The performance of paving block structures with mortar filled joints under temperature loading, accessed by means of numerical simulations

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Paving block structures with mortar filled vertical joints can exhibit a significantly higher load capacity as comparable structures with sand filled joints. For this reason, this pavement construction method is increasingly being used or would be used, respectively, if its performance could be estimated reliably. Specifically, the exact cause of cracks due to cooling in winter has not been fully understood yet and appropriate prediction tools do not exist. This motivated the development of a numerical simulation tool for such paving block structures under temperature loading, which is able to take the brittle failure mechanisms in-between paving blocks and paving blocks and the underlying mortar bed into account. By means of the proposed simulation tool in this paper, basic structural failure mechanisms of such paving block structures, due to different temperature events, could be identified and relationships between crack widths and different bonding strengths as well as installation temperatures were obtained. Finally, estimates for necessary bonding strengths between paving blocks and mortar bed to prevent large (visible) cracks due to temperature loads are given.

Keywords: Paving block structures; numerical pavement simulation; thermal loading; cohesive joint behaviour

1. Introduction

In recent decades, paving block structures have become a frequently used road construction method, especially in urban areas. Unfortunately, when it comes to rigidly laid paving block structures (structures with mortar filled vertical joints), cracks, usually induced by thermal stresses, are a common damage pattern (as exemplarily shown in Figure 1). Apart from the mechanical issues caused by such cracks, they also impair the visual appearance of these, not damaged very attractive, pavements. This greatly reduces the confidence in and acceptance of this type of construction and prevents a more frequent use.

A major reason for this performance problem can be attributed to the lack of appropriate design codes for the construction of rigidly laid paving block structures. In the German-speaking region, they have been considered as a special construction method until now. Nevertheless, in 2007 a guideline ‘Forschungsgesellschaft für Straßen- und Verkehrswesen (2007)’ with recommendations was published and in 2009 the ‘Wissenschaftlich-Technische Arbeitsgemeinschaft für Bauwerkserhaltung und Denkmalpflege (2009)’ disclosed a leaflet. These documents contain execution suggestions as well as material definitions for paving block structures. To avoid temperature-induced damage, both guidelines recommend the use of expansion joints, whereby

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the second also mentions a positive influence of a strong adhesive bonding between the paving blocks and the mortar bed. Most of these recommendations are based on empirical observations and simple design rules, but deeper mechanical explanations are missing. This was the main motivation for the present work, which aims at describing the response of paving block structures due to temperature loading as realistically as possible. Before discussing the objectives of the present work in detail in Section 1.2, a few fundamental considerations are made in the following.

1.1. Fundamental considerations

When a common building material is subject to a temperature load its volume changes. As the temperature increases the body expands (positive strain) and when it decreases the body contracts (negative strain). As long as the deformations of the body are not blocked the body remains free of stress. In case that the temperature is not evenly distributed over the whole body, even if the deformations are not blocked, temperature-induced stresses may occur. When two adjacent elements of a monolithic body are experiencing different thermal loads, their desired deformation is, in general, geometrically not compatible. Therefore, as long as this compatibility is maintained, temperature-induced stresses arise. This is demonstrated by means of a simple numerical model (shown in Figure 2), where two connected layers of a plate (frictionless supported on the bottom) are loaded by different temperatures. While the lower layer is maintained by the initial temperature of 0°C, the upper layer is cooled down to −20°C. The resulting normal stresses in longitudinal direction are shown in Figure 2(b), showing compression in the lower layer and tension in the upper layer. In a very simplified way, a paving block structure can be seen as such a two-layered plate. Then it is obvious that temperature drops, e.g. due to rainfalls or cooling in general, may lead to failure inducing stresses between paving
blocks or between paving blocks and the mortar bed, respectively. In this respect, the initial temperature as well as the magnitude of the temperature drop is significant. Stresses evolve proportional to the difference between the initial temperature and the actual temperature, and cracks occur when the tensile stress exceeds the resisting tensile strength, concluding a low initial temperature is beneficial to prevent cracks. On the other hand, a low initial temperature, e.g. constructing during wintertime, may result in high compressive stresses in summer. A clear statement about the optimal initial temperature can not be made based on such simple considerations. A low initial temperature may prevent the occurrence of cracks, while a high initial temperature leads to less expansion and compressive stresses during summer times. Furthermore, no statement about shear failure between paving blocks and the mortar bed is possible.

Moreover, if a homogeneous plate under constant temperature load can deform freely, the strain within the plate will be constant as well. Therefore, the stress will be constant when only the in-plane deformations are prevented and no bending occurs. Subsequently, we can easily show that the dimensions of such a structure do not affect the thermally induced stresses. This statement can be confirmed by applying the simple force method $\sum_{v=1}^{n} \delta_{uv} \cdot X_v = -\delta_{u0}$ on a simply supported beam, whereby $\delta_{uv}$ represents the compliance, $\delta_{u0}$ the displacement and $X_v$ the unknown reaction force. The corresponding delta values $\delta_{11} = N_1^2 \cdot I_s/EA$ and $\delta_{10} = N_1 \cdot \Delta T \cdot \alpha T \cdot I_s$, with $I_s$ for the beam length, $EA$ for the tensile stiffness, $\Delta T$ for the temperature difference and $N_1$ for the normal force, show that the resulting reaction force in the axis of the beam, $X_1 = -\delta_{10}/\delta_{11}$, is independent on the length of the beam.

A paving block structure is obviously an in-homogeneous structure with specific interactions and more complex boundary conditions. Nevertheless, this simple considerations lead to the assumption that the dimensions of a paving block structure are of no great influence on the stress leading to crack occurrence (which is sometimes claimed by engineers), but, in case of predominant cracks, on their width.

Such and other thoughts are to be investigated by means of numerical models in the present paper. Starting with a brief literature overview, the basic motivation and the research questions pursued are given in the following.

### 1.2. Motivation and research questions

Usually, when it comes to thermally induced stresses in paving block structures, the literature refers to articles dealing with thermal stress in concrete slabs or concrete pavements. Many authors concerned themselves with this topic, wherein only few of them, such as Plannerer (1998), Rostasy and Kraus (2001), Röhling (2005), and Schikora and Eierle (1999), investigated thermal effects due to hydration in the early stage of various concrete constructions. Bondy (1995) and Schweighofer (2011) engaged themselves with thermal stress in concrete
slabs and Maliha (2005) investigated the appearance of cracks in concrete pavements. Other contributions, focusing on the interaction between concrete slabs and base layers, can be found in Kolb (1988), Schütte (1997), and Petersson (1998). But since this construction method has gained significant market shares only recently, not much scientific research work is available yet. To the knowledge of the authors, only one work regarding numerical simulations of rigidly laid paving block structures, namely the dissertation of Buchholz (2010) dealing with thermally induced stresses, has been published. On the other hand, there have been several investigations regarding numerical tools for the performance evaluation of paving block structures with sand filled vertical joints, which can be found in Nishizawa, Matsuno, and Komura (1984), Jacobs and Houben (1988), Huurman, Houben, and Kok. (1992), Lerch (2005), Ascher, Lerch, Oeser, and Wellner (2006), Oeser and Chandra (2010), Füssl, Kluger-Eigl, and Blab (2016), and Hengl and Füssl (2016), to mention only a few of them.

For this reason, the motivation of this work has been to develop a numerical simulation tool which is able to predict the effects of thermally induced stresses in paving block structures with mortar filled joints and their influence on the occurrence of cracks. By focusing on the interactions between paving blocks, as well as between paving blocks and the mortar bed, this simulation tool should allow us to gain new knowledge about the mechanical mechanisms in the structure and to perform mechanically sound simulations which may help us to answer the following, in connection with this building method often discussed, questions:

- What is the impact of the bonding strength between paving blocks and the mortar bed on the mechanical performance of the paving block structure, and can a certain bonding strength be defined and practically achieved at which the structural performance under temperature loading is satisfactory?
- What is the influence of the ambient temperature at construction (installation) of a paving block structure on the occurrence of cracks and, if there is a critical temperature boosting cracking, can shading measures during the construction reduce this effect?
- Based on a better understanding of the mechanical behaviour of paving block structures under temperature loading, how can the benefit of expansion joints be evaluated and how should they be arranged?

In the following section, Section 2, identification experiments giving insight into mechanical properties of the superstructure (paving blocks, joints, mortar bed) are described. In Section 3, the developed numerical simulation tool is proposed. The identification of different response mechanisms, based on the numerical results, represents the main content of Section 4. The findings of various parameter studies are presented within several subsection, like the positive effects of shading measures. A brief summary, concluding remarks and a future outlook are given in Section 5.

2. Identification experiments for the shear strength between paving blocks and mortar bed

2.1. Samples and test set-up

To determine the maximum shear strength between paving blocks and mortar bed a new identification experiment has been developed. The main goal of this experiment was to compare different surfaces of paving blocks (split granite and formwork concrete) and the influence of transverse joints and primer. For the experiments five different samples were produced (Figure 3 (a)–(e)). These were made of three paving blocks (20/10/8 cm) paved on a 5-cm thick porous
Figure 3. Samples for experiments (a–e) top view of different blocks and joints and (f) side view of blocks on mortar bed with filled joints.

Figure 4. Test set-up for shear experiments.

The developed experimental set-up is illustrated in Figure 4. All samples were fixed in position only through the mortar bed. Then, a shear force $S$ with a rate of 200 N/s was applied to the paving blocks on one side of the sample, parallel to the continuous joints. The experiment was stopped when the maximum force $S$ was reached and a clear failure mechanism was formed, respectively.

### 2.2. Test results

For the evaluation of the maximum shear stress between the paving blocks and the mortar bed, the maximum shear force $S$ was divided by the contact surface $A$ of 64,000 mm$^2$ for each test sample. The results for the different variations are given in Table 1.

The results clearly show the better performance of the split granite paving block compared to the formwork concrete paving block. The rough surface of the granite blocks can withstand nearly twice the shear force as the smooth surface of the concrete blocks. Also a difference between the arrangements with and without transversal joints was obtained for the granite block samples. No influence of the transversal joints was observed for the concrete block samples.
Table 1. Accomplished shear experiments at TVFA Vienna.

| Paving Block (cm) | Joint width (mm) | Contact area (mm²) | Dead load (kN) | Contact pressure (MPa) | Shear force (kN) | Shear stress (MPa) | Appearance of fracture | priming slurry | Transverse joint |
|------------------|------------------|--------------------|----------------|------------------------|------------------|-------------------|------------------------|---------------|-----------------|
| Split granite 20/10/8 | 10 | 64,000 | 0.14 | 0.002 | 32.8 | 0.51 | Roughly | no | no |
| Split granite 20/10/8 | 10 | 64,000 | 0.14 | 0.002 | 44.9 | 0.70 | Roughly | no | yes |
| Concrete block 20/10/8 | 10 | 64,000 | 0.14 | 0.002 | 16.5 | 0.26 | Smooth | no | yes |
| Concrete Block 20/10/8 | 10 | 64,000 | 0.14 | 0.002 | 17.9 | 0.28 | Smooth | no | no |
| Concrete block 20/10/8 | 10 | 64,000 | 0.14 | 0.002 | 66.8 | 1.04 | Mortarbed crushed | yes | no |
which showed nearly the same shear strength for both tested samples. The positive influence of a primer could be demonstrated for concrete blocks. The achieved shear stress was four times higher than for concrete blocks without primer, and two times higher than for granite blocks without transversal joints. In Figure 5 the different breaking patterns are displayed. The failure surfaces for the samples (a) and (b) are rough, while for the samples (c) and (d) rather smooth failure surfaces developed. Due to a very good bond between the paving blocks (e) and the mortar bed, partial failure of the mortar bed was obtained.

Because only one sample was tested for each configuration, the obtained results allow only for a first estimate of the bonding strength. Nevertheless, the positive influence of split surfaces and the use of primer are obvious. Further investigations with different mortars and paving blocks are recommended to define appropriate values for load capacity analyses. However, the obtained results provide us with approximate shear strength values between different paving blocks and mortar bed, which will be sufficient for the interpretation of the subsequent numerical results. For this reason, these first experimental results have already been included within this paper.

3. Numerical model

The numerically modelled region of the considered paving block structure is shown in red in Figure 6, with a width $B$ of 40 cm and half the road widths $L/2$ of 2, 4, and 8 m. Symmetry boundary conditions have been applied to all three vertical sectional areas. The exact geometry, the finite-element mesh as well as loading, boundary and interaction conditions are shown in Figure 7. The whole numerical model consists of a paving block superstructure with 5 rows of 20 paving blocks (20/10/10 cm) each, laid in a cross laying pattern. A mean elastic modulus of the paving blocks of 35,000 MPa was obtained by ultrasonic measurements according to Füssl, Kluger-Eigl, Eberhardsteiner, and Blab (2015). The poisson ratio was set to 0.15, the thermal expansion coefficient to $1 \times 10^{-5} \text{K}^{-1}$, and the density to $2.4 \times 10^{-9} \text{t/mm}^3$. A table summarising all assigned material parameters to the numerical model and giving the associated sources can be found in Appendix A.

The interaction between paving blocks (for the 175 vertical joints) is realised by surface-based cohesive behaviour and a generalised traction-separation law. As illustrated in Figure 8, a linear elastic traction-separation relationship is assumed prior to damage and a linear post damage softening response. The area under the red curve in Figure 8(b) corresponds to the fracture energy, which was set to 0.34 mJ according to Trunk and Wittmann (2001). Damage occurs when the maximum of the following ratios, \( \max\{(t_n/t_n^s), (t_s/t_s^s), (t_t/t_t^s)\} \), reaches a value of 1, as defined in Corp. (2016). Thereby, $t_n$, $t_s$, and $t_t$ denote the traction forces in normal and two tangential directions of the respective contact surface, whereas the symbol $\langle \rangle$ is used to take into account that a purely compressive stress state will not initiate damage. The related strength
Figure 6. Considered paving block superstructure and numerically modelled region displayed in red.

Figure 7. Geometry, interactions and boundary conditions of the numerical model, as well as the two main temperature load cases applied.

Values are designated as $t_n^0$, $t_s^0$, and $t_t^0$, respectively. At each contact point an overall damage variable $D$ is introduced, capturing the combined effect of all active damage mechanisms by the introduction of an effective separation variable $\delta_m = \sqrt{\delta_n^2 + \delta_s^2 + \delta_t^2}$, as illustrated in Figure 8(a), according to Camanho and Davila (2002). $\delta_n$, $\delta_s$, and $\delta_t$ denote the separations between two contact surfaces (which belong together) in normal and the two tangential directions, respectively. The damage variable $D$ is then computed as $D = \delta_m^f \ast (\delta_m^{\text{max}} - \delta_m^0)/\delta_m^{\text{max}} \ast (\delta_m^f - \delta_m^0)$, where $\delta_m^f = 2G/t_m^0$ represents the effective separation at complete failure of the interface, with $t_m^0$ as the effective traction at damage initiation and $G$ as the fracture energy. $\delta_m^0$ denotes the effective separation at damage initiation and $\delta_m^{\text{max}}$ represents the maximum value of effective...
separation obtained during the analysis history. This overall damage variable is a scalar which monotonically evolves from 0 to 1 as damage increases and affects the contact stress components as follows: $t_n = (1 - D)\bar{t}_n, t_s = (1 - D)\bar{t}_s, t_t = (1 - D)\bar{t}_t$, where $\bar{t}_n, \bar{t}_s, \bar{t}_t$ refer to the contact stress components predicted by the elastic traction-separation behaviour for the current separations without damage.

Unfortunately, such cohesive interaction models (describing strong softening behaviour) often lead to severe convergence difficulties. To stabilise the numerical solution viscous regularisation of the constitutive equations (an artificial damping procedure) has been applied. Thereby, the traction-separation laws are regularised by the usage of a viscous stiffness degradation variable $D_v$, as defined in $d(D_v)/dt = 1/\mu * (D - D_v)$, where $\mu$ is a viscous coefficient, $D$ denotes the overall damage variable and $dt$ represents the current time step. $D_v$ is substituting the overall damage variable in the damaged response of the stabilised cohesive surface interaction given as $t = (1 - D_v)\bar{t}$. Thereby, the stabilised cohesive interaction permits stresses to be outside the limits of the traction-separation law. Further, $D_v$ is used to update the material tangent stiffness matrix of the softening contact interaction. By using a value of 0.002 for the viscous coefficient $\mu$, the convergence of the simulation has been improved without compromising the results. To exclude a significant influence of this procedure on the numerical solution, the viscous energy dissipation has been compared to the corresponding strain energy to verify that almost no artificial stiffness has been added to the system.

A bedding stiffness of 1400 MPa/mm in normal and 609 MPa/mm in tangential direction was assigned to the vertical joint interactions, to consider the thickness and mechanical behaviour of the mortar within the joints.

Below the superstructure a layer of mortar spans over the whole area with a thickness of 40 mm. Again, the material properties were obtained from experiments performed by TVFA Vienna, giving an elastic modulus of 14,000 MPa, a density of $1.9 e^{-9}$ t/mm³, a poisson ratio of 0.15 and a thermal expansion coefficient of $1 e^{-5}$. The interaction between paving blocks and the mortar bed were again realised with a cohesive surface to surface contact.

The pervious concrete layer underneath the mortar bed has the same areal dimensions but a thickness of 200 mm. The material behaviour is defined by an elastic modulus of 14,000 MPa, a density of $1.9 e^{-9}$ t/mm³, a poisson ratio of 0.15, and a thermal expansion coefficient of $1 e^{-5}$. The interaction law between this layer and the layer of mortar is defined in the same way as the interaction between the layer of mortar and the paving blocks. The whole model, as visualised in Figure 7, is supported in vertical direction by a rigid sub-base layer. This sub-base layer interacts
with the pervious concrete layer in tangential direction by a penalty frictional model with a frictional coefficient of 0.6.

The simulations were divided into two steps, first, the dead load of the paving block structure and, second, a static temperature gradient, defined by analytic fields, were applied. To define the temperature gradient the minimum temperature for the region of Vienna according to Wistuba (2003) was used. Although these temperature profiles are intended for asphalt pavements, due to the fact that the specific heat capacities of asphalt and concrete lie close together (at around 0.92 and 0.88 m²/s), they could be also used for the investigated paving block structures. Differences in the thermal conductivity could be neglected too, considering the long periods of night and day temperatures of several hours. In layers below the mortar bed, the used temperature gradient could differ in a greater extent, due to the lower density of the material. To find out about these deviations, temperature measurements are ongoing on full-scale paving block structures at TU Vienna.

All FE simulations were run with the commercial Finite-Element Software Abaqus, taking into account geometric non-linearity. More than 200 simulations were carried out on a HPC-cluster system at TU Vienna with an average total CPU time of 7.7 h for a 8 m model with 315 822 DOFs. In the course of the simulations, the maximum cohesive strength between paving blocks and the mortar bed, the maximum cohesive strength in-between paving blocks, the applied temperature, the model widths and the laying pattern have been varied.

4. Numerical results

4.1. Identification of response mechanisms under cooling

The cohesive strength between paving blocks and the underlying mortar bed is certainly one of the most important factors in determining the performance of such a structure under temperature loading (cooling). It can be assumed that the experimentally obtained strength values in Section 2 are not always reached in practice, especially not continuously over large areas. Laying paving blocks on already hardened mortar bed, for example, might result in a greatly reduced bonding strength.

This motivated the following simulation program, where the performance of a paving block structure with 15 different cohesive strength values varied from 0.00001 MPa up to 10 MPa has been investigated. The whole possible range of bonding, between paving blocks and mortar bed, in practice should therefore be covered and all possible response mechanisms should be obtained. Figure 7 defined load case ‘winter’ has been applied to all 15 configurations and as performance parameter the maximum occurring crack width \( w_{cr} \), defined as the maximum separation between two adjacent paving blocks, was chosen. The obtained maximum crack widths as a function of the cohesive shear strength between paving blocks and mortar bed, \( \tau_{crit} \), are plotted in Figure 9. It can be seen clearly that there is no smooth decrease in crack width with increasing cohesive strength. For very low as well as very high cohesive strength values the maximum crack width is almost constant, whereas a much larger crack width is obtained for a low bonding strength between paving blocks and mortar bed. The transition from one crack width plateau to the other takes place very quickly, which makes it possible to define a so-called transition zone, denoted as Region 3 in Figure 9. The cohesive strength areas divided by this zone are designated as Region 1 and Region 2, respectively. By comparing this relationship with the corresponding deformation fields of the paving block structures, also three different basic failure mechanisms, which can be related to the three different regions defined in Figure 9, can be distinguished:

Region 1: In case of a very low cohesive strength between paving blocks and mortar bed only a single distinct crack occurs and, consequently, a large maximum crack width is established.
Figure 9. Maximum occurring crack widths $w_{\text{max}}$ as a function of the cohesive shear strength $\tau_{\text{crit}}$ between paving blocks and mortar bed, and the three identified regions showing different structural failure mechanisms.

Such a mechanism is shown in Figure 10 (a), for a cohesive strength of 0.00001 MPa, leading to a single crack of 0.29 mm. All the vertical joints between other paving blocks remain closed or have at most a small opening which can be attributed to numerical regularisation. Due to a perfectly homogeneous cohesive strength distribution between the paving blocks and the mortar bed, the single crack occurs close to the boundary of the model, triggered by the slightly higher local structural stiffness induced by the boundary conditions. This result is in good agreement with observations in the field, where indeed very often large cracks develop in the boundary regions of roads. However, this single crack could occur at any point in the structure where the structural stiffness is locally increased. This could be caused by stiffness differences in the mortar bed, a locally better toothing of joint mortar and mortar bed, or various structural installations preventing a thermal contraction of the superstructure.

Region 3: The opposite case is represented by a structure with a very high bonding strength between paving blocks and mortar bed, which is exemplarily illustrated in Figure 10(c) (cohesive strength of 1 MPa). For these cases, a diffuse network of cracks has been developed, with a maximum crack width of 0.027 mm, being only one-tenth of the crack width obtained for models of Region 1. The paving blocks are more or less rigidly embedded into the mortar bed and, thus, transmit shear forces directly into the underlying layer. Each paving block deforms independently of the others and, thus, the resulting crack width seems to be only a function of the single paving block characteristics and the applied temperature loading. Paving blocks with larger dimensions would in this case lead to wider cracks, which would not be the case in Region 1.

Region 2: Finally, the transition zone between Region 1 and Region 3 is designated as Region 2, consisting of paving block structures which show both distinct cracks and additionally fine cracks between other paving blocks. An example is shown in Figure 10(b), having a cohesive strength of 0.005 MPa. This failure pattern represents a logical intermediate state between the two others, and it is important to show that the numerical simulation tool is able to capture such ‘mixed’ failure mechanisms accurately. A reliable identification of the (practically
Figure 10. Illustrative failure mechanisms for the three identified regions: (a) single distinct crack, (b) mixed mode, and (c) fine crack network. (a) $\tau_{\text{crit}} = 0.00001$ MPa (Region 1), (b) $\tau_{\text{crit}} = 0.005$ MPa (Region 2) and (c) $\tau_{\text{crit}} = 1$ MPa (Region 3).
relevant) transition zone, Region 3, should therefore be possible for different types of paving block structures.

The found relationship in Figure 9 and the qualitative division into three regions based on failure mechanisms could be an important insight for the further development of such paving block structures. It could be aimed at a bonding strength which ensures that no single distinct cracks occur.

Nevertheless, more loading cases and model configurations need to be investigated to reliably identify cohesive strength values at which the critical Region 2 starts. This has been done in the following.

4.2. Parameter studies

To figure out in which way the most important structural parameters influence the response of the model structure, e.g. the location of the three identified regions above, the following characteristics have been varied: (a) The road width, (b) the construction temperature, which was set to 5°C for all previous simulations, and (c) the bonding strength of the mortar in the vertical joints.

(a) Road width

As mentioned within the fundamental considerations in Section 2, the dimensions of a homogeneous body do not influence its thermally induced stresses under specific assumptions. Nonetheless, for the paving block structure considered, showing in-homogeneous failure mechanisms, the width \( L \) of the road strongly influences the maximum crack width \( w_{\text{cr}}^{\text{max}} \), as shown in Figure 11. The two additionally investigated road widths of \( L/2 = 2 \) and \( L/2 = 8 \), result in lower and higher, respectively, maximum crack widths. Understandably, this is only the case for Region 1, where single distinct cracks occur. In this region large parts of the structure behave as monolithic block and, thus, the length of the structure strongly influences the crack width. Interestingly, it seems that the maximum crack width increases overlinear with respect to the road width. In Region 2, the road width does not affect the maximum crack width, which is in good agreement with the above-made observation that in this case the crack widths are only a function of the single paving block characteristics. Despite the large differences in Region 1, the location of the transition zone (Region 3) is hardly affected. This gives reason to believe that a certain bonding strength, ensuring a paving block structure to behave according to Region 2, may possible be defined.

(b) Construction temperature

Since in reality the construction temperature can be higher than the assumed 5°C in previous simulations, the relationship presented in Figure 9 has also been determined for 15°C, 30°C, 45°C, and 60°C installation temperature (see Figure 12). The final temperature, however, was kept constant as defined by the ‘winter’ loading case shown in Figure 7. As expected, the maximum crack width increases with increasing installation temperature. But, also the critical cohesive strength value, defining the begin of the transition zone, increases one order of magnitude from about 0.01 MPa (for 5°C) to about 0.1 MPa (for 60°C). Comparing the latter value to the experimentally obtained strength value of 0.28 MPa for conventional concrete paving blocks (also given in Figure 12), we can note that the boundary of the transition zone comes very close to the measured values. Assuming that the bonding strength under laboratory conditions represents an upper bound to the strengths reached in the field, it is not unlikely that in practice paving block structures fall into the transition zone, Region 3. According to these simulation results, there is a risk that a combination of poor execution standards and high installation temperatures lead to
large distinct cracks due to cooling events in winter. This could explain practical observations of elusive damage of certain paving block constructions.

(c) Bonding strength of vertical joints
Finally, the effect of the cohesive tensile strength between paving blocks (mainly determined by the mortar of the vertical joints) on the previous findings was of interest. Thus, the relationship proposed in Figure 9 has been extended to this strength, denoted $\sigma_{n,\text{crit}}$, in the third dimension.
Figure 13. Influence of the cohesive shear strength between paving blocks and mortar bed $\tau_{\text{crit}}$ and the cohesive tensile strength of the vertical joints between paving blocks $\sigma_{n,\text{crit}}$ on the maximum occurring crack widths $w_{\text{cr}}^\text{max}$.

(see Figure 13). The influence of $\sigma_{n,\text{crit}}$ on the identified three regions is negligible. Interestingly, the crack width of a single distinct crack according to Region 1 increases with increasing bonding strength $\sigma_{n,\text{crit}}$ up to 2 MPa. A significant increase of the maximum crack width from about 0.25–0.35 mm was obtained, which can be traced back to an even higher stress and, subsequently, structural deformation concentration at the location of the critical crack. Accordingly, with respect to cracking, a higher cohesive tensile strength in vertical joints between paving blocks is not necessarily an advantage. Although, an additional data series with a cohesive strength between paving blocks of 4 MPa, which has been excluded from the graph for illustrative reasons, showed no cracking anymore. However, this strength will not be achievable with conventional construction methods.

### 4.3. Influence of non-constant construction temperature

In all former simulation the construction temperature (initial temperature) was constant throughout the paving block structure, because no reliable information about temperature gradients during the construction process were available. However, they were not necessary to obtain the desired statements. Nevertheless, hydration of the mortar bed as well as solar radiation during the installation phase might lead to in-homogeneous initial temperature distributions, which subsequently influence the occurrence of cracks in a positive or negative way. A fictional but realistic in-homogeneous temperature profile is shown in Figure 14(a), where the surface is heated by solar radiation from 5°C to 15°C and the temperature of the mortar bed is slightly increased.
(10°C) due to hydration. On the other hand, Figure 14(c) shows a temperature profile only characterised by the heated mortar bed, in case that the solar radiation is avoided by using shading measures on the construction site. Again, both models were loaded with a temperature field finally leading to the temperature distribution defined in Figure 7 for the load case ‘winter’. The corresponding deformation fields can be found in Figures 14 (b, d), respectively. In case of no shading measures (surface temperature of 15°C), a maximum crack width of 0.52 mm was obtained, while in the second case, where the surface temperature was assumed to be 10°C lower, the crack width reduces to 0.39 mm. Thus, a 33% higher crack width $w_{\text{max}}^{\text{cr}}$ is established only due to a higher surface temperature. Based on this numerical result, it can be assumed that shading or cooling measures during construction are useful to reduce the risk of large cracks during wintertime. This has been an ongoing controversial topic in engineering practice.

4.4. Expansion behaviour due to temperature increase during summer time

According to Figure 12, a low construction temperature is preferable to avoid cracks during wintertime. Unfortunately, such low construction temperatures lead to a larger expansion of the superstructure in summertime, which may result in critical compressive stresses or lift off of the paving block superstructure. Such a lift off of paving blocks from the mortar bed can be observed regularly during summertime. To investigate this effect, simulations have been performed with a constant construction temperature of 5°C and a summer temperature distribution according to Wistuba (2003), as defined in Figure 7. The cohesive tensile strength, $\sigma_{\text{crit}}^{n}$, has been varied from 0.00001 to 1 MPa and the corresponding maximum lift off $w_{\text{lo}}^{\text{max}}$ has been evaluated. The obtained relationship is shown in Figure 15 and two related deformation fields, showing the lift off of the paving block superstructure, are illustrated in Figure 16. Similarly to the parameter studies presented before, a highly non-linear relationship between the bonding strength and the considered performance parameter, in this case the amount of lift off $w_{\text{lo}}^{\text{max}}$, has been obtained. The transition zone, however, between ‘good’ and ‘bad’ performance is slightly larger. Allowing a rotation of the curbstone, a lift off, as can be seen in Figure 16, was obtained for low values of the cohesive tensile strengths between paving blocks and the mortar bed. But, according to Figure 15, a cohesive tensile strength of about 0.1 MPa seems to be sufficient to avoid this phenomenon.
Figure 15. Maximum lift off $w_{\text{max}}^{\text{lo}}$ of the paving block superstructure under load case ‘summer’ as a function of the cohesive tensile strength $\sigma_{n,\text{crit}}$ between paving blocks and the mortar bed.

Figure 16. Illustration of lift off of the paving block superstructure due to load case ‘summer’, for two different cohesive tensile strengths between paving blocks and mortar bed. (a) $\sigma_{n,\text{crit}} = 0.01 \text{ MPa}$ and (b) $\sigma_{n,\text{crit}} = 0.00001 \text{ MPa}$.

Interestingly, the limit value of cohesive tensile strength (around 0.1 MPa), ensuring no lift off of the paving block structure, is of the same order of magnitude as the necessary cohesive shear strength to avoid distinct cracking.

5. Conclusions and outlook

In this paper, a numerical simulation tool has been proposed allowing for a realistic reproduction of failure mechanisms of paving block structures with mortar filled vertical joints under temperature loading. Temperature loads, representing cooling periods in winter as well as heated paving block structures in summer, have been applied using analytical fields. Cohesive interaction behaviour between paving blocks and between paving blocks and the mortar bed gave access to crack widths, which were assumed to be an important performance evaluation characteristic.
The structural behaviour of numerical models with up to 556 cohesive interactions could be investigated stable. Therefore, it was necessary to employ viscous damage damping, but special attention was paid that viscous forces are ramped down sufficiently and comprehensive parameter studies were conducted to ensure the smallest possible effect of these regularisation measures.

Several hundred simulations with different bonding strength between paving blocks and paving blocks and mortar bed, temperature loading situations, and road widths have been performed to obtain a comprehensive picture of the mechanical behaviour of such pavement superstructures. Based on this extensive simulation program, two different failure mechanisms due to cooling in winter time could be distinguished and a rather small transition zone between them was identified. If there is a low bonding strength between paving blocks and mortar bed it is very likely that distinct single cracks will occur, while a rather fine crack network can be assumed in case of a high bonding strength. Since this fine cracks, distributed over the whole superstructure, are probably not be seen with the naked eye or even do not occur due to the not considered relaxation of mortar in the vertical joints, respectively, this case should be aimed at in practice. Thus, it is of outmost interest to identify the transition zone between those two failure mechanisms, which has been done in this work for several configurations.

Based on these investigations, answers to the three questions raised in the introduction can now be formulated:

- The bonding strength between paving blocks and mortar bed indeed seems to have a very large impact on the performance of a paving block superstructure under temperature loading. A characteristic shear strength larger than 0.1 MPa avoids the occurrence of distinct large cracks according to the performed numerical investigation, even under the worst-case scenario of very high installation temperatures (up to 60 °C). Shear strength values between 0.26 and 0.28 MPa were obtained experimentally for concrete paving blocks, and would therefore be sufficient. However, these values were obtained under laboratory conditions and, therefore, provide rather upper limits for the bonding strengths in the field. Thus, it is quite probable that a combination of poor execution and high construction temperatures cause paving structures to behave as it was numerically obtained for the transition zone, Region 3. This could be an explanation for elusive damage to paving block structures, frequently observed in engineering practice.

- A low installation (construction) temperature is basically beneficial to prevent cracking due to cooling during winter time, but it can lead to high compressive stresses and lift off of the paving blocks in summer. However, according to the performed simulations, a bonding strength of 0.1 MPa, in shear as well as normal direction to the interface between the paving blocks and the mortar bed, should be sufficient to avoid both distinct cracking in winter as well as lift off of the paving block superstructure in summer. Additionally, the numerical results give reason to believe that shading measures, in case of high solar radiation, are of benefit with respect to cracking in winter time.

- Based on the findings of this paper, expansion joints through the paving block superstructure only seem to be useful if the mentioned critical bonding strength cannot be reached and single large cracks are likely to occur. If only failure mechanisms according to Region 2 (fine crack network) arise, expansion joints lose its purpose and may be omitted as long as the structure and connected installations can resist the compressive stresses in summer and an adequate bond between mortar bed and the pervious concrete layer is provided. Following this approach, also the challenge to predict the right location of expansion joints, which was seen often failed in retrospect, could be avoided.
In summary, the proposed numerical simulation tool allowed us to shed light on some unanswered questions regarding the performance of paving block structures with mortar filled joints, even if they cannot be answered fully yet. Further investigations will focus on different laying patterns, as exemplarily shown in Figure 17, combined temperature and traffic loading and the description of more complex failure mechanisms (including cracking through paving blocks). Furthermore, similar to the work in Füssl, and Blab (2015) and Füssl, Hengl, Eberhardsteiner, Kluger-Eigl, and Blab (2016), the mechanical response under vertical loading will be investigated numerically. Also additional identification experiments on the mortar bed’s cohesive strength to the pervious concrete layer are contemplated.

Disclosure statement
No potential conflict of interest was reported by the authors.

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