Influence of Different Fillers on Mechanical Properties of Porous Asphalt Mixtures Using Microstructural Finite Element Analysis

Pengfei Liu[a], Guoyang Lu[b], Xu Yang[c], Can Jin[d], Sabine Leischner[e], Markus Oeser[f]

a. Senior Research Engineer, Ph. D, Institute of Highway Engineering, RWTH Aachen University, Mies-van-der-Rohe-Street 1, 52074 Aachen, Germany. Email: liu@isac.rwth-aachen.de;

b. Department of Civil and Environmental Engineering, ZS972, 9/F, South Tower, Block Z, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong. Email: guoyang.lu@polyu.edu.hk;

c. Lecturer, Ph. D, Department of Civil Engineering, Monash University, Clayton, VIC 3800, Australia Email: Xu.Yang@monash.edu;

d. Associate Professor, Ph. D, School of Automotive and Transportation Engineering, Hefei University of Technology, 193 Tunxi Road, Baohe District, Hefei, Anhui 230009, China. Email: jincan@hfut.edu.cn;

e. Senior Research Engineer, Ph. D, Institute of Urban and Pavement Engineering, TU Dresden, Dresden, Germany. Email: Sabine.Leischner@tu-dresden.de;

f. Professor, Ph. D, Institute of Highway Engineering, RWTH Aachen University, Mies-van-der-Rohe-Street 1, 52074 Aachen, Germany. Email: oeser@isac.rwth-aachen.de

**Corresponding Author: Pengfei Liu, Senior Research Engineer, Institute of Highway Engineering, RWTH Aachen University, Mies-van-der-Rohe-Street 1, 52074 Aachen, Germany. Tel: +49-241-8020389, Fax: +49-241-8022141; Email: liu@isac.rwth-aachen.de*

Abstract:

Currently, recovering the natural hydrological cycle and lowering the urban flood risk are global challenges. A permeable pavement with void-rich pavement materials, e.g., porous asphalt (PA), is believed as the one of the feasible and effective measures. Due to the specific gradation, the fillers can considerably influence the performance of the PA mixtures. In this study, the effect of four different fillers (Limestone, Dolomite, Rhyolite and Granodiorite) on the mechanical responses of the PA mixtures was investigated by the numerical method. X-ray computer tomography (X-ray CT) scanning and digital image processing (DIP) techniques were applied to detect and reconstruct the microstructure of PA specimens. Finite element (FE) method was conducted to simulate an indirect tensile test and by this means the mechanical responses of the PA mixtures (load-bearing capacity, von Mises stress and creep strain) were computed and compared. The results show that the different fillers have significant influence on the mechanical responses of the PA mixtures. Based on the computational results, the correlation between the mechanical responses of the PA mixtures and the filler properties is analysed. In addition, the performance of the PA mixtures with different fillers is ranked. Based on this ranking, it is possible to select an optimal filler to facilitate the improvement of the permeable pavement design.

Keywords: Mineral filler, Porous asphalt mixture; Digital image processing; Microstructural finite element analysis; Correlation analysis

1. Introduction

In order to avoid moisture penetrating into the structure and causing damage to it, pavements are designed to be sealed by the conventional dense materials. However, with the rapid increase of sealed areas as a result of urban development and industrial activity, the natural retention capacity has experienced a significant decrease (Scholz and Grabowiecki 2007). To recover the natural hydrological cycle and lower the urban flood risk, permeable pavements are implemented by directly allowing the rain water to seep through the pavement surface (Li et al. 2013).

To achieve high permeability, a void-rich pavement structure, such as porous asphalt (PA) and porous concrete (PC) pavements containing open-graded aggregate, is currently one of the feasible and effective ways (Cooley, L. A., et al. 2002; Kuang et al. 2011). Apart from the high hydraulic conductivity, porous structures can also enhance the noise absorption of the transportation system (Alber et al. 2018b; Alber et al. 2018a; Wang et al. 2017). However, due to the open porous design, the weak shear-stress resistance of the pore structure can cause high susceptibility to grain raveling, and thus the durability of porous pavement mixtures has been an obstacle restricting the application of permeable pavements (Hagos 2008; Mo et al. 2009; Mo et al. 2011; Wang et al. 2018; Xie et al. 2017; Zhang and Leng 2017).

Several studies have indicated that the geometrical, chemical and mechanical properties of fillers can influence the performance of the asphalt mixtures to some extent (Antunes et al. 2015; Rieksts et al. 2019; Wang et al. 2011). The filler can fill the void between coarse aggregates as an inert material and also interact with the bitumen at the interface as an active material (Kim and Little 2004). Particularly, the filler may stiffen and extend the bitumen, alter the moisture resistance, affect the ageing characteristics, the workability and compaction characteristics of the asphalt mixtures (Anderson 1987; Kavussi and Hicks 1997). Due to the specific aggregate gradation, the PA mixtures have relatively lower content of fine aggregate compared with the other conventional types of asphalt mixtures (Zhang and Leng 2017). The effect of the mineral fillers on the mechanical performance of the PA mixtures is more significant (Rochlani et al. 2019).

Because the filler can affect many aspects of asphalt mixture, it is essential to further verify the influence of the fillers on the mechanical response of asphalt mixtures. The mechanical response of asphalt mixtures has been widely studied by both experimental and numerical methods (Ban et al. 2018; Bhattacharjee and Mallick 2012; Liu et al. 2017b; Souza and Castro 2012; Wang and Al-Qadi 2010). The numerical methods have gained popularity compared to laboratory testing with high costs. For the implementation of numerical methods, asphalt mixtures were considered to be homogeneous due to the low computational capacity in the past (Liu et al. 2018b). Imaninasab et al. studied the impact of crumb rubber on improvement of PA mixtures. Particularly, the PA mixtures containing different modified binder contents were compared with control mixture using finite elment (FE) method. It is found that static loading resulted in slightly greater rut depth than repeated one and increase of the rubber content caused less rut depth (Imaninasab et al. 2016). However, at the microscale asphalt mixtures are typical heterogeneous materials consisting of aggregate, asphalt binder and air voids (Hu et al. 2018). During the last two decades the microstructure of asphalt mixtures has been reconstructed in different ways to allow for more realistic numerical simulations (Kollmann et al. 2019b; Liu et al. 2013; Liu et al. 2019; Wang et al. 2014; Yang et al. 2016). One of the mostly used algorithms is an image based method. A high-resolution camera or an X-ray computer tomography (X-ray CT) scanner are used to capture surface or cross sectional images of the asphalt mixtures (Hu et al.

2016; Hu et al. 2019; Li et al. 2020; Liu et al. 2017a; Yin et al. 2015). Using digital image processing (DIP) techniques, the microstructure of the asphalt mixtures containing aggregates, asphalt mastic / mortar and air voids can be constructed (Yin et al. 2015). By this means, Masad et al. firstly developed a two-dimensional (2D) microstructural finite elment (FE) model to simulate the strain distribution within the asphalt mixtures (Masad et al. 2001). Manrique-Sanchez and Caro used 2D FE modelling to evaluate the potential contribution of PA layers with different thicknesses to the overall structural capacity of different flexible pavements. The results showed that PA layers did contribute to the pavement structural capacity and this contribution strongly depended on their different microstructural and geometrical characteristics (Manrique-Sanchez and Caro 2019). The concentrations and distributions of stresses were investigated in three-dimensional (3D) FE models later with the improvement of the DIP techniques (Liu et al. 2018a; Wang 2003; Wollny et al. 2020; You et al. 2012). Rami et al. found that multiple 2D FE microstructures was an alternative-efficient approach to predict the actual 3D response of asphaltic mixtures (Rami et al. 2017). Currently, the 2D FE simulation is still the dominative method to analyze the mechanical performance of the asphalt mixtures (Kollmann et al. 2019a).

The numerical study focusing on the mechanical performance of the PA mixtures influenced by different fillers is seldom reported in the literature. The objective of this research is to fill the gap in this research field. The conventional filler Limestone and three other mineral fillers, Dolomite, Rhyolite and Granodiorite were selected and their physical and chemical properties have been tested. The rheological properties of the asphalt mastics with the four fillers were measured to provide material parameters to FE simulations. A common used type of PA mixture (PA 8) was selected in this study to provide the microstructure. X-ray CT scanning was carried out to obtain gray images of the PA specimens. The cross-sectional structure of the PA specimens was reconstructed by means of DIP techniques and then used in the 2D microstrutrual FE simulations. An indirect tensile test was simulated to investigate the mechanical responses of the PA mixtures with different fillers. The correlation between the mechanical responses of the PA mixtures and the filler properties was analysed based on the computational results. Finally, the computed mechanical performance of the PA mixtures was ranked.

2. Research Methodology

2.1 Properties of filler materials

A detailed study on the physical and chemical properties of the four fillers has been conducted in the previous research (Rochlani et al. 2019). These filler properties were used to analyze their correlation with the computational mechanical responses of the PA mixtures. Table 1 lists the physical properties of the fillers, such as specific surface area (SSA), pore volume (PV), average pore size (POS), and density. SSA is a property of solids defined as the total surface area of a material per unit of mass. PV is defined as the porous material's air volume per unit of mass. POS is the average of the pore diameters in the porous material. These tests were done using a 3H-2000PS1 Surface and Pore Size Analyzer in static measurement mode. The physical properties of the considered fillers are stable during these analyses and the state is representative of the state in a porous asphalt mixture as well. It can be observed that the Granodiorite filler has the largest SSA, which is 4.4 times higher than Limestone with the smallest SSA value. The Rhyolite has the highest PV and highest POS. The Granodiorite has the smallest POS, while the Limestone has the lowest PV. In addition, the Rhyolite has the lowest density, while the Dolomite has the highest one.

In terms of the chemical properties, various oxide profiles acquired from X-Ray Fluorescence

(XRF) tests (PAN Analytical PW4400 spectrometer) are listed in Table 2 (Rochlani et al. 2019). It can be observed that CaO dominates the composition of the Limestone and Dolomite (92.97% and 61.97%). The Dolomite also contains a significant portion of MgO (26%) which almost can be negligible in the other fillers. The oxide compositions of the Rhyolite are similar with those of the Granodiorite, i.e., both of them consist of the highest percentage of SiO_2 (61%-66%), followed by Al_2O_3 (18-20%).

2.2 Preparation of PA samples

In order to get the same microstructure of the specimens, the PA mixture with the filler of Limestone was selected for the later X-ray CT scanning and DIP procedure. Besides the Limesone, the PA specimens with maximum grain size of 8 mm (designated as PA 8) were composed of crushed diabase aggregate and bonded by a bitumen with a 50/70 penetration grade. The bitumen and the Limestone were blended in the laboratory to prepare asphalt mastics respectively with a binder-filler mass ratio of 1:1.6. This value was chosen to mimic the bitumen-filler ratio of a stone mastic asphalt, SMA 11S, which is the most popular asphalt mixture used in Germany according to the German guideline TL Asphalt-StB. The basic technical properties of the bitumen are shown in Table 3.

The mixtures were prepared by means of Marshall Compaction (50 impacts per side). According to a Germany standard (Forschungsgesellschaft für Straßen- und Verkehrswesen 1999), the grain size distribution and detailed mixture design of the PA 8 specimens are given in Fig. **1** and Table 4 respectively.

2.3 Strain and frequency sweep tests on asphalt mastics

In order to determine the material properties of the asphalt mastics with different fillers which were used in the FE simulations, the strain and frequency sweep tests were carried out in this study. The strain sweep tests were first performed separately at temperatures -10°C, 10°C, 30°C, 50°C and 70°C for each sample type. The linear viscoelastic (LVE) limit is denoted by the strain value where the absolute complex modulus equates to 95% of the initial value. These strains are further reduced by 20% to ensure that the frequency sweeps are carried out within the LVE region.

There were two frequency sweep tests done on every sample. One was conducted in the temperature range of -10°C to 30°C using an 8 mm diameter parallel plate with specimen thickness of 2 mm. While, the second one was performed in the range from 30°C to 70°C using a 25 mm diameter parallel plate and 1 mm thick specimen.

All the tests were performed by using an DSR test device (Anton Paar MCR 502 Modular Compact Rheometer), as shown in Fig. **2**. The details results derived from the DSR tests were introduced in the previous research (Rochlani et al. 2019).

2.4 X-ray CT scanning and DIP techniques

The internal microstructure of the PA mixture was detected by the X-ray CT scanning. Scanning intervals were set to 0.1 mm. The resolution of the gray images was 1024 pixel x 1024 pixel with each pixel being 80 μm.

Based on material density, the gray values ranged from 0 to 255, which were determined by the X-ray CT device. Within the PA mixtures, aggregates resulted in the maximum gray values while air-voids returned the minimum. The binary images were extracted from the gray scale images by means of the DIP techniques to reconstruct the microstructure for the FE simulation, as shown in Fig. **3**. For a more detailed overview of the process to create binary images, previous research is referred to (Hu et al. 2017).

2.5 Development of 2D microstructural FE models

Three 2D FE models were created in the FE software ABAQUS, as shown in Fig. **4**. These three models were derived from one randomly chosen X-ray CT scanned image as shown in Fig. **3**, i.e., the microstructure was the same; the second and third models were created by anticlockwise rotating the first model by 120° and 240° respectively. The threshhold size to distinguish aggregates from fillers was defined as 0.5 mm, i.e., aggregates with the size smaller than 0.5 mm were regarded as part of the asphalt mastic. The aggregates were assumed as linear elastic and independent on temperature with a Young's modulus of 55000 MPa and a Poisson's ratio of 0.25 (You et al. 2008). The asphalt mastics with different fillers were considered as LVE and temperature-dependent. Different Prony series were used to compute the mechanical responses of the mastics at 0 °C and 50 °C (Blasl et al. 2019). The parameters were derived from the strain and frequency sweep tests introudced in the section 2.3.

The FE model of the PA mixture was discretized by 59057 linear triangle 3-node plane stress elements (CPS3) (Dassault Systèmes Simulia Corp 2014). Hard contact conditions were defined for the interaction between aggregates and the aggregates were tied with the asphalt mastic. To simulate the indirect tensile test, the width of the loading and support strips was set to 12.7 mm. The loading was conducted at a constant deformation rate of 50 mm/min for 2 s, which was believed not to cause cracks in the specimens. The support strip was fixed. The reliability of the FE models has been validated in a previous investigation (Kollmann et al. 2019b).

3. Analysis and Discussion

3.1 Load- bearing capacity at lower and higher temperatures

The computed load-bearing capacities of the PA mixtures with the Limestone are compared in Fig. **5**. The load-displacement curves from the different models at the initial stage within the displacement of 0.5 mm are close, and afterwards the differences become larger due to the different structures. The absolute differences between each value and the corresponding average value are less than 15%, which proves the consistency of the computational results as well as the reliability of the FE models.

In order to compare the load-bearing capacity of the PA mixtures with different fillers, the average values of the loads derived from three models are plotted in Fig. **6**. The performances of the load-bearing capacities from the PA mixtures are totally different at 0°C and 50°C. From Fig. **6** (a), one can see that at 0°C the PA mixture with Granodiorite has the largest load-bearing capacity and followed by the ones with Dolomite, Rhyolite and Limestones. The load-bearing capacities of the PA mixtures with Granodiorite and Dolomite are close throughout the whole loading process. Before the displacement reaches 1.6 mm, the load-bearing capacity of the PA mixture with Limestone is larger than that with Rhyolite, but afterwards the result seems to reverse. The stiffnesses (the slope of the curves) of the PA mixtures with Granodiorite and Limestone decrease with increase of the displacement, while the stiffnesses of the PA mixtures with Dolomite and Rhyolite are almost constant. While in Fig. **6** (b), at 50°C the PA mixture with Rhyolite has the largest load-bearing capacity and followed by the ones with Granodiorite, Dolomite and Limestones. The load-bearing capacities of the PA mixtures with Granodiorite and Dolomite are still close throughout the whole loading process. All stiffnesses of the PA mixtures increase with increase of the displacement at this temperature.

Using these results, it is possible to conclude that at 0°C, the PA mixture with Granodiorite has better load-bearing capacity performance, while the ones with Limestone and Rhyolite have the least favourable performance. The mixtures with Rhyolite and Limestone have the best and least load-bearing capacity performance at 50°C, respectively. The conclusion is consistent with the experimental results in the previous study (Rochlani et al. 2019), and the corresponding analysis related to the physical properties and oxide composition of the fillers will be discussed later.

3.2 Von Mises stress at lower temperature

In order to compare the damage resistance of the PA mixtures with different fillers at 0°C, the von Mises stresses were determined from asphalt mastics in these PA mixtures loaded by 80 N. It was found that the distributions of the von Mises stresses in the different mastics are similar, and only a small amount of a large values exists. Therefore, only the distribution of von Mises stress in the asphalt mastic with the Limestone is shown in Fig. **7**. The areas with the values of von Mises stress higher than 6 MPa are colored in red. From this figure, one can see that the von Mises stress mainly concentrates in the central region along the loading and support strips. Furthermore, the stress concentration is obvious at the interface between aggregates and mastic, especially around the aggregates with sharp corners.

The evolution of von Mises stress derived from the location with maximum value (shown in Fig. **7**) is illustrated in Fig. **8**. As the external load increases, the von Mises stress also increases. The Rhyolite mastic presents the highest von Mises stress throughout, followed by the Limestone, the Dolomite and the Granodiorite. Furthermore, at higher load levels (higher than 60 N), the

Rhyolite and Limestone mastics have similar values of von Mises stress while the Dolomite and Granodiorite have similar and smaller values. The asphalt mastic with higher stiffness at 0°C generates less von Mises stress under the same external load, which has a better damage resistance. This phenomenon is consistent with the results derived from the previous section.

3.3 Creep deformation at higher temperature

Rutting is a frequently observed phenomenon in asphalt pavement and one important reason is creep of the asphalt mastic. Therefore, the distribution of the creep strain in the four mastics under the external load of 0.01 N at 50°C was investigated. If the values of creep strain are higher than 0.08, the corresponding areas are colored in red, as shown in Fig. **9**.

One can see that the most considerable creep occurs in the Limestone mastic and the difference is significant compared with the others. The creep strain in the Rhyolite mastic is the least in the four asphalt mastices. The distribution and the magnitude of the creep strain in the Dolomite and Granodiorite mastics are similar. The maximum creep strains tend to accumulate around narrow gaps between sharp aggregate edges.

The maximum creep strains in the four mastics are compared in Fig. **10**. The Limestone mastic shows the highest maximum value while the Rhyolite shows the lowest one (only 37% of the value from Limestone mastic), and the maximum creep strains in the Dolomite and Granodiorite mastic are in between and the values are close to each other. The asphalt mastic with higher stiffness at 50°C shows better rutting resistance under the same external load.

3.4 Correlation analysis between filler properties and mechanical behaviours of the PA mixtures

In order to investigate the influence of the filler properties (physical properties and chemical composition) on the mechanical behaviours of the PA mixtures, correlation analyses which can reveal mathematical correlations between different sets of parameters were conducted in this study.

The Pearson's correlation matrix results between the filler properties and the mechanical responses of the PA mixtures are shown in Table 5. The R and Sig in this table are the correlation coefficient and the level of significance, respectively. The value of R represents the linear relation between any two variables. It is in the range of -1.0 to 1.0, i.e., a value of -1.0 denotes a perfect negative correlation and 1.0 denotes a perfect positive correlation. The correlation gets weaker when R approaches 0.0 from either side and no relation between variables when R equals to 0.0. The Sig denotes the probability of rejecting the correlation. If Sig is higher than absolute vaule of R, the correlation can be deemed as improbable. The absolute values of R higher than 0.7 are highlighted in Table 5 to easily identify the parameters presenting a correlation.

The results show that the SSA has hardly significant correlation with any computational mechanical responses of the PA mixtures. The other oxides of the fillers listed in Table 2 were ignored, because they made up a very small percent of the material and no significant relations were observed.

When focus on the mechanical responses of the PA mixtures which can be correlated with some fillers properties, it is observed that the load-bearing capacity at 0°C of the PA mixtures is correlated with two physical properties of the fillers (POS and density), while the load-bearing capacity at 50°C is highly correlated with PV and three chemical compositions of the fillers (Al_2O_3, SiO_2, and CaO). The correlation between the von Mises stress and the filler properties is similar with that between the load-bearing capacity at 0°C and the filler properties. The same phenomenon is also observed from the creep strain and the load-bearing capacity at 50°C. It is easily understood that the von Mises stress and the creep strain are also related to the load-bearing capacity of the PA mixtures at different temperatures. But the extents of their correlations with the filler properties are different.

3.5 Performance diagram of PA mixtures with different fillers

In order to evaluate the performance of the PA mixtures with different fillers, a radar diagram or performance diagram was developed in this study.

Fig. **11** shows the performance diagram which is structured in such a way that an improvement in a material property can be expected with an increasing distance from the axis cross. Therefore, the PA mixture with a specific type of filler that covers a larger area in the diagram is believed to have a better performance.

For the case of the PA mixtures with the four fillers evaluated, it is clear that the PA mixture with Granodiorite has the largest area within the performance diagram, followed by the Dolomite, Rhyolite, and the Limestone. As a result, the Granodiorite is the most suitable filler to provide high-performance behaviour (load-bearing capacity, creep resistance and damage resistance investigated in this study) in this kind of PA mixture with the specific base bitumen and temperatures. It is noteworthy that the PA mixture with the Rhyolite shows significantly better performance at higher temperature than the others. Based on this ranking, it is possible to select an optimal filler for a specific material design.

4. Conclusions and Outlook

The influence of the different mineral fillers (Limestone, Dolomite, Rhyolite and Granodiorite) on the mechanical response of PA mixtures was studied using the 2D microstructural FE simulations. The correlation between the mechanical responses of the PA mixtures and the filler properties was analysed based on the computational results and the mechanical performance of the PA mixtures with the different fillers was ranked. The results are summarized by the following aspects:

- At the constant deformation rate of 50 mm/min, the PA mixture with Granodiorite has better load-bearing capacity performance, while the ones with Limestone and Rhyolite have the least favourable performance at 0°C. And the PA mixtures with Rhyolite and Limestone have the best and least performance at 50°C, respectively.
- When the PA mixtures are loaded by 80 N, the distribution of the von Mises stress in the different mastics is similar at 0°C, and only a small amount of a larger values is found. The Rhyolite mastic presents the highest von Mises stress throughout, followed by the Limestone, the Dolomite and then the Granodiorite.
- The most considerable creep occurs in the Limestone mastic and the difference is significant compared with the others. The creep strain in the Rhyolite mastic is the least in the four asphalt mastices.
- The load-bearing capacity at 0°C of the PA mixtures and the maximum von Mises stress in the asphalt mastics have correlations with POS and density of the fillers, while the load-bearing capacity at 50°C of the PA mixtures and the maximum creep

strain in the asphalt mastics are highly correlated with PV and contents of Al_2O_3, SiO_2, and CaO in the fillers.

- According to the performance diagram, the Granodiorite is the most suitable filler to provide a high-performance behaviour in this PA mixtures with the specific tested base bitumen, followed by the Dolomite, Rhyolite, and Limestone. However, the PA mixture with the Rhyolite shows significantly better performance than the others at 50°C.

The different mineral fillers significantly influence the mechanical response of the PA mixtures. The abovementioned conclustions contribute to the current knowledge, and based on this algorithm, it is possible to select an optimal filler for a specific pavement design. However, the 2D computational approach will only provide the qualitative results, i.e., the quantitative results or absolute values from the simulation are not suitable to be directly compared with the experimental results. The further investigation needs to be carried out, for example., 3D FE model with advanced consititutive material laws will be developed. Furthermore, the mechanism of the influence of the chemical properties of fillers on the chemical interaction at the interface between the asphalt binder and the aggregate will be investigated in the future research.

5. Acknowledgements

The work underlying this project was carried out under the research grant numbers FOR 2089/2 (OE514/1-2, WE 1642/1-2 and LE 3649/1-2), on behalf of the grant sponsor, the German Research Foundation (DFG) and the grant number 57446137 funded by German Academic Exchange Service (DAAD) and Universities Australia, as well as the grant number 51978228 funded by National Natural Science Foundation of China.

Data Availability Statement

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

- Geomtry model of PA mixtures in INP format.
- Material properties of PA mixtures.

References

Alber, S., W. Ressel, P. Liu, J. Hu, D. Wang, M. Oeser, D. Uribe, and H. Steeb. 2018a. "Investigation of microstructure characteristics of porous asphalt with relevance to acoustic pavement performance." *International Journal of Transportation Science and Technology*, 7(3): 199–207. https://doi.org/10.1016/j.ijtst.2018.06.001.

Alber, S., W. Ressel, P. Liu, D. Wang, and M. Oeser. 2018b. "Influence of soiling phenomena on air-void microstructure and acoustic performance of porous asphalt pavement." *Construction and Building Materials*, 158: 938–948. https://doi.org/10.1016/j.conbuildmat.2017.10.069.

Anderson, D. A. 1987. "Guidelines for Use of Dust in Hot-Mix Asphalt Concrete Mixtures." *Journal of the Association of Asphalt Paving Technologists*, 56: 492–516.

Antunes, V., A. C. Freire, L. Quaresma, and R. Micaelo. 2015. "Influence of the geometrical and physical properties of filler in the filler–bitumen interaction." *Construction and Building Materials*, 76: 322–329. https://doi.org/10.1016/j.conbuildmat.2014.12.008.

Ban, H., S. Im, Y.-R. Kim, and J. S. Jung. 2018. "Laboratory tests and finite element simulations to model thermally induced reflective cracking of composite pavements." *International Journal of Pavement Engineering*, 19(3): 220–230. https://doi.org/10.1080/10298436.2017.1279491.

Bhattacharjee, S., and R. B. Mallick. 2012. "Effect of temperature on fatigue performance of hot mix asphalt tested under model mobile load simulator." *International Journal of Pavement Engineering*, 13(2): 166–180. https://doi.org/10.1080/10298436.2011.653565.

Blasl, A., M. Khalili, G. Canon Falla, M. Oeser, P. Liu, and F. Wellner. 2019. "Rheological characterisation and modelling of bitumen containing reclaimed components." *International Journal of Pavement Engineering*, 20(6): 638–648. https://doi.org/10.1080/10298436.2017.1321415.

Cooley, L. A., (JR.), B. D. Prowell, and E. R. Brown. 2002. "Issues pertaining to the permeability characteristics of coarse-graded Superpave mixes.", 71: 1–29.

Dassault Systèmes Simulia Corp. 2014. *Abaqus Analysis User's Guide*.

Forschungsgesellschaft für Straßen- und Verkehrswesen. 1999. *Technische Prüfvorschriften für Asphalt im Straßenbau - Teil: Einaxialer Druckschwellversuch - Bestimmung des Verformungsverhaltens von Walzasphalt bei Wärme (TP A-StB)*.

Hagos, E. T. 2008. *The effect of aging on binder properties of porous asphalt concrete*.

Hu, J., P. Liu, and B. Steinauer. 2017. "A study on fatigue damage of asphalt mixture under different compaction using 3D-microstructural characteristics." *Front. Struct. Civ. Eng.*, 11(3): 329–337. https://doi.org/10.1007/s11709-017-0407-9.

Hu, J., P. Liu, D. Wang, and M. Oeser. 2018. "Influence of aggregates' spatial characteristics on air-voids in asphalt mixture." *Road Materials and Pavement Design*, 19(4): 837–855. https://doi.org/10.1080/14680629.2017.1279072.

Hu, J., P. Liu, D. Wang, M. Oeser, and Y. Tan. 2016. "Investigation on fatigue damage of asphalt mixture with different air-voids using microstructural analysis." *Construction and Building Materials*, 125: 936–945. https://doi.org/10.1016/j.conbuildmat.2016.08.138.

Hu, J., Z. Qian, P. Liu, D. Wang, and M. Oeser. 2019. "Investigation on the permeability of porous asphalt concrete based on microstructure analysis." *International Journal of Pavement Engineering*: 1–11. https://doi.org/10.1080/10298436.2018.1563785.

Imaninasab, R., B. Bakhshi, and B. Shirini. 2016. "Rutting performance of rubberized porous asphalt using Finite Element Method (FEM)." *Construction and Building Materials*, 106: 382–391. https://doi.org/10.1016/j.conbuildmat.2015.12.134.

Kavussi, A., and R. G. Hicks. 1997. "Properties of Bituminous Mixtures Containing different Fillers." *Journal of the Association of Asphalt Paving Technologists*, 66: 153–186.

Kim, Y.-R., and D. N. Little. 2004. "Linear Viscoelastic Analysis of Asphalt Mastics." *J. Mater. Civ. Eng.*, 16(2): 122–132. https://doi.org/10.1061/(ASCE)0899-1561(2004)16:2(122).

Kollmann, J., P. Liu, G. Lu, D. Wang, M. Oeser, and S. Leischner. 2019a. "Investigation of the microstructural fracture behaviour of asphalt mixtures using the finite element method." *Construction and Building Materials*, 227: 117078. https://doi.org/10.1016/j.conbuildmat.2019.117078.

Kollmann, J., G. Lu, P. Liu, Q. Xing, D. Wang, M. Oeser, and S. Leischner. 2019b. "Parameter optimisation of a 2D finite element model to investigate the microstructural fracture behaviour of asphalt mixtures." *Theoretical and Applied Fracture Mechanics*, 103: 102319. https://doi.org/10.1016/j.tafmec.2019.102319.

Kuang, X., J. Sansalone, G. Ying, and V. Ranieri. 2011. "Pore-structure models of hydraulic conductivity for permeable pavement." *Journal of Hydrology*, 399(3-4): 148–157. https://doi.org/10.1016/j.jhydrol.2010.11.024.

Li, H., J. T. Harvey, T. J. Holland, and M. Kayhanian. 2013. "The use of reflective and permeable pavements as a potential practice for heat island mitigation and stormwater management." *Environ. Res. Lett.*, 8(1): 15023. https://doi.org/10.1088/1748-9326/8/1/015023.

Li, T., P. Liu, C. Du, M. Schnittcher, J. Hu, D. Wang, and M. Oeser. 2020. "Microstructural analysis of the effects of compaction on fatigue properties of asphalt mixtures." *International Journal of Pavement Engineering*: 1–12. https://doi.org/10.1080/10298436.2020.1728532.

Liu, P., J. Chen, G. Lu, D. Wang, M. Oeser, and S. Leischner. 2019. "Numerical Simulation of Crack Propagation in Flexible Asphalt Pavements Based on Cohesive Zone Model Developed from Asphalt Mixtures." *Materials (Basel, Switzerland)*, 12(8). https://doi.org/10.3390/ma12081278.

Liu, P., J. Hu, D. Wang, M. Oeser, S. Alber, W. Ressel, and G. Canon Falla. 2017a. "Modelling and evaluation of aggregate morphology on asphalt compression behavior." *Construction and Building Materials*, 133: 196–208. https://doi.org/10.1016/j.conbuildmat.2016.12.041.

Liu, P., J. Hu, H. Wang, G. Canon Falla, D. Wang, and M. Oeser. 2018a. "Influence of Temperature on the Mechanical Response of Asphalt Mixtures Using Microstructural Analysis and Finite-Element Simulations." *J. Mater. Civ. Eng.*, 30(12): 4018327. https://doi.org/10.1061/(ASCE)MT.1943-5533.0002531.

Liu, P., D. Wang, F. Otto, J. Hu, and M. Oeser. 2018b. "Application of semi-analytical finite element method to evaluate asphalt pavement bearing capacity." *International Journal of Pavement Engineering*, 19(6): 479–488. https://doi.org/10.1080/10298436.2016.1175562.

Liu, P., Q. Xing, D. Wang, and M. Oeser. 2017b. "Application of Dynamic Analysis in Semi-Analytical Finite Element Method." *Materials (Basel, Switzerland)*, 10(9). https://doi.org/10.3390/ma10091010.

Liu, Y., Z. You, L. Li, and W. Wang. 2013. "Review on advances in modeling and simulation of stone-based paving materials." *Construction and Building Materials*, 43: 408–417. https://doi.org/10.1016/j.conbuildmat.2013.02.043.

Manrique-Sanchez, L., and S. Caro. 2019. "Numerical assessment of the structural contribution of porous friction courses (PFC)". *Construction and Building Materials*, 225: 754–764. https://doi.org/10.1016/j.conbuildmat.2019.07.200.

Masad, E., N. Somadevan, H. U. Bahia, and S. Kose. 2001. "Modeling and Experimental Measurements of Strain Distribution in Asphalt Mixes." *J. Transp. Eng.*, 127(6): 477–485. https://doi.org/10.1061/(ASCE)0733-947X(2001)127:6(477).

Mo, L., M. Huurman, S. Wu, and A.A.A. Molenaar. 2009. "Ravelling investigation of porous asphalt concrete based on fatigue characteristics of bitumen–stone adhesion and mortar." *Materials & Design*, 30(1): 170–179. https://doi.org/10.1016/j.matdes.2008.04.031.

Mo, L. T., M. Huurman, S. P. Wu, and A.A.A. Molenaar. 2011. "Bitumen–stone adhesive zone damage model for the meso-mechanical mixture design of ravelling resistant porous asphalt concrete." *International Journal of Fatigue*, 33(11): 1490–1503. https://doi.org/10.1016/j.ijfatigue.2011.06.003.

Rami, K. Z., S. Amelian, Y.-R. Kim, T. You, and D. N. Little. 2017. "Modeling the 3D fracture-associated behavior of viscoelastic asphalt mixtures using 2D microstructures." *Engineering Fracture Mechanics*, 182: 86–99. https://doi.org/10.1016/j.engfracmech.2017.07.015.

Riekstս, K., M. Pettinari, and V. Haritonovs. 2019. "The influence of filler type and gradation on the rheological performance of mastics." *Road Materials and Pavement Design*, 20(4): 964–978. https://doi.org/10.1080/14680629.2018.1428216.

Rochlani, M., S. Leischner, G. C. Falla, D. Wang, S. Caro, and F. Wellner. 2019. "Influence of filler properties on the rheological, cryogenic, fatigue and rutting performance of mastics." *Construction and Building Materials*, 227: 116974. https://doi.org/10.1016/j.conbuildmat.2019.116974.

Scholz, M., and P. Grabowiecki. 2007. "Review of permeable pavement systems." *Building and Environment*, 42(11): 3830–3836. https://doi.org/10.1016/j.buildenv.2006.11.016.

Souza, F. V., and L. S. Castro. 2012. "Effect of temperature on the mechanical response of thermo-viscoelastic asphalt pavements." *Construction and Building Materials*, 30: 574–582. https://doi.org/10.1016/j.conbuildmat.2011.11.048.

Wang, D., P. Liu, Z. Leng, C. Leng, G. Lu, M. Buch, and M. Oeser. 2017. "Suitability of PoroElastic Road Surface (PERS) for urban roads in cold regions: Mechanical and functional performance assessment." *Journal of Cleaner Production*, 165: 1340–1350. https://doi.org/10.1016/j.jclepro.2017.07.228.

Wang, D., P. Liu, H. Xu, J. Kollmann, and M. Oeser. 2018. "Evaluation of the polishing resistance characteristics of fine and coarse aggregate for asphalt pavement using Wehner/Schulze test." *Construction and Building Materials*, 163: 742–750. https://doi.org/10.1016/j.conbuildmat.2017.12.147.

Wang, H., and I. L. Al-Qadi. 2010. "Near-Surface Pavement Failure under Multiaxial Stress State in Thick Asphalt Pavement." *Transportation Research Record*, 2154(1): 91–99. https://doi.org/10.3141/2154-08.

Wang, H., I. L. Al-Qadi, A. F. Faheem, H. U. Bahia, S.-H. Yang, and G. H. Reinke. 2011. "Effect of Mineral Filler Characteristics on Asphalt Mastic and Mixture Rutting Potential." *Transportation Research Record*, 2208(1): 33–39. https://doi.org/10.3141/2208-05.

Wang, H., J. Wang, and J. Chen. 2014. "Micromechanical analysis of asphalt mixture fracture with adhesive and cohesive failure." *Engineering Fracture Mechanics*, 132: 104–119. https://doi.org/10.1016/j.engfracmech.2014.10.029.

Wang, L. 2003. "Stress concentration factor of poroelastic material by FEM simulation and X-ray tomography imaging." *ASCE Engineering Mechanics Conference*.

Wollny, I., F. Hartung, M. Kaliske, P. Liu, M. Oeser, D. Wang, G. Canon Falla, S. Leischner, and F. Wellner. 2020. "Coupling of microstructural and macrostructural computational approaches for asphalt pavements under rolling tire load." *Computer-Aided Civil and Infrastructure Engineering*, 43: 86. https://doi.org/10.1111/mice.12535.

Xie, X., G. Lu, P. Liu, D. Wang, Q. Fan, and M. Oeser. 2017. "Evaluation of morphological characteristics of fine aggregate in asphalt pavement." *Construction and Building Materials*, 139: 1–8. https://doi.org/10.1016/j.conbuildmat.2017.02.044.

Yang, X., Z. You, Z. Wang, and Q. Dai. 2016. "Review on heterogeneous model reconstruction of stone-based composites in numerical simulation." *Construction and Building Materials*, 117: 229–243. https://doi.org/10.1016/j.conbuildmat.2016.04.135.

Yin, A., X. Yang, C. Zhang, G. Zeng, and Z. Yang. 2015. "Three-dimensional heterogeneous fracture simulation of asphalt mixture under uniaxial tension with cohesive crack model." *Construction and Building Materials*, 76: 103–117. https://doi.org/10.1016/j.conbuildmat.2014.11.065.

You, T., R. K. Abu Al-Rub, M. K. Darabi, E. A. Masad, and D. N. Little. 2012. "Three-dimensional microstructural modeling of asphalt concrete using a unified viscoelastic–viscoplastic–viscodamage model." *Construction and Building Materials*, 28(1): 531–548. https://doi.org/10.1016/j.conbuildmat.2011.08.061.

You, Z., S. Adhikari, and Q. Dai. 2008. "Three-Dimensional Discrete Element Models for Asphalt Mixtures." *J. Eng. Mech.*, 134(12): 1053–1063. https://doi.org/10.1061/(ASCE)0733-9399(2008)134:12(1053).

Zhang, Y., and Z. Leng. 2017. "Quantification of bituminous mortar ageing and its application in ravelling evaluation of porous asphalt wearing courses." *Materials & Design*, 119: 1–11. https://doi.org/10.1016/j.matdes.2017.01.052.

Fig. 1. Grain size distribution of the PA8 mixture

Fig. 2. The illustration of the test. (a) DSR Test device. (b) Specimen for strain and frequency sweep test.

Fig. 3. Binary images extracted from X-ray CT gray image. (a) Original gray image. (b) Binary image of air-voids. (c) Binary image of aggregates.

Fig. 4. 2D microstructural FE models. (a) Model 1. (b) Model 2. (c) Model 3.

Fig. 5. Comparison of load–displacement curves from different models with the Limestone at different temperatures. (a) 0°C. (b) 50°C.

Fig. 6. Comparison of load–displacement curves from the PA mixtures with different fillers at different temperatures. (a) 0°C. (b) 50°C.

Fig. 7. Distributions of von Mises stress in the Limestone mastic at 0°C.

Fig. 8. Evolution of the von Mises stress with external load at 0°C.

Fig. 9. Distributions of creep strain in the asphalt mastic at 50°C. (a) Limestone; (b) Dolomite; (c) Rhyolite and (d) Granodiorite.

Fig. 10. Maximum creep strains derived from different mastic at 2 s.

Fig. 11. Performance diagram with normalized data for the PA mixtures with different fillers.

Table 1. Physical properties of the fillers

	Specific surface area [m^2/g]	Pore Volume [ml/g]	Average Pore Size [nm]	Density [g/cm^3]
Limestone	4.1904	0.0168	16.04	2.72
Dolomite	6.4282	0.0202	12.57	2.85
Rhyolite	6.6294	0.0603	36.38	2.62
Granodiorite	18.4665	0.0411	8.9	2.74

Table 2. Oxide composition of the fillers investigated in [%]

	Na_2O	MgO	Al_2O_3	SiO_2	K_2O	CaO	TiO_2	Fe_2O_3	others
Limestone	0.18	2.02	1.29	1.94	0.19	92.97	0.12	0.82	0.46
Dolomite	0.27	26.02	2.26	5.23	0.61	61.97	0.07	1.91	1.60
Rhyolite	1.42	0.41	19.65	65.69	8.98	0.26	0.26	3.04	0.24
Granodiorite	3.22	2.44	18.09	61.70	3.42	2.73	1.04	6.35	0.58

Table 3. Basic technical properties of bitumen 50/70

Indexes	Test value
Penetration@25°C/0.1mm	52
Softening point (R&B)/°C	51.4°C

Table 4. Mix design of the PA 8 mixture

Component	Grain size [mm]	Mass percentage [%]	Apparent density [g/cm^3]	Air void content	bitumen content
Limestone	0-0.063	5.0	2.820	-	-
Diabase	0.063-2	15.0	2.820	-	-
	2-5.6	37.0	2.820	-	-
	5.6-8	43.0	2.820	-	-
Mixture	-	-	2.541	26.2 Vol.-%	6.5 %

Table 5. Correlation coefficients between mechanical properties and filler properties

		SSA [m^2/g]	PV [ml/g]	POS [nm]	Density [g/cm^3]	Al_2O_3 [%]	SiO_2 [%]	CaO [%]
Load- bearing capacity at 0°C	R	0.700	-0.162	**-0.716**	**0.707**	0.063	0.075	-0.251
	Sig	0.300	0.838	0.284	0.293	0.937	0.925	0.749
Load- bearing capacity at 50°C	R	0.329	**0.906**	0.575	-0.424	**0.842**	**0.837**	**-0.913**
	Sig	0.671	0.094	0.425	0.576	0.158	0.163	0.087
Von Mises stress	R	-0.659	0.387	**0.884**	**-0.785**	0.128	0.113	0.028
	Sig	0.341	0.613	0.116	0.215	0.872	0.887	0.972
Creep strain	R	-0.430	**-0.812**	-0.402	0.233	**-0.789**	**-0.786**	**0.902**
	Sig	0.570	0.188	0.598	0.767	0.211	0.214	0.098

SSA: Specific Surface Area, PV: Pore Volume, POS: Average Pore Size, R: Correlation to Pearson, Sig: Significance (2-sided)