Future roads and mobility

A sustainable solution to increase the service life of asphalt pavements by harvesting energy from roads

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Abstract

The locale climatic conditions have a major impact on asphalt pavement structures. Higher temperatures within the construction lead to a reduction in durability. However, increasing temperatures in conjunction with the large road network possess a huge potential to use asphalt pavements as renewable energy sources. Thus, the use of heat from pavements can extend their service life and contributes to the reduction of fossil energy demands. Including a system of pipes into the binder course could be used to cool the paved road, generate electricity, and keep the pavement ice-free during winter. Two numerical models were developed to investigate the influence of thermal management inside the asphalt pavements. A thermal model was used to simulate the transient temperature distribution within the construction over several years. Characteristic temperature profiles were determined on a longtime scale. These representative temperature profiles where then used to simulate the mechanical behavior under consideration of traffic loads with a FEM model. Based on the results, a fatigue analysis of the road construction was done by using the German mechanistic design methodology (RDO Asphalt 09). It predicts an increased durability if high temperatures are reduced and of the amount of usable heat. This thermal energy can be transformed into electric energy by using an Organic Rankine Cycle with an estimated efficiency of about 4 % to 6 %. A test system was built at the Demonstration, Investigation and Reference Area of the German Federal Highway Research Institute. The main objectives were the examination of new installation technologies for the pipe collector and the implementation of a temperature measurement system inside the road construction. Comparisons were made between simulations and measured results. The mechanical properties of the asphalts were determined experimentally with the cyclic indirect tensile test.

This paper was first published in 2020 in version 1.0 of the proceedings of the 7th E&E Congress. This second edition (version 1.1.) of the proceedings is published in June 2021. The content of this paper has not changed, but the author(s) may have provided additional information in the form of an annex.

1. INTRODUCTION

Local climatic conditions have an major influence on asphalt pavement structures. Due to the high absorption level of the surface, all layers of the asphalt pavement could be heated up and reaching temperatures above 60 °C in the upper parts of the construction on sunny days. This may lead to increased rutting and fatigue. On the other hand, these temperatures offer in combination with the size of the surface area a huge potential for using thermal energy stored in the asphalt. The integration of pipe collectors inside the pavement could reduce the thermal loads and increase the durability of road constructions. The implementation of such a system in an urban area may be realized with the scenarios shown in Figure 1. The heat from the asphalt collector systems can be converted to electric energy or could be used in heat pump systems for nearby buildings. During winter, the system could be used for snow melting and for frost protection of the construction by heating the road with thermal energy from borehole heat exchangers or groundwater. In summer, the boreholes could be regenerated by using the extracted heat from the pavement. Moreover, there might be the possibility to apply the integrated pipe systems as reinforcement to increase the stability of the asphalt pavement layers.

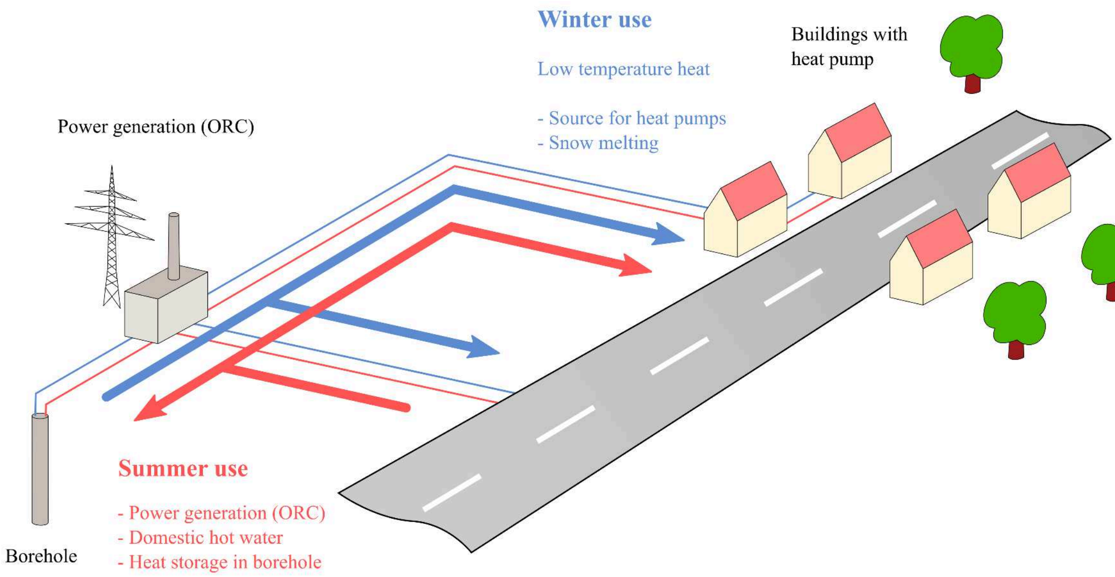

Figure 1: Possible scenarios of asphalt pavements with thermal collector systems

In this paper, selected results of the research project *SEDA* [1] are presented. The objective of the project was the investigation of the thermal and mechanical behavior of asphalt pavements with integrated pipe collector systems. For this purpose, numerical simulations and experimental investigations were combined to determine material parameters and to obtain data for model validation. Simulation results such as temperature distributions and mechanical stresses were then taken as input to estimate the effects on the durability of the road construction based on the German standard for sizing of asphalt pavements [2].

The next sections describe general assumptions, the numerical models, and the simulation results. Subsequently, the usage of pipe collectors for thermal energy harvesting and their influence on the structural design of asphalt pavements will be discussed. The results are then summarized and an outlook for future research is given.

2. GENERAL ASSUMPTIONS AND PARAMETERS

A test track which contains different collector systems has been built on the duraBASt Demonstration, Investigation and Reference Area operated by the German Federal Highway Research Institute (BASt). Experimental investigations were carried out to provide validation data for simulation models. In order to improve comparability, the dimensions and materials of the asphalt pavement were chosen to be identical for the test tracks and the numerical models. The principle design of the pavement is shown schematically in Figure 2. For model variations containing a collector system, the pipes are embedded in the binder course (BC). The thicknesses of the construction layers and the materials used are listed in Table 1.

Different collector variations have been investigated by means of numerical simulations in the project. Two scenarios were illustrated here. The first scenario is the standard road construction without collector. The second variation is a collector with pipes with an outer diameter of 25 mm embedded in a depth of 40 mm (pipe axis) and a distance of 100 mm between the pipes.

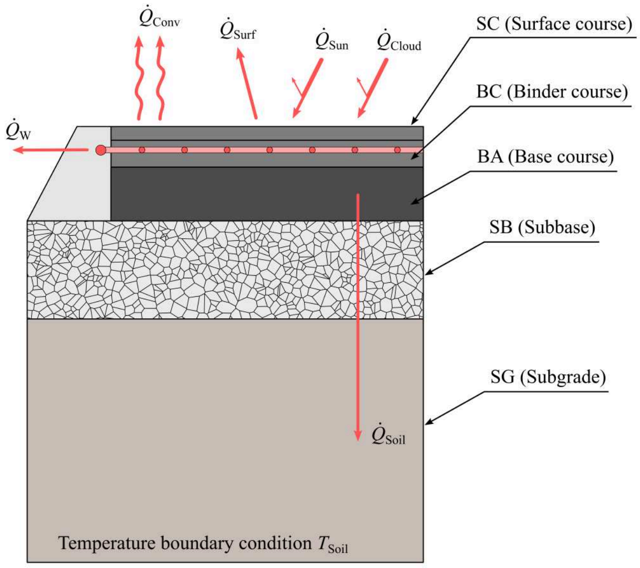

Figure 2: Road construction and energy balance

Table 1: Dimensions and materials of the road construction

Layer	Abbrev.	Material	Layer thickness
Surface course	SC	AC 5 D	2 cm
Binder course	BC	MA 8 S	4 cm
Base course	BA	AC 22 T S	20 cm
Subbase	SB	FS PA2	56 cm
Subgrade	SG	BS PA2	218 cm

Numerical investigations where strongly coupled to experimental characterization. The mechanical properties (fatigue and master curve) were determined by cyclic indirect tensile test. The thermal conductivity and the specific heat capacity were measured with a portable heat transfer analyzer ISOMET 2114 from Applied Precision Ltd. The material parameters are listed in the Tables 2 and 3.

Table 2: Mechanical properties of the asphalt materials

Material	Master curve					Fatigue	
	E_{min}	E_{max}	b_0	b_1	m	C_1	C_2
AC 5 D	0	18527.510	−0.9444	2.433	18000.0	1.2768	−3.4040
MA 8 S	0	34456.969	−0.7359	1.352	19569.0	0.7064	−3.8360
AC 22 T S	0	25281.447	−0.7152	1.410	18000.0	1.3813	−3.3460

Table 3: Thermophysical properties of the asphalt materials

Material	Bulk density ρ in g/cm^3	Thermal conductivity λ in $W/(m\,K)$	Specific heat capacity c_p in $J/(kg\,K)$	Thermal diffusivity a in $10^{-6}\,m^2/s$
AC 5 D	2.531	1.46	654.1	0.8840
MA 8 S	2.557	1.64	675.8	0.9491
AC 22 T S	2.558	1.33	648.6	0.8045

3. THERMAL MODEL AND SIMULATION RESULTS

The thermal models aim to simulate the thermal behavior of asphalt pavements with integrated pipe collectors to get a picture with respect to temperature profiles and energetic usage potentials. Due to a high impact of temperature deviations, the model should be fast enough to simulate large time periods of multiple years or even decades. This would also enable the model to investigate the influence of climatic conditions on the road constructions.

All models have been implemented in the multi-domain modeling language Modelica [3]. This object-oriented, declarative programming language allows the development and testing of single components – like asphalt layers and pipe heat exchangers – that could then be combined to describe complex systems. The simulations were done with the free and open-source tool OpenModelica [4].

The model design and the energy balance of the road construction comprising different heat transfer mechanisms are shown in Figure 2. The road consists of multiple solid layers made of different materials. Inside these layers, the heat is transported by conduction, that mainly depends on the thermal conductivity of the materials. In the model, the conductive heat transfer is treated as one-dimensional in order to achieve a high calculation performance. This simplified method is reasonable, as the area of the curb is much smaller than the remaining area of the asphalt. This assumption is also valid with respect to pipe collectors, if a bifilar layout is used like in floor heating systems. In this layout, there is always a hot pipe besides a cold one, resulting in a nearly homogeneous temperature distribution over the surface.

At the surface of the road, heat is exchanged with the ambient through various mechanisms (see Figure 2). Energy is introduced by the sun with the short-wave radiant flux $\dot{Q}_{\mathrm{Sun}}$ and by the atmosphere with the long-wave radiant flux $\dot{Q}_{\mathrm{Cloud}}$. A portion of these incoming energy flows is reflected depending on the albedo of the asphalt surface. Due to its temperature, the asphalt surface emits the radiation heat flow $\dot{Q}_{\mathrm{Surf}}$. The convective heat flow $\dot{Q}_{\mathrm{Conv}}$ is transferred between the surface and the ambient air. The convection mainly depends on the temperature difference and on the heat transfer coefficient, that is a function of the fluid velocity, the fluid properties, the surface, and the geometry. In the model the heat transfer coefficient is calculated by Nusselt equations. By using a pipe collector with a circulating heat transfer fluid (e.g. water/glycol mixture), the heat flux $\dot{Q}_{\mathrm{W}}$ is removed from the binder course or introduced to it. At the bottom, the road construction is coupled to the underlying soil. This is modeled with a temperature boundary condition, so that heat can be exchanged with the ground.

To consider transient environmental conditions such as air temperature, radiation, wind speed, and snow, weather data from the climate model REMO-UBA with emission scenario A1B [5] and hourly resolution was used for the city of Dresden, Germany. Future climate changes are highly uncertain, e.g. by changes in future greenhouse gas (GHG) emissions. The *Intergovernmental Panel on Climate Change* (IPCC) has published different emission scenarios with estimates of future development of economic growth and GHG emissions [5]. The chosen scenario A1B describe a globalized world with a rapid economic growth and a balanced emphasis on fossil and non-fossil energy sources. According to Solomon et al. [6, p. 13] this is a mean scenario in terms of the projected values for temperature change and sea level rise at the end of the 21st century. To illustrate the associated climate changes, the duration curves of the ambient temperature for different years from 2010 to 2100 are shown in Figure 3. The curves indicate for how many hours a year the ambient air temperature exceeds a given value. A future trend of rising temperatures can be clearly seen. Climate projections using other scenarios can result in huge deviations. For future evaluations also more optimistic or pessimistic emission scenarios could be used to see their influence on asphalt road pavements.

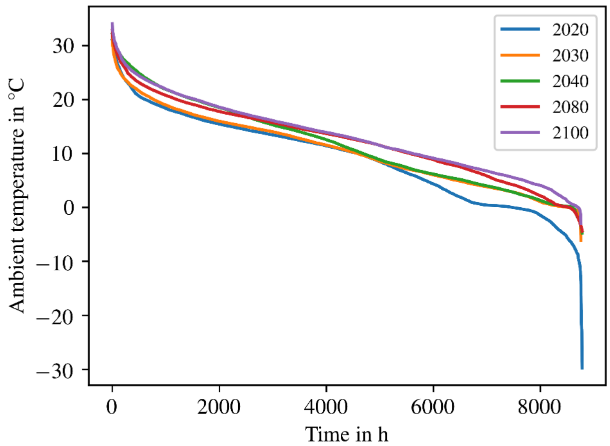

Figure 3: Duration curves of ambient temperatures for different years (climate data [7], city of Dresden)

With the described model, simulations were carried out for the reference road and for the pipe collector. For the latter, two scenarios were investigated. The first scenario is cooling in summer with both the mass flow and collector inlet temperature held constant. The cooling circuit is only activated, if the asphalt temperature in the binder course is higher than the fluid inlet temperature. The second scenario is a combination of cooling in the summer and heating during winter time for snow melting and frost protection. The winter operation also works with constant mass flow and fluid inlet temperature and will be activated if the ambient air temperature is less than 5 °C. All simulations were done for the period from 2010 to 2100.

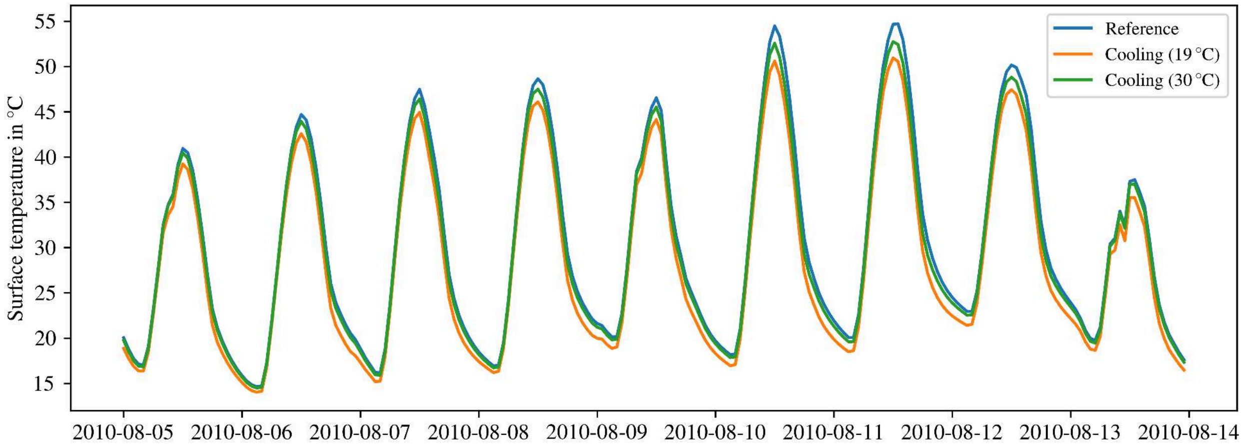

Figure 4: Simulated evolution of the surface temperature for different variations (climate data [7], city of Dresden)

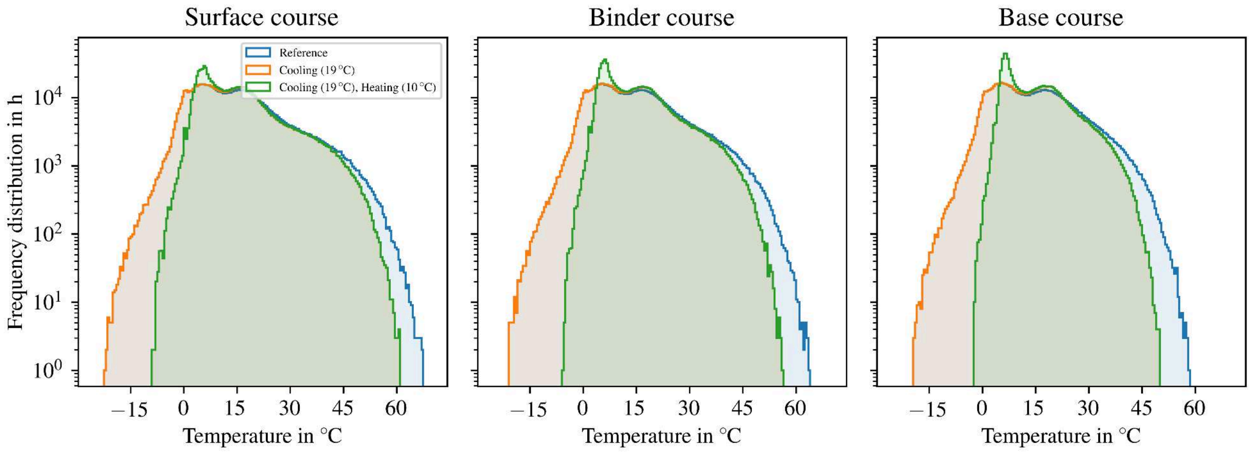

Figure 5: Simulated temperature distribution at the surface of several layers for different model variations for the period from 2010 to 2100 (climate data [7], city of Dresden)

In Figure 4 simulation results for the road surfaces temperature are compared for different model variations for a hot summer period in the year 2010. The reference road reaches temperatures up to 54.7 °C. With the pipe collector system the maximum surface temperatures can be reduced by 2.0 K and 3.8 K for fluid inlet temperatures of 30 °C and 19 °C, respectively. Lower fluid temperatures increase the heat transfer and the cooling effect for the asphalt pavement. At the same time, the fluid outlet temperature is lowered and the potential for using the extracted heat to generate electricity is reduced.

However, the collector not only influences the surface temperature as shown before, but also the temperature distribution in deeper layers. This is illustrated in Figure 5. The diagrams show the frequency distribution of the temperature at the top of the surface course, binder course, and base course within the period from 2010 to 2100 for the city of Dresden. The reference road obviously has the largest temperature range. Cooling in summer and heating during winter leads to a reduction of the extreme temperatures on both sides. At the reference road the temperatures at the top of the surface course (left diagram in Figure 5) can reach values from −22.5 °C up to 67.5 °C. Cooling with an inlet temperature of 19 °C cuts this temperature maximum to about 61.0 °C. The winter heating with a fluid inlet temperature of 10 °C enhances the temperature minimum to about −9.0 °C At the base course with heating in winter the lowest temperature can be shifted from −19.5 °C to about −2.5 °C, giving a reliable frost protection.

The simulation model can also be used to calculate the extracted heat for a given period. In Figure 6, the simulated heat production for the pipe collector with an fluid inlet temperature of 19 °C is compared for two different time periods of 30 years. Due to the predicted climate change, the estimated mean annual heat production increases from 70.4 $\mathrm{kWh/(m^2\,a)}$ in the period 2020–2049 by 25 % to 88.0 $\mathrm{kWh/(m^2\,a)}$ in the period from 2070 to 2099. The diagram also shows the mean distribution of the heat production for the complete year with respect to the calendar weeks. As expected, the system

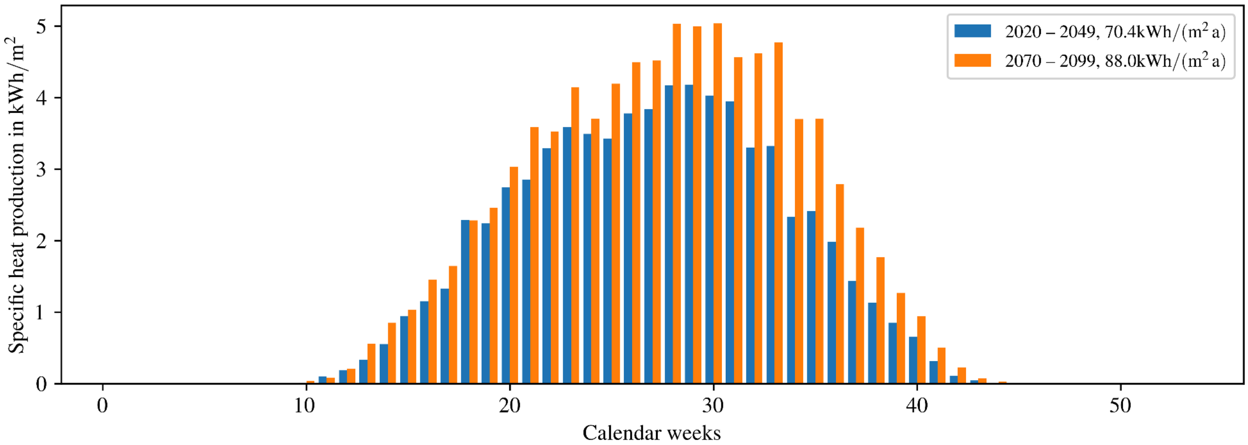

Figure 6: Comparison of simulated mean weekly heat production for the scenario Cooling (19 °C) **for different 30 year periods (climate data [7], city of Dresden)**

only supplies thermal energy in summer. At German locations, solar thermal collectors for buildings show annual yields of around 400 kWh/(m^2 a) to 600 kWh/(m^2 a). Thus, the asphalt collector system can achieve about 12 % of the yield of conventional solar thermal collectors – but the collector outlet temperatures are also much lower than on conventional systems.

Another question of interest is the potential for generating electricity from the extracted heat was evaluated. Generation of electricity is realized via an Organic Rankine Cycle (ORC). The ORC is a thermodynamic cycle using organic working fluids with low boiling temperature. In the cycle the fluid is evaporated with the heat from the asphalt collector first. The vapor will then be expanded in a turbine or a piston expansion machine, where mechanical energy is released and converted to electricity by a power generator. The expanded vapor is then condensed by transferring the heat to a low-temperature sink such as a borehole heat exchanger. After that, a pump is used to bring the liquid working fluid to the evaporation pressure and the process starts again. Due to the small temperature difference between the hot side (asphalt collector) and the cold side (borehole) of the process, the thermal efficiency η_{th} is quite low. The efficiency η_{th} describes which fraction of the heat input is converted to mechanical or electrical energy. Propyne was selected here as a potential working fluid. With temperatures of 40 °C and 14 °C for the evaporation and condensation respectively, a thermal efficiency of about 6.2 % can be achieved. However, it has to be stated that a temperature of 40 °C can only be reached for a few hours a year. If the ORC will be used with lower temperatures, then the thermal efficiency will also become smaller.

4. MECHANICAL MODEL AND SIMULATION RESULTS

A model based on the Finite Elements Method (FEM) was designed to determine the mechanical behavior of the asphalt pavement and the pipe system. The model comprises a detailed representation of the geometry from the construction and the pipe collector.

The mechanical model was build as a full 3D FEM model considering symmetry boundary conditions to reduce the number of elements and speed up the calculation (Figure 7). The mesh near the center of the road construction was designed as fine mesh, and with increasing distance to the center the mesh structure will be coarser (Figure 8). The mesh next to the pipes was built differently. The elements of the binder course with the integrated pipes of the collector are changed to triangular prism. The surrounding volume of the layer was divided in subparts, and the mesh around the pipes was redefined. The gradients of the stresses and strains in this area are very high, so a fine mesh is necessary to describe mechanical behaviour in a realistic manner. The contact between the asphalt layers where defined as fully connected without the possibility to slide or separation. The material of the pipes is a composite laminate consisting of polymer, aluminum and second layer of polymer. During asphalt paving of the mastic asphalt the outer polymer layer is heated up. Thus, the asphalt and the outer layer of the pipe are fusing together, so an excellent contact between asphalt pavement and the pipes exists. These considerations will be taken into account by the contact definition of the FEM model. All other contacts where defined as frictionless. A sliding of the layers is possible, but the layers can not penetrate.

Test tracks have been built at the duraBASt area to consider possible designs and improve the construction techniques of the pipe collector. The material properties of the used asphalt mixtures were charactericed by the cyclic indirect tensile test. The specimens were extracted from the test tracks. The behavior of the stiffness and fatigue for the different asphalt mixtures were determined and used for the FEM simulations. The thickness of the asphalt layers of the road construction

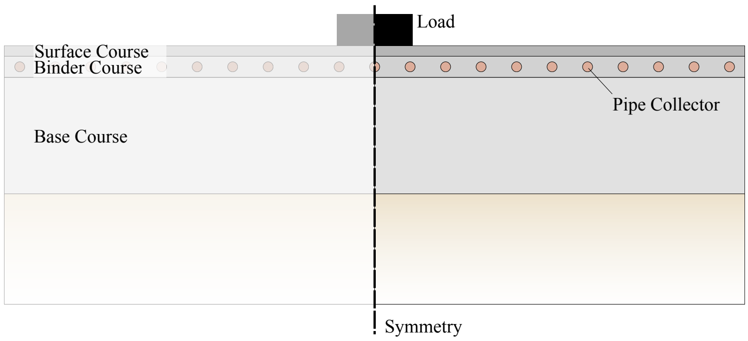

Figure 7: Sketch of the road construction

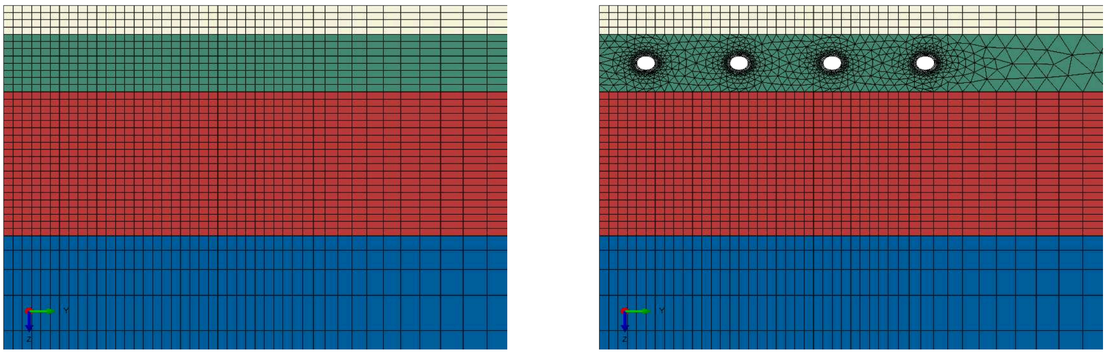

Figure 8: Mesh of the Finite Elements model; left: standard road construction; right: road construction with integrated pipe collector

were minimized to increase the potential of thermal energy harvesting. Furthermore, higher loads will be expected and the vulnerabilities of the systems could be exposed. The thicknesses of the layers were defined to be 20 mm for the asphalt surface course, 40 mm for the asphalt base course, and 200 mm for the the base course, see Table 1.

The influence of the locale climate conditions from the thermal simulation model and the frequency of the loads from the vehicles were considered in the FEM model. For the process of dimensioning of the asphalt pavements the strains inside the construction were simulated for a number of 156 different temperature profiles [8].

Figure 9 shows the distribution of the principal strains for a simulation with a surface temperature of 17.5 °C. The blue and red colors indicate compression and strains, respectively. At the top of the standard road construction (left) is a region with heigh compression. Strains occurred at the bottom of the construction and next to the load area. The integration of the pipe system did not change the strain distribution completely. Next to the first pipe there is a circular area with higher strains, which might be cause a detaching between the pipe and the asphalt mixture. The resulting strains above the second pipe are high concentrated. These strains lead to initial cracks starting from the vertex of the pipe. Further loads lead to a expansion of the cracks and reduce the durability of the surface and binder course. On the other hand the integration of the pipe collector reduces the strains in the base course. Typically this is the layer of the road construction with the highest resulting strains and the signs of fatigue for the whole construction.

5. INFLUENCE OF STRUCTURAL DESIGN ON ASPHALT PAVEMENTS

Thermal simulations for the basic scenario as well as for the scenario with integrated collector system were analyzed according to the methodology by Kayser [8], and the frequency distribution of the characteristic standardized temperature profiles were determined. Figure 10 compares the results of these examinations. The distribution of the basic scenario shows that a significant number of conditions are present in the range of negative surface temperatures. The active heating of the road construction to keep the ice and snow free leads to a significant reduction of the occurrence of lower temperature conditions. The road surface is still affected by conditions in which additional effort must be made to ensure driving safety. Active cooling in summer reduces high temperatures within the road construction. The frequency of the characteristic standardized temperature profiles in the upper and high temperature range is reduced in the scenario with collector system compared to the basic scenario. Under the same climatic conditions, this tends to result in a higher stiffness of the asphalt in comparison to the standard road. It can be assumed from the thermal simulations that active temperature control of the road construction can reduce the range of occuring temperatures. This leads to a high probability that the resulting total duration of the use of the road construction will increase. In the report [1] the potential of asphalt

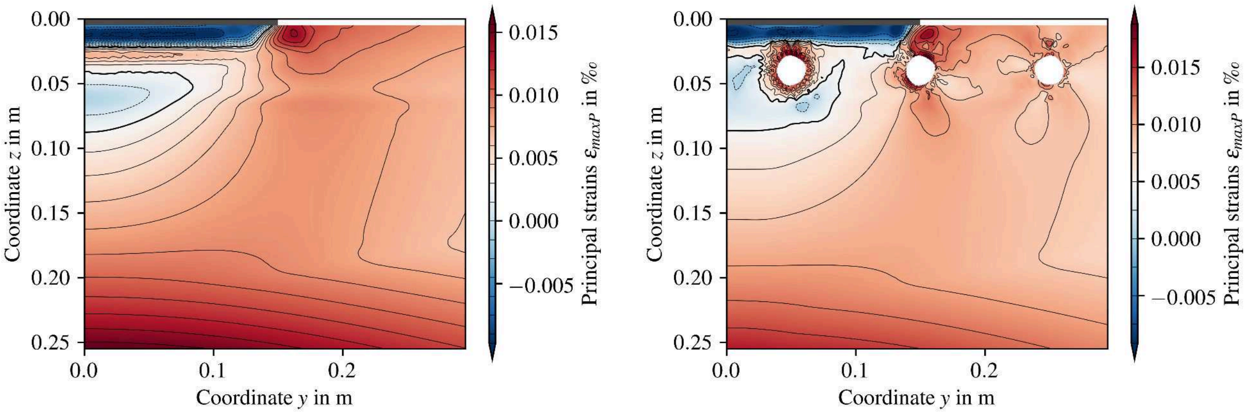

Figure 9: Principal strains in the center of the load area; characteristic standardized temperature profiles 8; surface temperature 17.5 °C**; load 1 t**

optimization was not further investigated. However, the choice of an optimised asphalt for the reduced temperature range could have a significant influence on the resulting performance of the road construction.

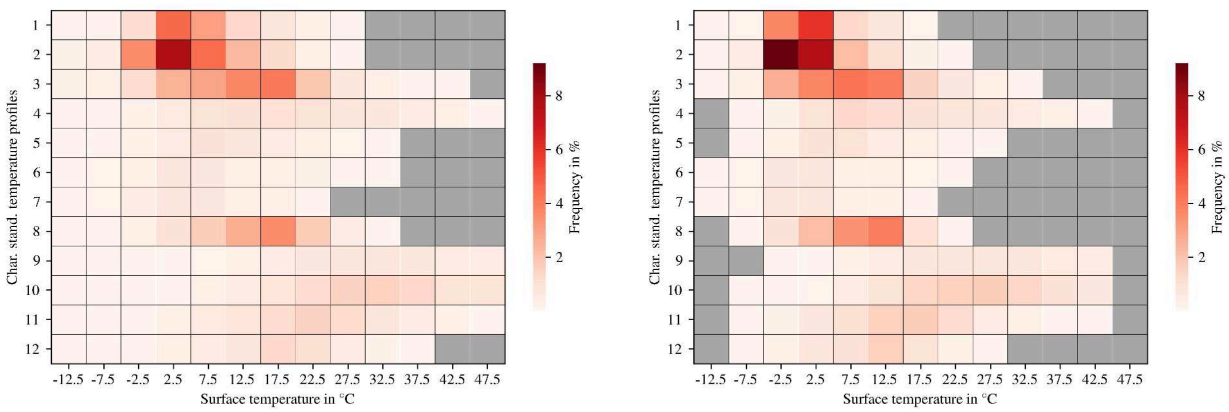

Figure 10: Distribution of the normalized characteristic temperature profiles; left: reference variation; right: cooled variation in summer with snow melting in winter

For determining the effect of active tempering, numerical simulations have been carried out and analyzed. The resulting strains inside the asphalt layers can cause cracks. The German dimension methodology [2] provides a procedure to evaluate the effects of mechanical loads by the Miner's linear damage hypothesis (Equation. 1). The different climate and load conditions are valued on the proportion of the existing load cycles (Equation 2a) to the permissible number of load cycles (Equation 2b). Because of the simulations, which are linear-elastic, the influence of different traffic loads were considered by multiplying the results of the FEM simulations with fractions of different axis loads. Thus, up to 1716 different load cases (11 load classes multiplied by 156 temperature profiles) were calculated to consider the operating conditions of the road construction. The single results are then accumulated and representing the design service life of the road construction.

$$\sum_{i=0}^{n} \frac{\mathrm{N_{ex,i}}}{\mathrm{N_{per,i}}} \leq 1 \tag{1}$$

$$\text{(a) } \mathrm{N_{ex,i}} = \mathrm{N} \cdot \mathrm{H_{climate}} \cdot H_{loads} \qquad \text{(b) } \mathrm{N_{per,i}} = \frac{\mathrm{SF}}{\mathrm{F}} \cdot \mathrm{a} \cdot \varepsilon^{\mathrm{b}} \tag{2}$$

The results of these calculations clearly exhibit differences between the two road constructions (Figure 11). The calculated design service life of the asphalt base course for the standard variation has a duration of 24.6 years. The integration of the pipe collector lower the strains at the bottom of the base course and the conditional design service life increases up to nearly 34.7 years. But the integration of the pipe collector also increase the strains in the two upper layers of the road construction. The maximum design service life next to the pipes reduces from 8.9 years to 4.8 years, which represents a reduction of the calculated service life of the surface course to about 55 %.

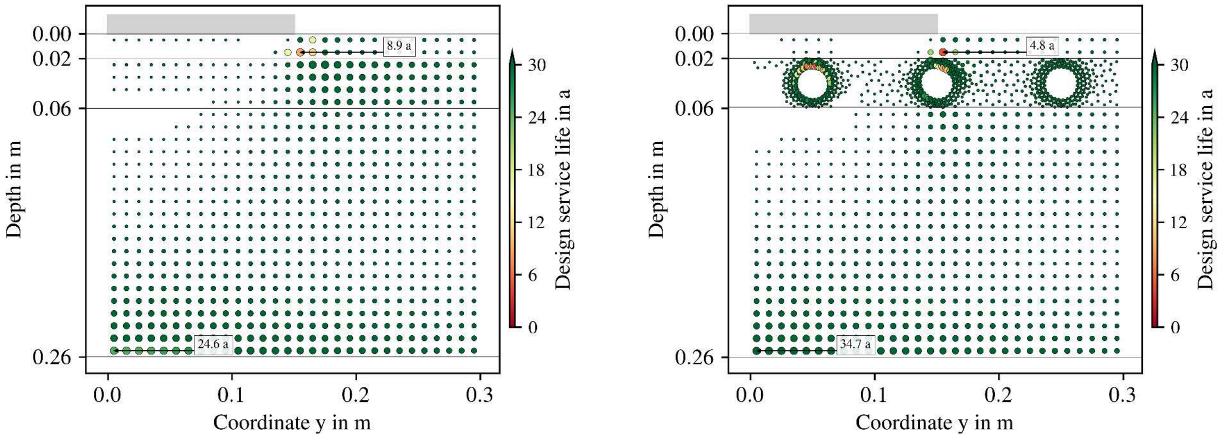

Figure 11: Calculated design service life of the examined road constructions, year 2020 to 2049

6. SUMMARY

Within the research project *SEDA* [1], various concepts of asphalt solar collectors were evaluated with respect to their energetic potential, mechanical stability, and installation requirements. A integrated pipe collector was selected as the preferred scenario and investigated in more detail by means of numerical simulations. The mechanical behavior and the predicted life span of the pipe collector system was then compared with a standard road construction.

In a first step a numerical model was built to describe the thermal behavior of road constructions with integrated collector systems. The model can be used to simulate the transient temperature distributions in the road constructions and shows a qualitatively good agreement with experimental results from test tracks on the duraBASt Demonstration, Investigation and Reference Area. With the performed simulations it could be shown that by using a collector system the temperatures in the construction can be reduced significantly. With the pipe collector the reduction of the maximal temperature stress in the surface course, binder course and base course is between 5 K to 9 K. The thermal model also allows simulating the formation and melting of snow layers.

The results of the thermal simulations were reprocessed and analyzed according to the Kayser [8] method. This allows to represent the multitude of temperature conditions by a reduced number of characteristic standardized temperature profiles, and therefore to optimize the number of required mechanical simulations. The results show that an active temperature control of a road construction can have a significant influence on the occuring thermal conditions. The heating of the roads during winter by means of a pipe collector leads to the fact that negative temperatures occur less frequently. Active cooling during summer further reduces temperature peaks. A positive influence of the thermal conditions within a road construction by using a pipe collector can therefore be considered as evident.

The mechanical stresses caused by road traffic were calculated using a FEM model, which considers specific thermal conditions, material parameters for the individual layers as well as different traffic loads. A pipe collector was integrated and adaptations were made to the mesh of the FEM model. For each model scenario a total number of 156 individual FEM calculations were performed and post-processed for calculating the durability of the road construction.

Based on the computational dimensioning method [2], the designed life span of the different scenarios was calculated according to the layers of the road construction. Fatigue is the evaluation criterion of the analyses and the plastic deformations were not calculated. The mechanical calculations show that the service life of the asphalt base course could be significantly increased by integrating the pipe collector. A reduction of high temperatures within road constructions results in an increased stiffness of the asphalts. This leads to a reduction in the stresses caused by traffic, and therefore to decreasing strains in the asphalt package.

Due to the ultra-thin design of the asphalt surface course and asphalt binder course at the test tracks and the created models, cracks are highly likely to form above the collector pipes. Appropriate preventative action must be taken to avoid this type of damage. Adding fibres to asphalt mixtures is a relatively cheap possibility to improve the resistance against fatigue cracking [9]. Maybe it is also possible to use reinforcement meshes to increase the durability of the surface course.

Further research is needed for the modeling of these composite materials. Another option would be to simply enhance the thickness of the surface course, but this would increase the installation depth of the pipes and therefore reduce the possible fluid outlet temperature. Thus, an optimization of the road constructions can lead to a more efficient solution for a variety of possible use cases.

Within the context of the research, it could be shown that the integration of a pipe collector for active temperature control in road constructions is possible and also has several advantages over conventional road constructions. The main benefits are the increased service life in the area below the pipe collector and the potential of using the extracted thermal energy.

The input parameters for the simulations can vary due to technical conditions. Asphalts are highly inhomogeneous mixtures with local fluctuations of thermophysical and mechanical properties, future traffic loads are highly likely to differ from current assumptions and future climatic conditions strongly depend on economic and technical evolution. All these factors influence the mechanical behaviour of the road construction and the resulting service life. In this study, the potential was evaluated using a deterministic approach with fixed parameters. A probabilistic analysis with statistical scatter of the input parameters and applied loads is recommended and should be carried out in the future research.

In Germany the predicted climate changes leads to significant higher mean air temperatures [10, 11]. The risk of extreme weather situations rises and increasing occurrence of heat waves and droughts are measured and predicted. This effects leads to a significant reduction of the designed service life of road constructions built from asphalt mixtures. The integration of a pipe collector is a possible solution to reduce these detrimental effects and can be seen as a method for mitigation of climate change.

ACKNOWLEDGEMENT

The authors gratefully acknowledge the support provided by the German Federal Ministry for Education and Research BMBF (Ref. 13N13610).

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