Maintenance and Rehabilitation

Using pavement heat transfer systems for optimized pavement rehabilitation

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Abstract

Heat transfer systems in asphalt roads are able to collect solar induced heat energy. The energy can directly be used or stored in thermal probes. In combination with temperature sensors, a heat pump and the analyses of fatigue and plastic deformation behavior the possibility to optimize rehabilitation measures arises. Within the project a comparison between a typical Spanish and a typical German asphalt wearing course was conducted. Based on the concept of dissipated energy the fatigue behavior of the Spanish BBTM 11 B with 45/80-60 B and the German SMA 8 S with 25/55-55 A and 50/70 were evaluated. The tests were done at different testing temperatures and frequencies. For this, the Spanish UGR-FACT method was transferred and adapted to German standard testing conditions. The analyses was done using different damage criterions, with the ROWE-approach allowing for the determination of the macro crack initiation and the approach of MORENO NAVARRO additionally for the plastic deformation properties. It could clearly be shown, that next to the well known influence parameters as type of binder and type of mix also the testing temperature has a significant influence, which questions the German design method where the prognosis of the fatigue behavior is based on tests with only one temperature. The testing frequency itself did not provide any differentiation possibilities. The results allow for theoretical calculations to quantify the possible influence of road heating and cooling systems on the pavement life time.

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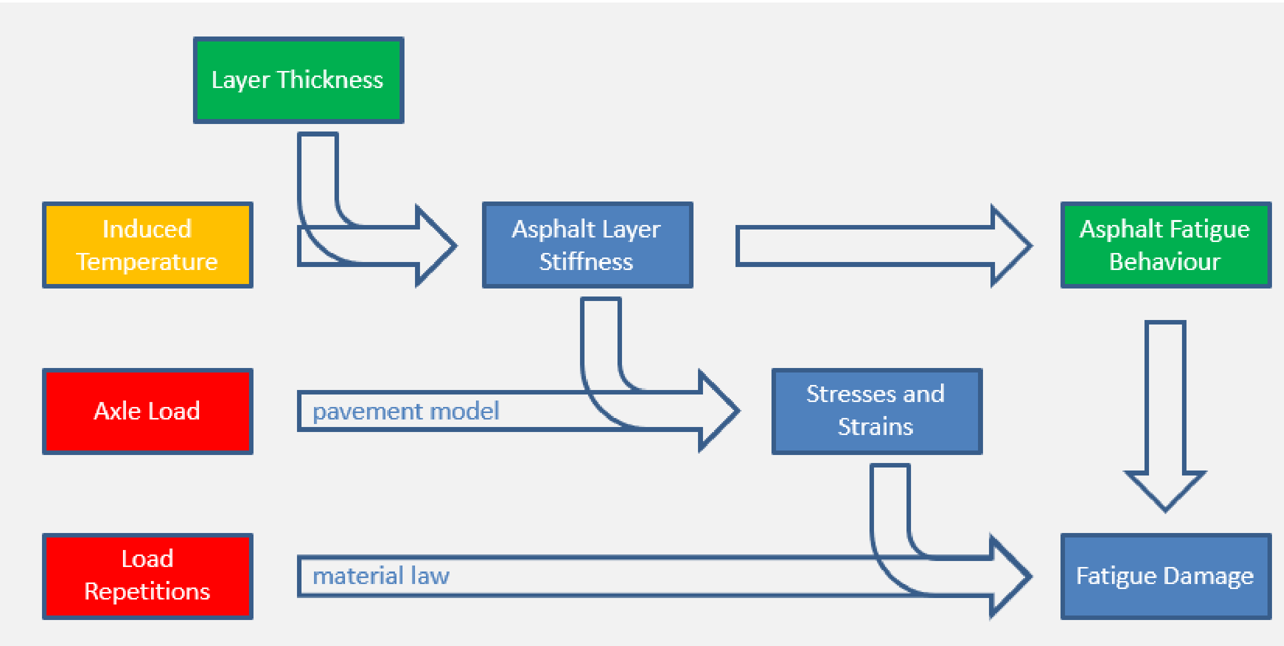
1. INTRODUCTION

Pavement heating systems based on pipes being incorporated into asphalt pavements have been used for some decades. Main applications are often ramps for car traffic in buildings (e.g. parking lots). Normally these systems are connected to an external heating generator which warms the liquid circulating through the pipes. Technically and energetically optimized and adapted, these systems can also be used to collect the heat energy which builds up in the road pavement due to solar energy [1]. This heat energy can subsequently be stored in deep soil probes in order to be retrieved and re-used within the same system to remove ice and snow from the road surface. Another possible use for the heat energy generated by the road could be warm swimming pools or to be transferred to another temperature level by a heat pump and then to heat buildings or other facilities. If the heat energy induced into the road pavement by solar energy is transferred to the liquid flowing in the pipe system and then exchanged for further use, it automatically leads to a cooling of the pavement itself, as the heat energy is extracted from the pavement. So, the use of pavement heating systems leads to divergent temperature gradients due to solar exposure.
Temperature has a significant influence on a lot of asphalt pavement parameters like stiffness, plastic deformation and fatigue behavior. These material parameters can generally well be assessed by the use of dynamic asphalt testing, and at least for stiffness and plastic deformation this is often done in European countries for modern pavement design methods; some countries take temperature influences into consideration when assessing fatigue behavior, some do not. Pavement design methods normally make use of layer stiffness to be used in calculation models to obtain stresses and strains at specific points in the pavement system. These values are then inserted into material laws based on fatigue testing to optimize the pavement service life (allowable repetitions of loads). A direct connection to plastic deformation is often difficult to realize as these linear models can only give a rough estimation of the real behavior. Modern analyzing tools [2] now give more insight into these interactions.
The road pavement consists of different layers (bound and unbound). The individual thickness form the pavement structure. Weather conditions (e.g. irradiation, air temperature) can induce heat energy into pavement structures. It initially affects the surface temperature and is subsequently transferred to the lower layers depending on physical characteristics (thicknesses, conductivity, overall temperature state). Also asphalt fatigue behavior depends on induced heat energy. By inputting layer thicknesses, layer stiffnesses and the loading conditions into pavement models, one can derive stresses and strains anywhere in the pavement structure. With the knowledge about asphalt fatigue behavior, stresses and strains in the pavement and the expected load repetitions one can predict the occurrence of fatigue damage. To optimize pavement structures within the design phase, normally thicknesses are adjusted. Traffic characteristics like axles load distributions and load repetitions depend on multiple reasons which normally cannot be influenced by the road pavement designer. Improving asphalt fatigue behavior (e.g. by using modified binders or optimized volumetric asphalt design) surely can minimize fatigue damage. This paper deals with the question, if the transfer of heat energy from the road to other places can positively influence fatigue life. To answer it, detailed input data like complex load and temperature distributions have to be taken into account (cf. Figure 1).

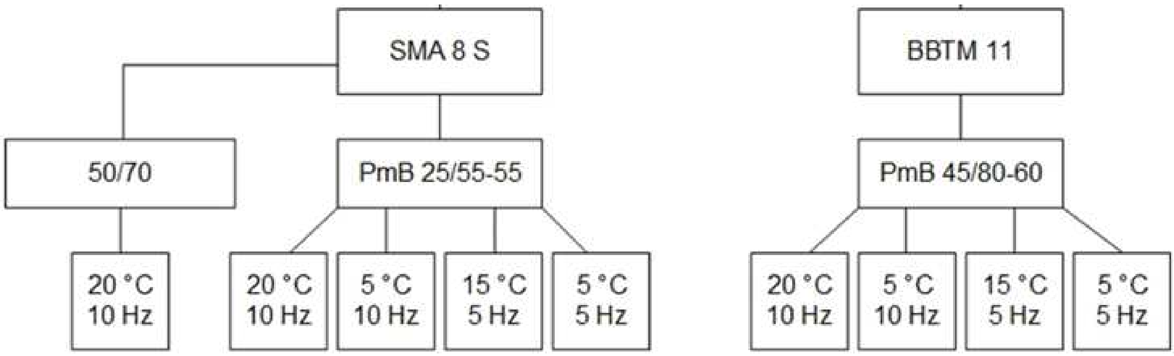
Figure 1: general relations in pavement design [9]



2. MATERIAL TESTING

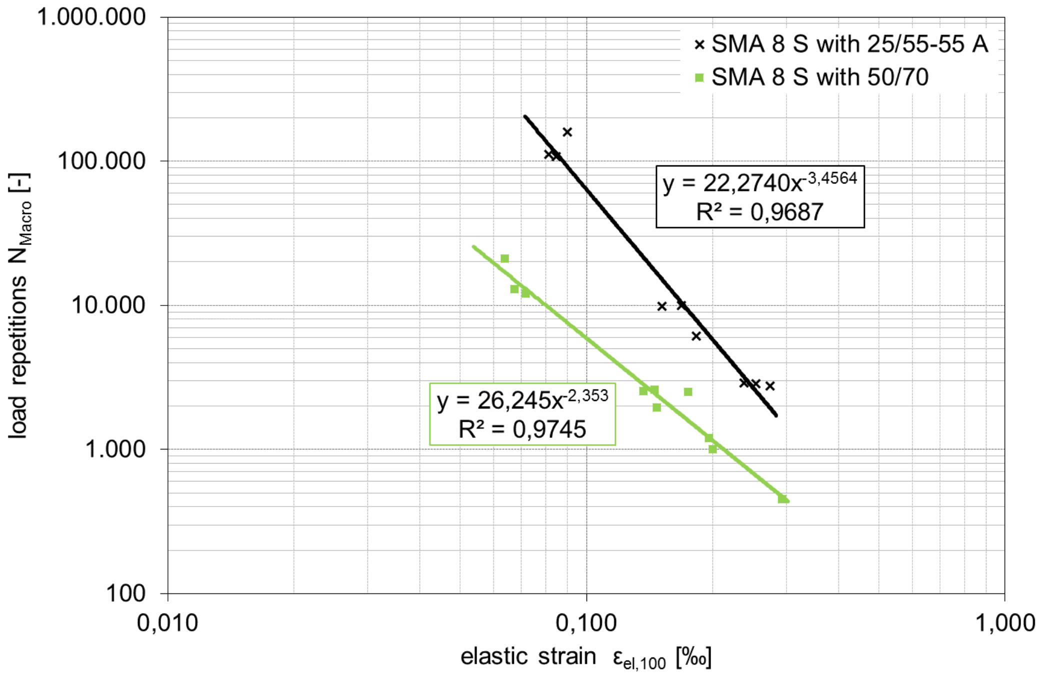
To analyze the temperature depending material parameters of typical asphalt pavement wearing course materials used for high trafficked roads in Spain and Germany a joint study was performed in the context of a master thesis at the Ruhr-University Bochum in cooperation with University of Granada, EUROVIA Spain and EUROVIA Germany [3]. A BBTM 11 with a polymer modified bitumen 45/80-60 according to Spanish regulations and an SMA 8 S with a polymer modified bitumen 25/55-55 A as well as a penetration grade bitumen 50/70 according to German regulations have been tested with dynamic indirect tensile testing at different parameters according to Figure 2.

Figure 2: Tests performed in the study [3]



The influence of the specific binder type or modification on fatigue behavior is widely known and has been confirmed within this study. Although the calculated stiffness of 4.026 MPa for the SMA with a penetration grade bitumen and 3.904 MPa for the same type of mixture with a polymer modified binder are on the same level, the fatigue resistance is varying significantly (see Figure 3). The polymer modified binder generates a huge advantage in terms of allowable load cycles until failure over the whole practical range of elastic strains, which normally occur on a standard road. On the other hand, the damage progression of the mix with the polymer modified binder has an exponent of -3,45 compared to -2,35 for the unmodified binder, and thus is much more depending on the height of the load.

Figure 3: Comparison of fatigue behavior of SMA 8 S with unmodified and modified bitumen [3]



The testing frequency was found to have a minor influence on the fatigue behavior within the tested range. As well as for the SMA with PmB as for the BBTM the relationships for fatigue are not significantly differing from each other at 5 °C for 5 Hz and 10 Hz (see Figure 4 and Figure 5). As for low temperatures asphalt material is often dominated by elastic behavior, this outcome may appear logical. And although in this evaluation due to other constraints, the relation could not be verified for other temperature conditions, it is known from literature that this can also be found at 20 °C [8].

Figure 4: Comparison of fatigue behavior of SMA 8 S at different frequencies [3]

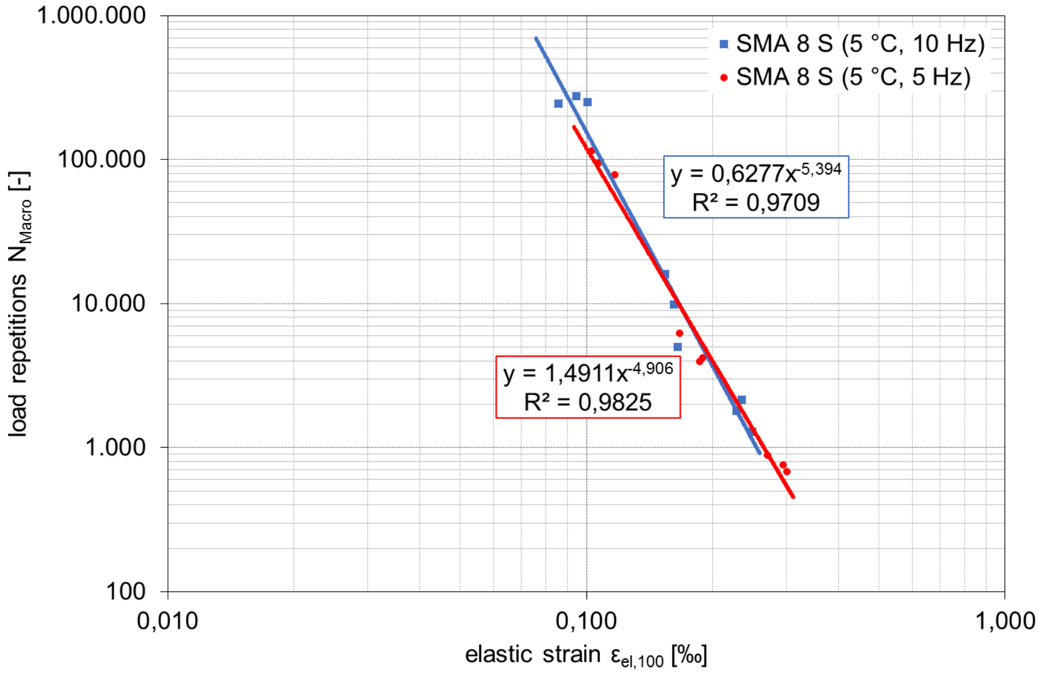


Figure 5: Comparison of fatigue behavior of BBTM 11 at different frequencies [3]

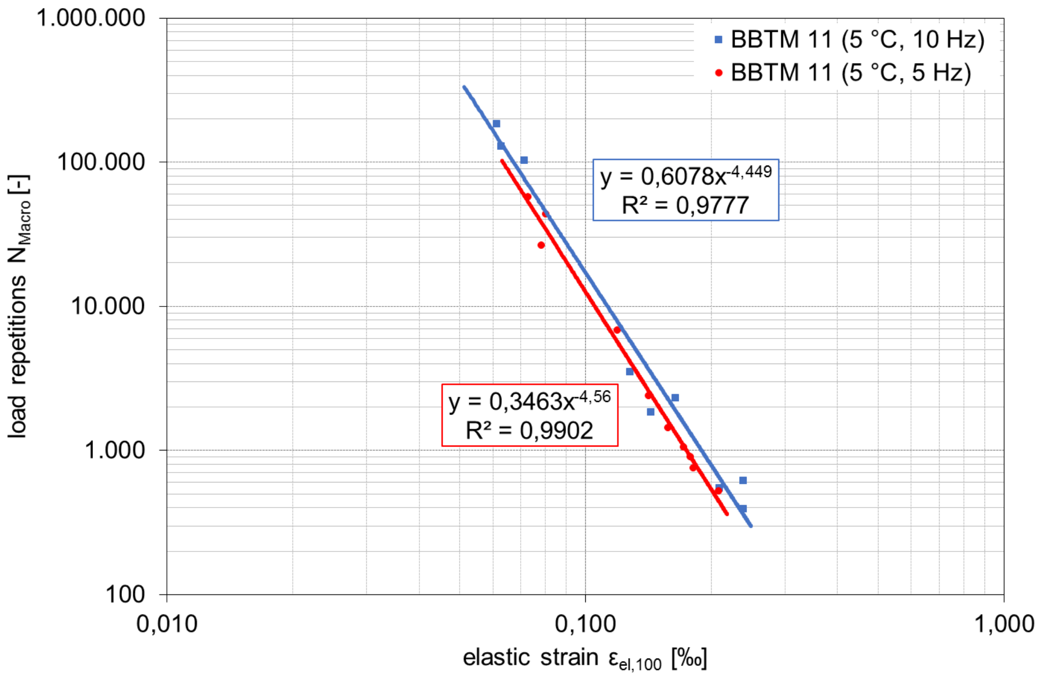
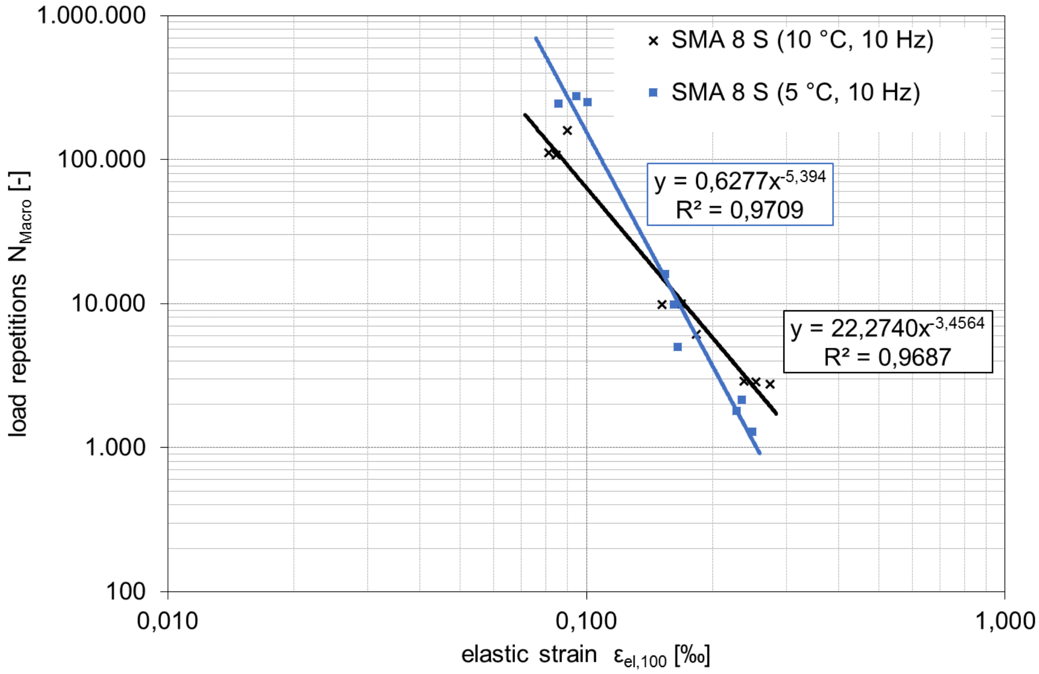


Figure 6 shows the results for the SMA at different testing temperatures. Although the total load repetitions at standard loads do not differ too much, the load dependency is significantly higher, which shows that the temperature-frequency-equivalence often seen with stiffness of asphalt mixes cannot always be found in fatigue testing, too. This may be due to healing effects, which will be more relevant at elevated temperatures or to the fact, that maintaining higher testing temperatures can be seen as constantly inducing energy to the system which significantly affects material behavior.

Figure 6: Comparison of fatigue behavior of SMA 8 S at different temperatures [3]



3. INFLUENCE ON ANALYTICAL DESIGN

Within bearing capacity design of road pavements, the expected load repetitions are usually related to those determined by tests. In general, the rule of Miner applies, which states that the micro damage fractions resulting from different loads and pavement conditions (stiffness due to temperature and moisture) can each be combined according to the Miner law. It is agreed on that failure of the pavement occurs, if the sum of the damage fractions according to this rule reaches the value of 100 % (see Equation 1). The allowable load repetitions N_{all} for each of these individual states is usually obtained from fatigue tests, which may well be performed differently in the different countries of Europe. As can be seen from the equation, during the summation, both, the different loads to be expected on the respective pavement, and the stresses and strains resulting from changing temperature conditions must be taken into account. Here, especially the temperature-dependent stiffness of the asphalt has to be considered. The two characteristic values axle load and temperature are subject to statistical distributions, which vary greatly across Europe. The knowledge of these distributions makes it possible to calculate for each selected pavement at a defined location for each of the combinations of axle load and temperature occurring there, how large the proportion of the damage to be calculated according to the Miner rule is. The summation of all Miner fractions for all occurring axle load and temperature conditions results in the damage state expressed as a percentage for this pavement (see Equation 2).

Equation 1: Miner Law

$$\sum \frac{N_{exp,AL,T}}{N_{all,AL,T}} \leq 1$$

with

$N_{exp, AL,T}$ expected load repetitions for a specific axle load and temperature condition [-]

$N_{all,AL,T}$ allowable load repetitions for a specific axle load and temperature condition [-]

Equation 2: Miner Law detailled for temperature and load conditions

$$S_{Miner} = \sum_{AL} \sum_{T} \frac{p_{AL,T} \cdot N_{exp}}{N_{all,AL,T}}$$

with

AL axle load conditions

T temperature conditions

$p_{AL,T}$ probability for the occurrence of a specific axle load and temperature condition [%]

N_{exp} total expected load repetitions [-]

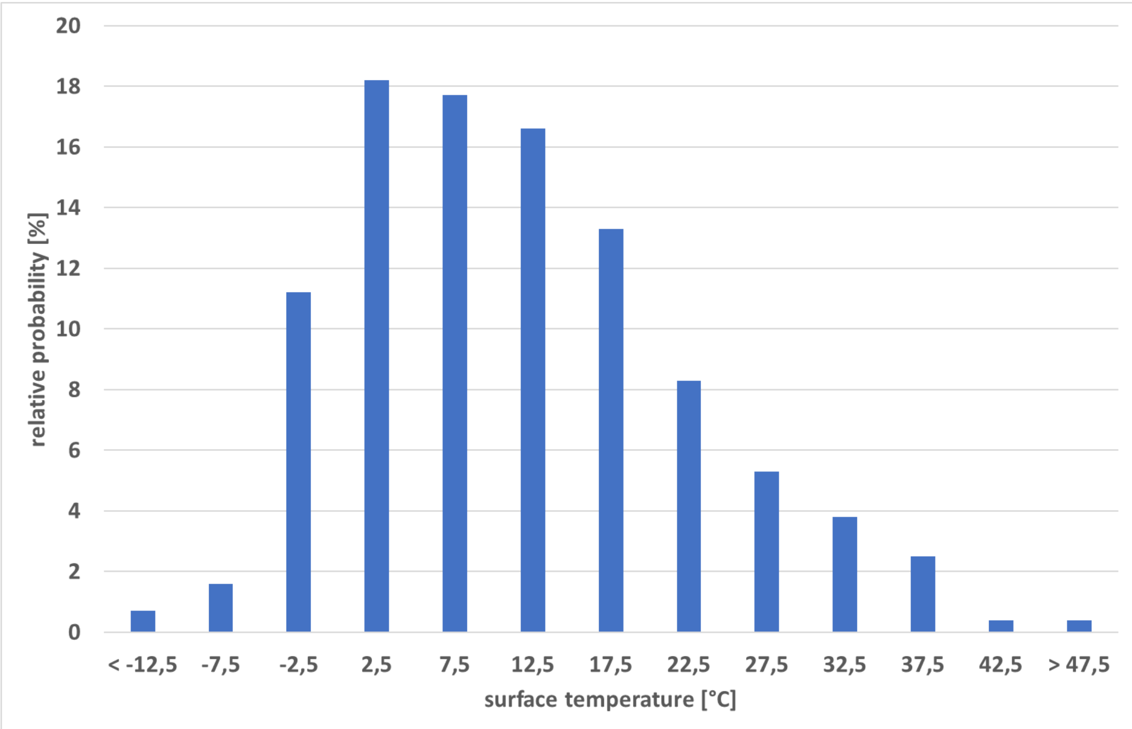
$N_{all,AL,T}$ allowable load repetitions for a specific axle load and temperature condition [-]

To be able to do such a consideration, the knowledge of extensive and detailed data is necessary, which is often not directly available in a suitable form. While climate data is usually easy to obtain, the identification of relevant axle load collectives requires the provision of complex axle load scales and a complex statistical evaluation. For Germany, such considerations have been made in the preparation of the first regulation for analytical design [4]. Depending on the geographical location and the road function, it contains very detailed values for the probability of the occurrence of both, axle load and surface temperature conditions. Table 1 shows the example of the axle load distribution on highways with predominantly long distance traffic and in Figure 7 the distribution of surface temperatures in class 4 (e.g Düsseldorf). From these distributions, the individual occurrence probabilities of the combined states of axle load and temperature can easily be calculated (see Equation 3).

Table 1: axle load distribution (probability of each axle load class) [4]

	Axle load class (static axel load) [t]										
	0 - 2	2 - 4	4 - 6	6 - 8	8 - 10	10 – 12	12 - 14	14 - 16	16 – 18	18 – 20	> 20
Highway with long distance traffic	2,8396 %	21,4670 %	26,4848 %	30,7195 %	11,7032 %	4,9098 %	1,6540 %	0,2087 %	0,0126 %	0,0007 %	0,0001 %

Figure 7: surface temperature probability for class 4 [4]



Equation 3: combination of distributions for axle load and temperature conditions

$$p_{Al,T} = p_{Al} \cdot p_T$$

Since this data was not available for Spain, it was attempted to make an approximation. Initially, it was assumed that the axle load distributions were also correct for at least some part of the Spanish road road network, so that they did not have to be changed. With regard to the occurring surface temperatures and their seasonal distribution, an attempt was made to make a reasonable estimate. For this purpose, the climate data for Madrid [5] and Düsseldorf [6] were compared with regard to the maximum and minimum monthly temperatures as well as the sunshine times. They are shown inFigure 8. Madrid only has a 3.5 ° C higher average temperature over the year; however, in summer times the monthly difference rises to as high as 5.5 ° C in August, while in April it drops to 2 ° C. In this respect, the form of the real distribution will differ from the German one. However, since this cannot be reasonably adapted without further data, the temperatures of the distribution are raised uniformly by 3.5 ° C, while the probabilities for the occurrence of the respective temperature plus the addition of 3.5 ° C are left unchanged. A graphical display of the given examples for the defined probabilities is shown in Figure 9 for Germany exemplarily. It can be seen that the axle load distribution is clearly concentrated, which of course is primarily due to the controllability of this value. The temperature distribution, on the other hand, is obviously much more uneven; significant frequencies occur in a range of about 40 °C.

Figure 8: Monthly mean temperatures for Madrid and Düsseldorf [5], [6]

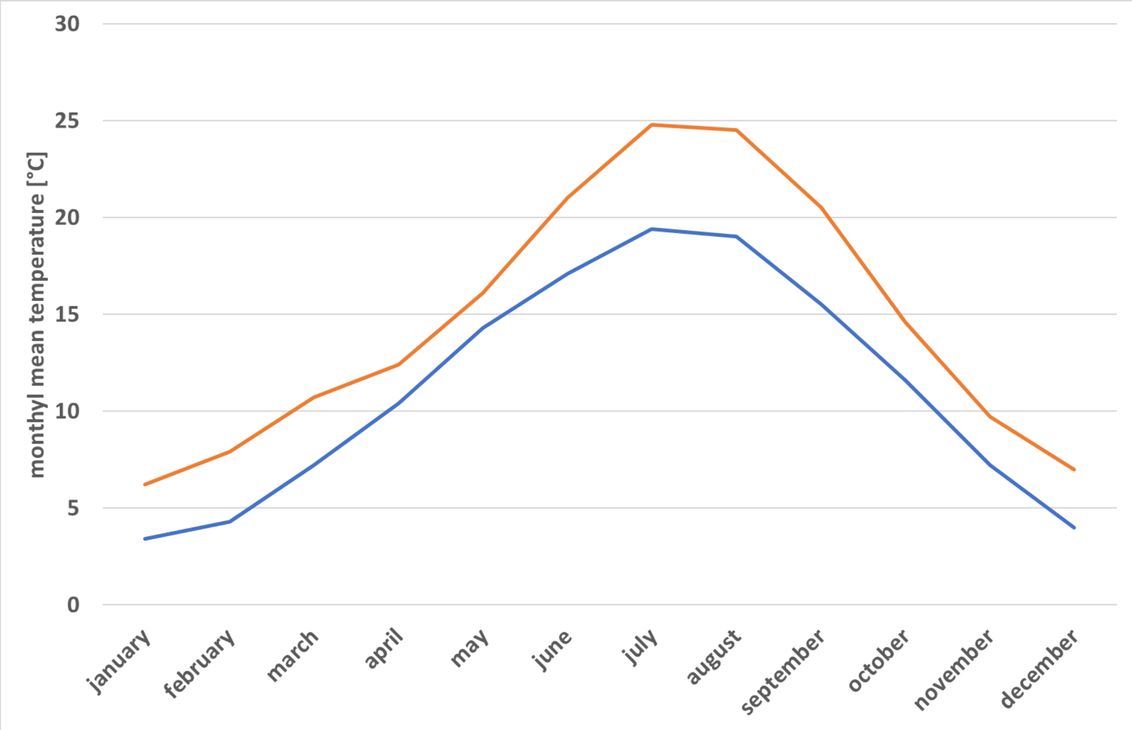
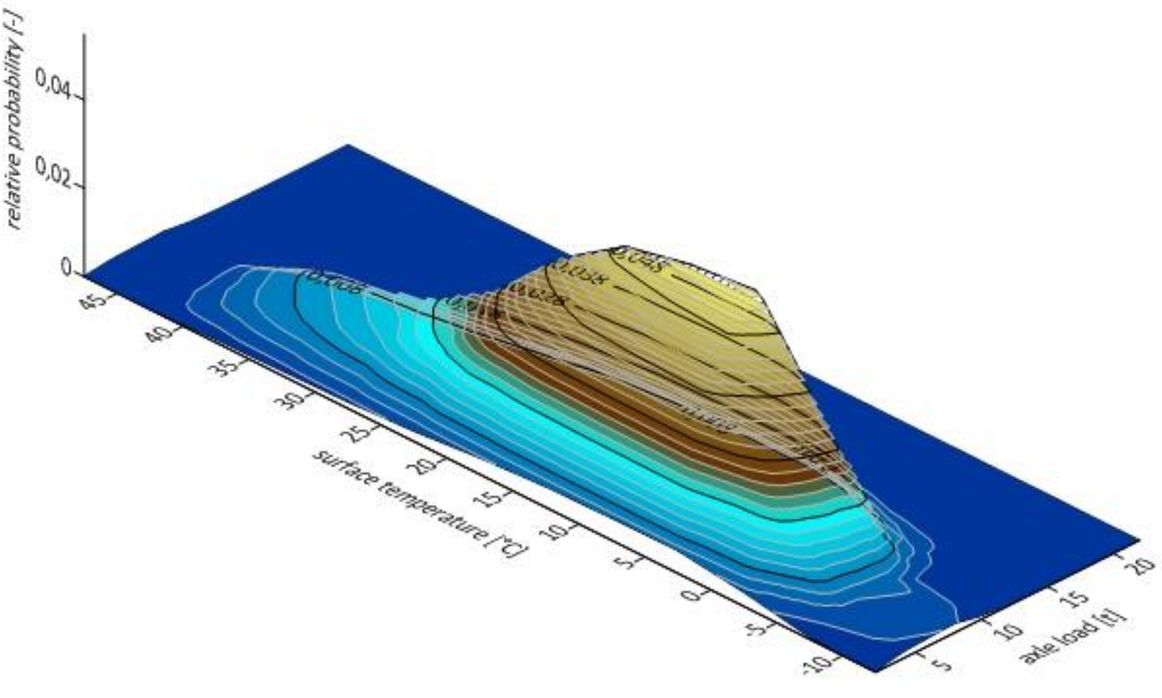


Figure 9: Combined probabilities of axle load and surface temperature for Germany (climatic zone 4)



To get the allowable load repetitions for each combination of axle load and temperature, several fatigue tests have to be performed. Conventional fatigue tests cover the whole range of strains that occur in road pavements. The functions obtained are generally well described by regression with power functions, so that the entire axle load range can be considered. With increasing number of load cycles the allowable load repetitions get lower at constant circumstances.

Deviating from this, however, fatigue tests are often carried out only in a very narrow temperature range; in Germany, the standard testing temperature is 20 °C. However, various studies have shown that the fatigue behavior changes with changing temperatures (see [3]). Higher temperatures can clearly be compared with a continuous energy input, which usually improves the fatigue behavior in a medium temperature range up to approx. 20 °C. At the same time, as the temperatures continue to increase, the plastic deformation of the asphalt increases, so that the actual fatigue damage, which manifests itself in the form of cracking, increasingly turns into deformation damage (see [2], [7]). Within conventional laboratory testing and analysis both types of damage are hardly separable from each. In summary, on a temperature scale, from low to high, there are initially increasing numbers of allowable load repetitions, as the increasing temperature has a positive effect. However, at a point on the temperature scale to be determined in experiments, this behavior is reversed due to the increasing plastic deformation, so that the allowable load repetitions decrease again. Thus, the fatigue on the temperature scale results in an optimum temperature to be determined from tests, in which a defined axle load contributes the least contribution to the damage accumulation according to Miner.
In the context of the thesis [3], due to limited time and laboratory capacities, only a narrow temperature range could be addressed by testing. The fatigue relationships were described by using a power law regression according to Equation 4. The regression parameters a and b were derived as stated in Table 2. As stated above, the testing frequency has a minor effect on fatigue relationships, which is also obvious when comparing the results for 5 °C/10 Hz and 5 °C/5 Hz, respectively. Taking this into account, for the ongoing regression calculations, the combinations 20 °C/10 Hz, 15 °C/5 Hz and 5 °C/10 Hz are used.

Equation 4: Power law regression

$$N_{all} = a \cdot \varepsilon^b$$

Table 2: Fatigue relationsships for SMA 8 S with 25/55-55 A

Frequenz	Temperatur	a	b
10	20	22,274	-3,4564
5	15	10,451	-3,725
10	5	0,6277	-5,394
5	5	1,4911	-4,906

Obviously, within the framework of this investigation, the optimum temperature could be found. However, in order to be able to estimate a broader temperature range by calculation, the regression parameters of the fatigue functions were extrapolated. The regression approaches used are shown in Figure 10. Of course, the regression parameters obtained are good because of the rather small number of values. Whether they can simulate real behavior could not be verified in this investigation. If the regression parameters obtained from this extrapolation are used mathematically, then the allowable load repetitions for all occurring combinations of axle load size and temperature can be calculated. They are shown in Figure 11. If the respective probabilities of axle loads and temperatures for both countries are superimposed with the allowable load repetitions, one can calculate the respective damage fraction according to Miner for each combination and each climate zone or country. It takes into account the current traffic distribution as well as the probability of occurrence of the respective temperatures and is shown in Figure 12 for Spain and in Figure 13 for Germany. The displayed Miner sum per axle load and temperature condition represents the sum of all damage fractions generated within this specific state. The volume of the curve thus represents the whole damage of the pavement.

Figure 10: Regression parameters a and b

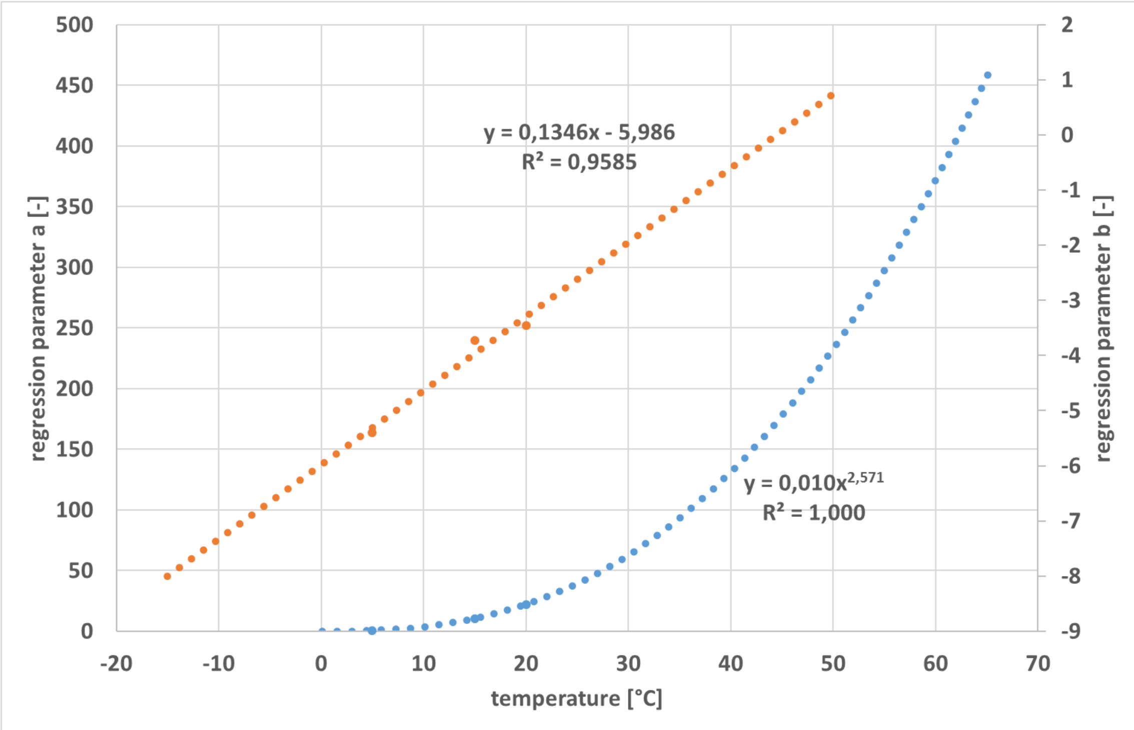


Figure 11: Allowable load repetitions in relation to axle load and temperature

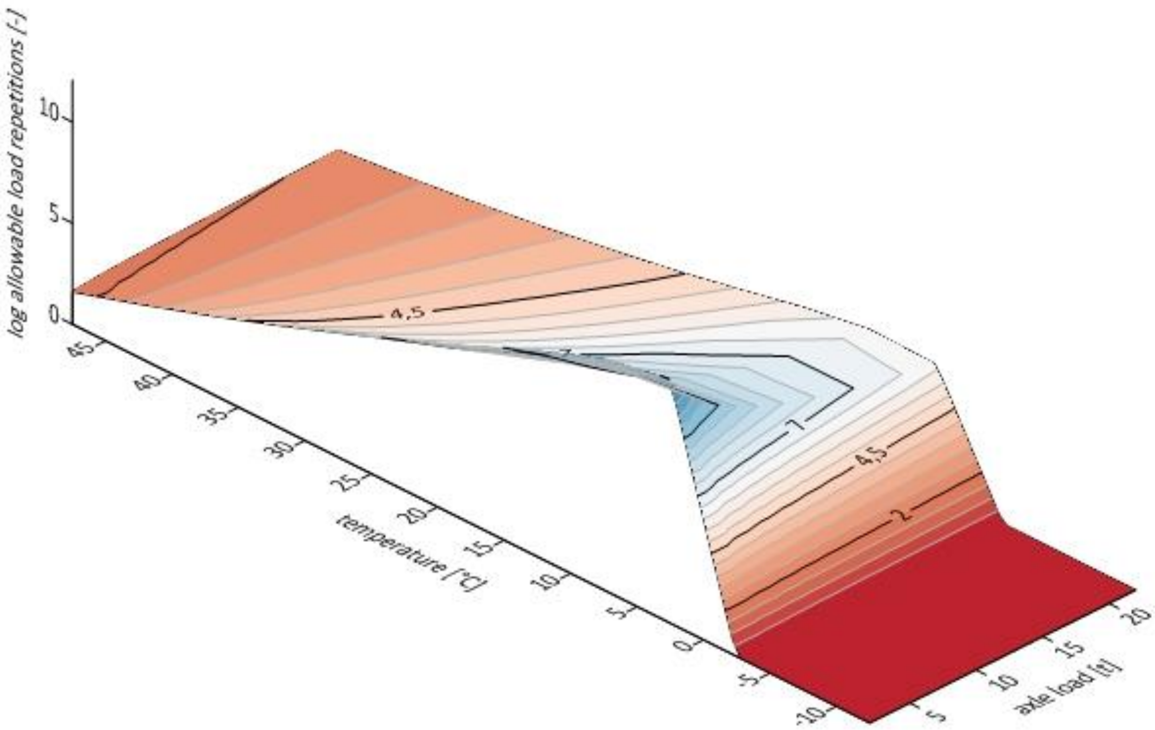


Figure 12: Allowable load repetitions superimposed with probabilities for Spain

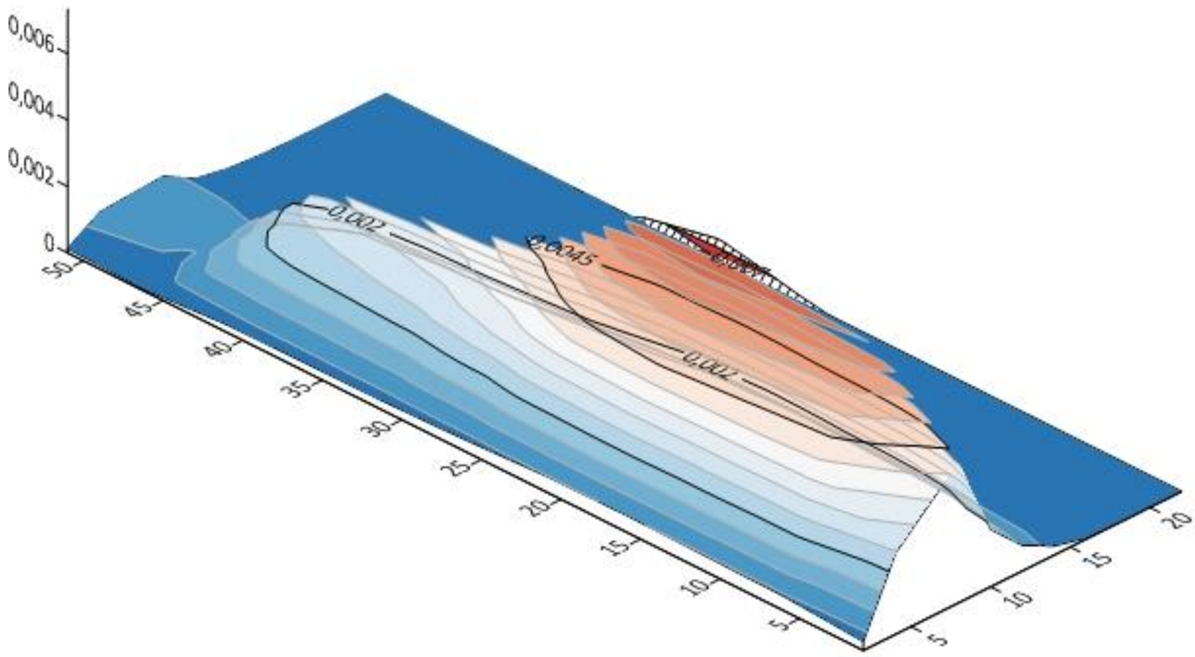
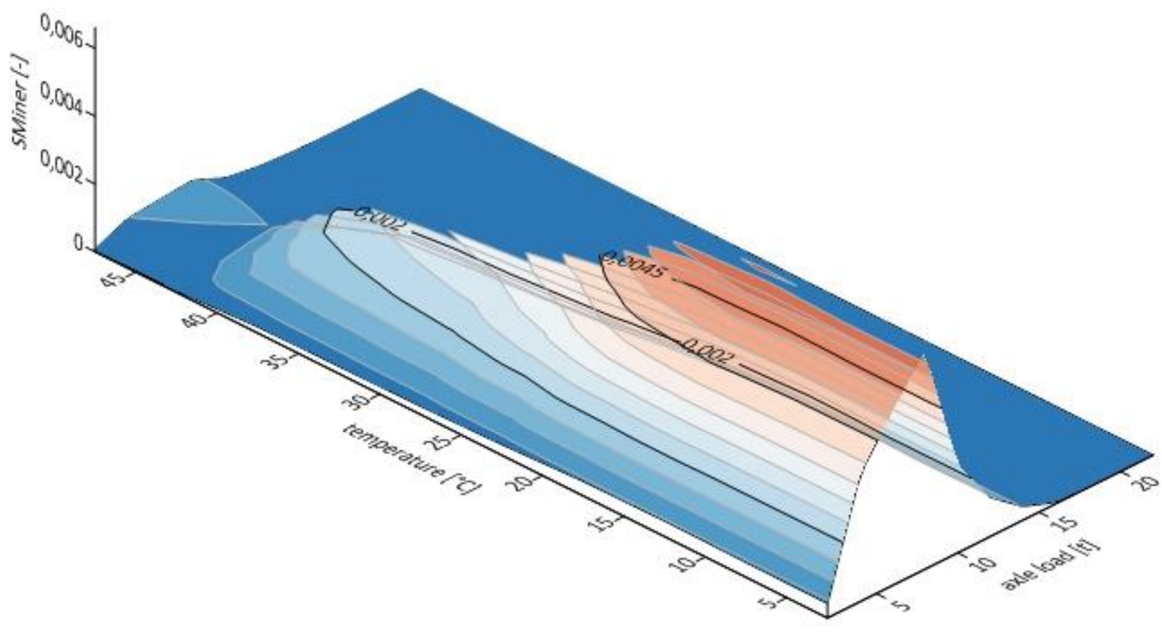


Figure 13: Allowable load repetitions superimposed with probabilities for Germany



The comparison of both graphs shows the influence of pavement temperature on the damage behavior. With all other circumstances left constant, only the different temperature conditions in both countries lead to different pavement life times. The wearing course within Spanish climatic conditions obviously suffers more from traffic induced damage than the same pavement in Germany. Different climatic conditions lead to different pavement lifetimes although all over circumstances like axle load distribution and pavement parameters remain unchanged. In this example, lower temperatures around 5 °C contribute significantly more to the damage in German conditions than in Spain, whereas the overall damage for the Spanish pavement is obviously higher. These results can now be used to optimize pavement lifetime with the help of pavement heat exchangers. It seems theoretically possible to maintain a temperature range in the pavement which – taking temperature depending material parameters into consideration – inhibits a significantly lower damage fraction than without this system. This can help optimizing pavement rehabilitation measures by monitoring and – within realistic limits – control or influence pavement temperature by extracting or inducing heat energy to the system. The evaluation showed, that the pavement system’s energy balance plays a major role in lifetime expectancy. Controlling pavement temperature therefor is one of the key aspects to optimize rehabilitation concepts.

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