/or top-down fatigue crack initiation. Road Mater Pavement Des 2009;10:125–54.
[12] Huurman M, Pronk A. A detailed FEM simulation of a 4-point bending test device. Four point bending; 2012. p. 3.
[13] Kulash DJ. Toward performance-based specifications for bitumen and asphalt mixtures. Proc Instit Civ Eng-Trans 1994;105:187–94.
[14] Lee HJ, Lee JH, Park HM. Performance evaluation of high modulus asphalt mixtures for long life asphalt pavements. Constr Build Mater 2007;21:1079–87.
[15] Mampearachchi WK, Fernando PRD. Evaluation of the effect of superpave aggregate gradations on Marshall mix design parameters of wearing course. J Natl Sci Found Sri Lanka 2012;40:183–94.
[16] Monismith CL, Deacon JA, Leahy RB. Asphalt/binder-aggregate mix design and analysis – a performance-based approach. Recent Dev Soil Pavement Mech 1997:367–80.
[17] Mun S, Guddati MN, Kim YR. Fatigue cracking mechanisms in asphalt pavements with viscoelastic continuum damage finite-element program. Pavement Des Accelerated Test 2004;2004:96–106.
[18] Owende PM, Hartman AM, Ward SM, Gilchrist MD, O'Mahony MJ. Minimizing distress on flexible pavements using variable tire pressure. J Trans Eng 2001;127:254–62.
[19] Poulikakos LD, Pittet M, Dumont A-G, Partl MN. Comparison of the two point bending and four point bending test methods for aged asphalt concrete field samples. Mater Struct 2015:1–13.
[20] Shen J, Arnirkhanian S, Tang B. Effects of rejuvenator on performance-based properties of rejuvenated asphalt binder and mixtures. Constr Build Mater 2007;21:958–64.
[21] Shu X, Huang BS, Vukosavljevic D. Laboratory evaluation of fatigue characteristics of recycled asphalt mixture. Constr Build Mater 2008;22:1323–30.
[22] Taylor RL. FEAP – a finite element analysis program. Berkeley: University of California; 2013.
[23] van Thanh D, Cheng PF. Study on Marshall and Rutting test of SMA at abnormally high temperature. Constr Build Mater 2013;47:1337–41.

[24] Weise C, Werkmeister S, Oeser M, Sydney U. Determination of the fatigue behaviour of asphalt base mixes using the indirect tensile and the 4 point bending test. In: 2nd Workshop on 4PB, 24–25th September 2009. Guimaraes, Portugal: University of Minho; 2009.

[25] White TD. Marshall procedures for design and quality control of asphalt mixtures. In: Association of asphalt paving technologists proc; 1985.

[26] Williams RC, Hill DW, Rottermond MP. Utilization of an asphalt pavement analyzer for hot mix asphalt laboratory mix design. Performance tests for hot mix asphalt (HMA) including fundamental and empirical procedures. J ASTM Inter 2005;2(4). http://dx.doi.org/10.1520/JAI12268.