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THERMO – MECHANICAL MODEL OF CONCRETE PAVEMENT IN HARDENING PHASIS

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Abstract

This paper is focused on the analysis of concrete pavements using finite element method (FEM). Specifically, it deals with the analysis of temperatures in the initial phasis of hardening and their influence on mechanical behavior of concrete pavement. High temperatures from hydration and climatic conditions in the early phase of concrete hardening co-operate and may initiate the formation of a network of micro-cracks on the surface of the concrete slab. The resulting temperatures (from hydration and climate) can theoretically be positively influenced by determining the start of concreting, so that the maximum temperatures do not meet at the same time. However, from a practical point of view the use of retarders is more realistic. Another possibility is to reduce the hydration heat by changing the composition of the concrete mixture (amount of cement, type of cement, use of alternative binders). Based on the knowledge of the material composition of the concrete and the specific temperature behavior during the concrete laying, it will be possible to predict the durability of concrete pavement in the future. Using weak formulation FEM model with quadratic base functions, the 2D heat transfer model was created. Boundary conditions were determined from experimental measurement on highway D1 in the Czech Republic. When this model was fitted to experimental data, the 3D coupled thermo - mechanical model was created. Soil and concrete elastic material characteristics had been taken over from Czech technical norms. Soil was modelled as Winkler-Pasternak 2D plate. Parameters c1 a c2 were assessed from comparison with 3D model with soil modelled as multiple layer system.

Keywords: concrete, pavement, FEM, cement hydration, heat transfer

1 Introduction

Rigid pavements are assumed to be loaded by combination of wheel load and linear temperature distribution over its thickness. The effects of thermal stress are determined for the maximum temperature differences of the upper and lower surface, usually assuming a linear temperature distribution over the thickness of the concrete slab. When determining the effects from temperature, the self-weight due to the stresses caused by the activation of the bending moment when the plate is bent (positive or negative temperature gradient) is a significant influence. The most significant fatigue stresses (tensile stresses) of the concrete pavement during its service life are from the combination of time-varying temperature and wheel loads. We can use numerical solutions [9] to analyze the phenomena, in this paper the FEM software OOFEM [1] is used.

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The goal is to evaluate time dependent mechanical behavior from temperature loading. Temperature behavior is solved independently in heat transfer model, taking into account climatic boundary conditions and cement hydration. The temperature field obtained from this model is then exported to mechanical model, that evaluates stress and strain behavior of concrete pavement.

However, in order to correctly predict the future behavior of the concrete pavement, it is necessary to pay attention to the construction process of the concrete slab and take into account the conditions, under which it was made (air temperature, foundation system, sunlight, treatment after construction), in different words to monitor and influence the temperatures during the construction. The primary precondition for a more accurate determination of service life is the accuracy of the input data, such as specific concrete formula (water content, amount of cement, types and amounts of additives and admixtures, etc.) for road concrete. Changes in the approach to pavement concrete recipe [4] are currently being discussed in the Czech Republic, this should lead to more ductile concretes, rather than achieving the highest possible strength (i.e. use of less cement, use of mixed cements, higher water content). The above can affect the speed (slowing down) of hydration and thus reduce the formation of microcracks, which in the future may be a significant source of failure of the concrete pavement. Current state of work is limited to elastic material properties, the future progress should be related to usage of damage models or viscoelastic material parameters with aging, such as B3 [11] or MPS [12] model for concrete creep. Another field of interest should be moisture transfer [10] in concrete pavement and creation of complex coupled hygro-thermo-mechanical model. Heat and moisture transfer with cement hydration for concrete pavements were done before [13], but there several new viewpoints to be still observed.

2 Long-term temperature monitoring on the D1 highway

In the summer of 2018 during construction of the D1 highway (the section between Přerov and Lipník nad Bečvou) temperature and strain gauges were installed. The monitoring is still underway, and we now have data from construction and from service phasis. The monitoring is carried out in cooperation of CTU, VUT, Skanska and ŘSD (Road and Motorway Directorate of the Czech Republic) under leadership of Vít Šmilauer from CTU.

In this test section, the use of cement with slag admixture (CEM I 75 % and 25 % slag) is tested, instead of pure Portland cement (CEM I 100 % used exclusively for concrete highways in Czech Republic). The pavement consists of not reinforced concrete slabs, made using two-layer concreting. Dowel bars were inserted into the transverse joints as usual and anchors were placed in the longitudinal joints to prevent the plates from moving relative to each other. The gauges were placed at a safe distance from shrinkage joints. The lower layer of concrete was laid in the thickness of 240 mm and the upper layer in thickness of 50 mm.

As part of the monitoring a total of 18 gauges (18 temperature and 18 strain gauges) were installed in 6 places. In each place 3 gauges were installed in different height levels at (-50, -140 and -240 mm from the surface, see Fig. 1). At the same time gauges were installed to measure solar radiation and air temperature.

Figure 1 Placement of gauges (Photo: S. Šulc)

3 Use of monitoring for thermo-mechanical analysis

After performing the experimental measurement, it was necessary to process a large amount of data and create a mathematical description of the functions that would best describe the phenomena of air temperature and sun irradiation. The two functions were created to describe the weather conditions during the four days after constructing of the pavement, the functions describe representative summer days. First the function which describes the course of the air temperature (Fig.2). In the longer term this phenomenon can be described with a different function. However, for this numerical analysis it was only necessary to capture the range that had to be simulated (in this case four days). Furthermore, a more complex function was created which describes sun irradiation (based on Stefan-Boltzmann's law) again within four days after construction (Fig.2). These functions can be adjusted for specific weather conditions by simply changing the constants.

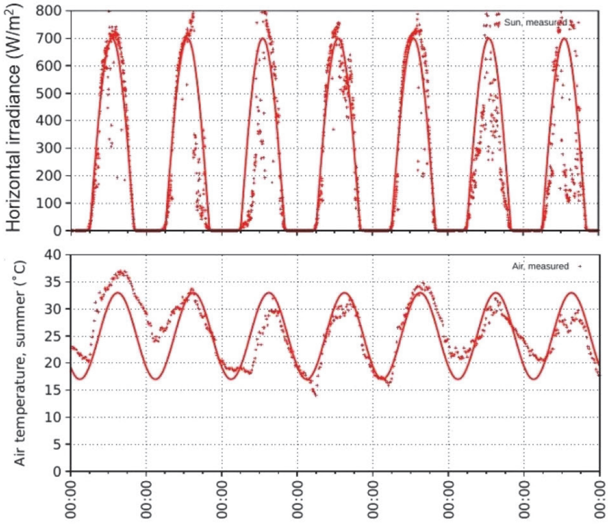

Figure 2 Comparison and validation of the two functions for sun irradiation (upper) and air temperature (lower) with experimental data

4 2D Heat transfer analysis of concrete pavement

Based on the experimental data, a 2D model was created, that contains the functions (1) and (2) as boundary conditions. Cement hydration model is implemented (“HydratingConcreteMat” [5]), it uses material parameters (potential heat of hydration, cement content, activation energy and others obtained from measurements with an isothermal calorimeter) and works with the hydration of cement over time. 2D model of heat conduction solves the balance equation

$$-\nabla^T q(x) + \bar{Q}(x,t) = \rho(x) c_v(x) \frac{\partial T(x,t)}{\partial t} \tag{1}$$

where: q is heat flux, Q is heat from hydration, T is temperature field.

The model was created as one half of the concrete slab (section in the longitudinal direction) due to the optimization of the computational task and assumption of axial symmetry. We assume that higher temperature profiles have a direct effect on reducing road durability [8], as higher temperatures accelerate cement hydration and increase shrinkage. Shrinkage cannot be completely removed but its size can be reduced significantly. There are several possible ways to achieve the reduction. It is possible to use other types of binder which would significantly slow down the so-called “kinetics” of hydration, it would reduce the development of hydration heat and thus reduce the formation of cracks and microcracks. The influence of different types of cement on the resulting temperature is evident from Fig.3. Material parameters were taken from the literature ([2] and [3]). The created model therefore allows the analysis of specific conditions for hardening phasis of road concrete in terms of temperature. Its use for various analyzes is obvious.

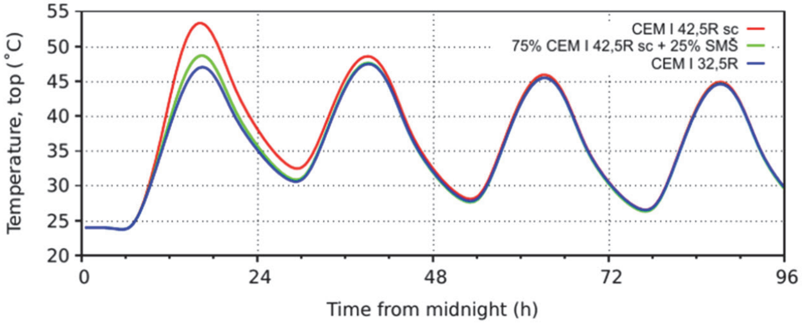

Figure 3 Influence of the type of cement binder on maximal temperature on the slab surface

5 Influence of the time, when the construction begins on the maximal temperature in the concrete slab

The created 2D model for heat conduction was also used to analyze the effect of the time, when we carry out the construction of the slab (four summer days) on the resulting temperature on the top of the slab. The results are interesting. Construction companies (for practical reasons) usually start the construction in the early morning during summer days. This setting results in the worst temperature combination where the maximal temperature from the hydration of the binder reaches a maximum value together with the highest daily air temperature. It is also favorable to delay the temperature peak because of mechanical properties of concrete. The total temperature profiles on the upper and lower surface of the slab depending on the beginning of concreting are evident from Fig. 4 and Fig. 5. Theoretically, it would be more appropriate to start the construction process in the afternoon during summer, based on this model. However, it will be necessary to validate this during real construction to approve this assumption.

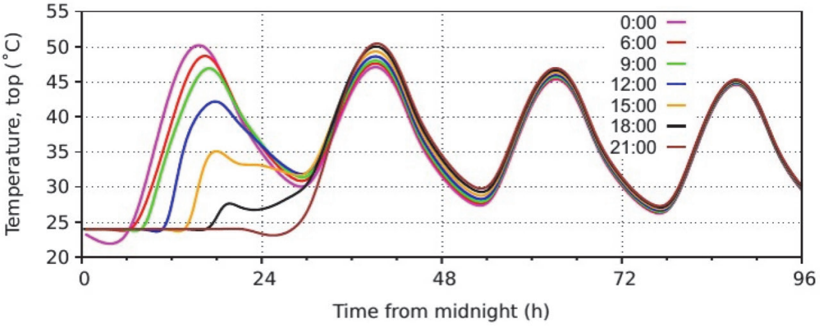

Figure 4 Influence of the time, when the construction begins on the maximal temperature on the slab surface

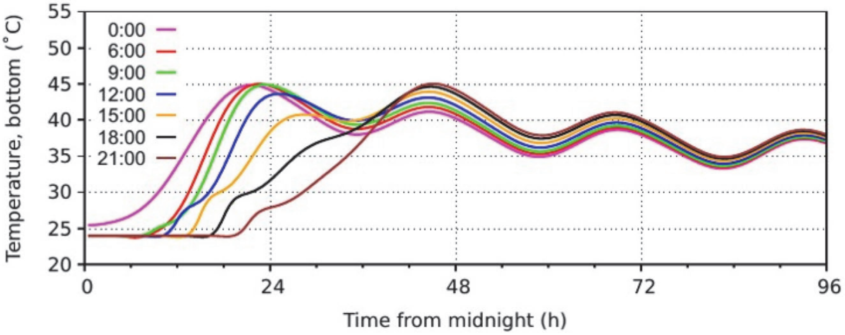

Figure 5 Influence of the time, when the construction begins on the maximal temperature on the slab bottom

6 3D Thermo - mechanical analysis of concrete pavement

The most important part for us is to obtain stress and strain fields from the time variable heat transfer task shown above. This can be achieved by weakly coupled thermo-mechanical task. The principle is that in each individual step of the calculation, the temperature field is calculated using the heat transfer model and then “exported” to the “mechanical” model as loading (MUPIF framework). This requires the creation of a “3D - heat transfer model”, this can be quite easily achieved by rewriting the previous 2D model. Then we must create the 3D mechanical model for concrete pavement, that should be able to cope with the temperature field in the requested way [6]. The 3D mechanical model was considered as 3D slab with elastic material parameters on the Winkler - Pasternak (W-P) subsoil [7]. It was also necessary to assign parameters to the individual materials, relating to thermal capacity, thermal conductivity and thermal expansion. The development and more accurate modeling of this task is expected in the future, because in the hardening phase the stiffness of the cross-section changes considerably and for a more accurate description, it will be necessary to use for example viscoelastic material with aging, moisture transfer and shrinkage. The interface between W-P and concrete slab is represented by non-linear interface elements with different stiffness in tension and compression. When certain tensile deformation is exceeded, the separation of the slab is allowed. As shown in the Fig.6 and Fig.7, we obtain quite significant reduction of stress using blend of CEM I 42,5 with slag against pure CEM I 42,5, with both separated from the W-P subsoil.

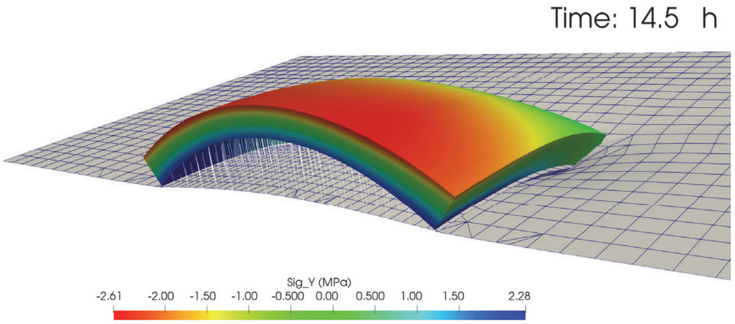

Figure 6 Stress field at 14:30, 8:30 after beginning of construction with only CEM I 42,5

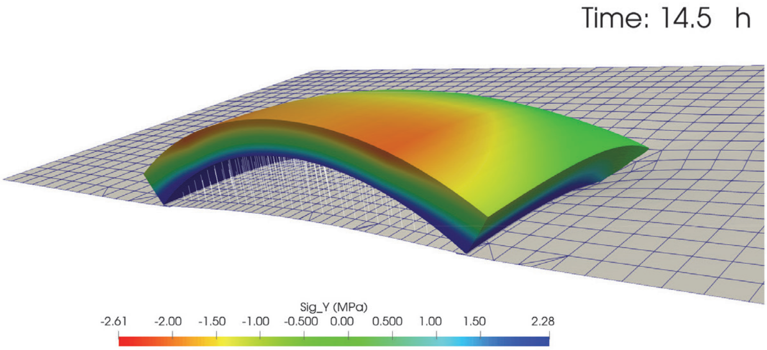

Figure 7 Stress field at 14:30, 8:30 after beginning of construction with blend of CEM I 42,5 with slag

7 Conclusion

The thermo-mechanical model of the concrete pavement helps to better understand the processes in concrete during the construction and hardening of concrete, considering the type of material and external temperature conditions. Future analysis and results of thermo-mechanical models with variable material properties and temperature conditions may lead us to determine the ideal parameters during construction. The aim should be the reduction of the formation of more microcracks in the initial phase of concrete hardening. This would positively affect (extend) the life of the concrete pavement. Further use of these models is possible in predicting the residual life of the concrete pavement and thus future applications in road management systems. We can also validate usage of less resource and environmental draining binder than pure Portland cement.

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