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INFLUENCE OF BONDING CONDITION ON MECHANICAL PERFORMANCE OF SYNTHETIC SPORTS SURFACES BY FEM[1]

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The purpose of the study was to evaluate the effect of interlayer bonding conditions on the mechanical performance of a synthetic sports track with time. A two-dimensional finite element model of the synthetic sports track was developed in order to calculate the track temperature stress and strain in thermal environmental conditions. Thermal and structural responses of the multi-layer sports ground were simulated using a transient thermal and structural analysis in one day. Based on that, different physical parameters of the interlayer were considered to analyze the influence of the bonding layer status on the potential damage of the surface layer in the sports track. The results indicated that different bonding conditions would affect the strain difference between the top and bottom of the synthetic sports layer, which might cause a weak mechanical performance of the synthetic sports layer. Finally, 2D finite element analysis was regarded to be a proper tool to simulate the transient thermal and mechanical behavior of the synthetic sports track. The suggested simulation model can predict the influence of bonding conditions on damage of the synthetic sports track, which can provide some guidance for engineers and technicians working on constructions of synthetic sports tracks.

Keywords: bonding condition, synthetic sports surface, finite element method

1. Introduction

Modern synthetic surfaces are special surfacing systems. Compared with other surface systems, they have not only superior dynamic characteristics but also hardly need any maintenance (World Athletics, 2019). It is a high-performance system with durable design which can provide athletes with the best combination of dynamic performance (World Athletics, 2019). As a part of sports facilities, synthetic surfaces are increasingly used in many athletic grounds. However, some damage, for example, crack of a synthetic surface layer and separation between every layer often occur with an increase of service time. Moreover, various damage of synthetic surfaces in sports tracks still occur before the surface materials have achieved their fatigue life. The synthetic sports track has a structure similar to highways. Cracks in highways are an important cause of structural degradation which increases the cost of pavement maintenance and rehabilitation (Kim and Buttlar, 2009). Cracks in a synthetic athletic track are also the same. Cracking of an athletic track may occur due to daily thermal changes (Kim and Buttlar, 2015). Especially, the cyclic temperature changes are one of the main reasons of pavement cracking (Chun *et al.*, 2015). Because of thermal expansion and cold contraction, seasonal and daily temperature changes would lead to thermal contractions of every layer of the pavement resulting in the critical tensile stress in the pavement materials (Mukhtar and Dempsey, 1994). Just like the road pavement, the synthetic sports track is also in the same situation. And additional concentrated tensile stress in

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the overlay may be caused due to shrinkage of discontinuities around the exiting joints or cracks in the underlying layer (Kim and Buttlar, 2015).

Based on two types of modern synthetic sports track surfaces: precast sheets and in-situ systems, different construction schemes have different types of surfaces (Wang *et al.*, 2019). The base layer is always asphalt concrete regardless of constructional solutions of the modern synthetic athletic tracks (Wang *et al.*, 2019). In prefabricated sheets systems, the synthetic surface and asphalt base layer are bonded by a weather-sensitive adhesive (World Athletics, 2019; Wang *et al.*, 2019). In the in-situ systems, synthetic surfaces are paved above the asphalt base layer directly (World Athletics, 2019; Wang *et al.*, 2019). There should be no water or steam in the construction when the related synthetic material is paved accordingly with construction regulations. However, water vapor from the ground is inevitable, especially in summer. All those may affect the bonding conditions between the synthetic surfaces and the base layers. Figure 1 shows some forces which the synthetic sports track may sustain. When the first crack appears

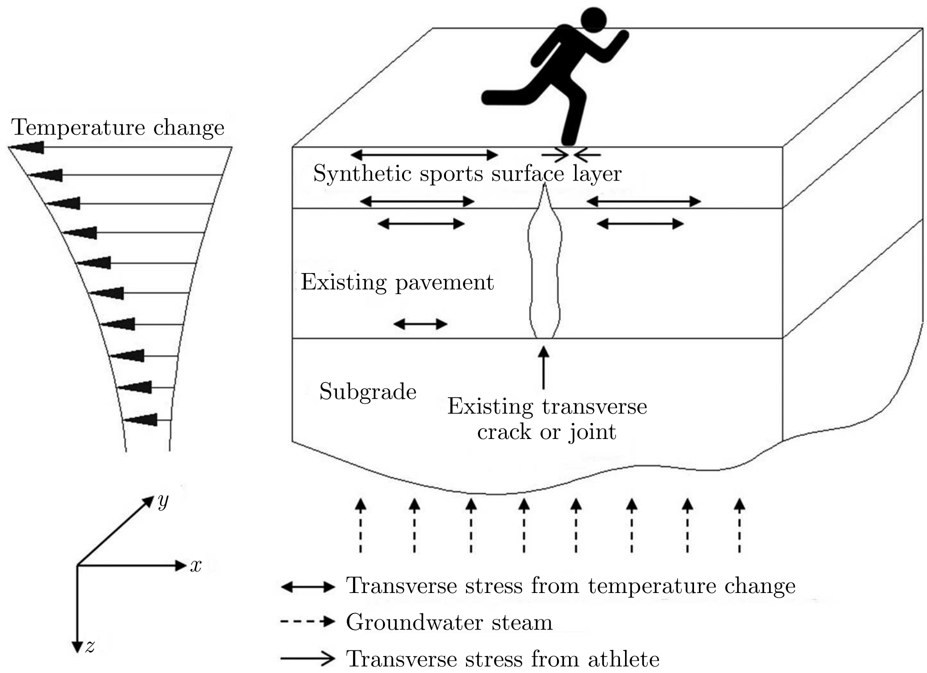

Fig. 1. Forces which the synthetic sports track may sustain

on the surface layer, it will hardly affect damage expansion of the synthetic surface whether the structural bonding layer is continuous or not between the top and bottom layer (Wang *et al.*, 2015). Previous studies showed that the bonding conditions of the interlayer had played a key part in the mechanical behavior of flexible pavement systems (i.e., stress-strain distribution), so the service life of the pavement was based on some analytical and experimental results (Chun *et al.*, 2015). Although there are few references about cracking in synthetic sports tracks, similar structures, for example, road pavements had been studied. Proper bonding connection between every layer might reduce stress concentrations and improve the resistance of bonding structural components to fatigue and damage (Baker *et al.*, 2012). The study from Xue *et al.* (2013) showed that temperature gradient and external loading could cause deformation and failure of the pavement structure directly. The key factors which might affect damage of the pavement were simulated and analyzed (Xue *et al.*, 2013). Si *et al.* (2019) analyzed pore water pressure of a pavement structure under rainfall infiltration and determined thermal stress using the Abaqus software. The longitudinal stress, vertical stress, shear stress and transverse stress of different structural layers were calculated and analyzed under the multi-field condition. The study of

Zhao *et al.* (2021) showed that the top-down cracks of the surface layer appeared in mode II mainly and, in summer, the crack would enlarge with an increase in load.

Synthetic surface materials are mixtures consisting of inorganic, polymeric and organic compounds which are easy to age due to weathering and other complex leaching behavior in rainwater. And all those can reduce their service life (Wachtendorf *et al.*, 2017). Synthetic sports surfaces are completely exposed to natural environmental hazards (Xue *et al.*, 2013). Therefore, it is inevitable that some climate environmental factors may have some effect on the synthetic materials, such as wind speed and solar radiation (Xue *et al.*, 2013). Especially, deformation resistance of the structure layers might be weaken when temperature of synthetic sports surfaces reach some certain temperature (Xue *et al.*, 2013).

In the study, a two-dimensional finite element model of a synthetic sports track was established in order to effectively simulate the effect of bonding conditions between the synthetic surface and asphalt pavement on the mechanical responses of the surface layer. Fluctuations of temperature stress and strain caused by thermal environment conditions were considered. The thermal and structural response of the synthetic sports track was simulated through one-day transient thermal and structural analysis. Based on that, different physical parameters of the interlayer were considered to analyze the influence of the bonding status on the mechanical performance of the surface layer in the synthetic sports track.

2. Methods

2.1. Basic principles

Temperature of a synthetic sports track depends on external environmental temperature and has some rippling effect with time (Xue *et al.*, 2013). Complexity of external climate changes will lead to changes of the unsteady heat flow above the upper boundary of the structural body of the synthetic sports track (Xue *et al.*, 2013). The temperature distribution should be controlled by the principles of heat conduction and energy interaction between synthetic surfaces and their surrounding environment.

2.1.1. Conduction heat transfer

The first law of thermodynamics and Fourier's law are used to solve the heat conduction problem (Minhoto *et al.*, 2005). For a constant thermal conductivity and an isotropic medium, the related equation is expressed as follows

$$\Big(\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}+\frac{\partial^2}{\partial z^2}\Big)T=\frac{1}{\alpha}\frac{\partial T}{\partial t} \qquad \alpha=\frac{k}{\rho c} \tag{2.1}$$

where x, y, z are components of the Cartesian coordinate system, T is temperature, α is thermal diffusivity, k is thermal conductivity, ρ is density, c is specific heat, t is time.

2.1.2. Interaction between the athletic track and its surroundings

The heat transfer by energy interaction between the athletic track and the surrounding environment includes radiation balance and convection exchange on a sunny day. All those include solar radiation, radiant heat flow and convection heat flux on the synthetic surfaces. Solar radiation heat flux is the net solar radiation absorbed by the synthetic surface in Eq. $(2.2)_1$. It is assumed that the earth's surface emits long-wave radiation into atmosphere. And the atmosphere absorbs the radiation, then emits it as long-wave radiation to the earth. This radiation balance between the atmosphere and the synthetic surface can be expressed by Eq. $(2.2)_2$ (Yavuzturk *et* *al.*, 2005; Barber, 1957). Equation $(2.2)_3$ gives the convective heat transfer between the synthetic surface and the air directly above it (Yavuzturk *et al.*, 2005; Chiasson *et al.*, 2008)

$$\begin{aligned} q_s &= \alpha' I \\ q_t &= \varepsilon\sigma(T_a^4 - T_s^4) = \varepsilon\sigma(T_a^2 + T_s^2)(T_a + T_s)(T_a - T_s) = h_t(T_a - T_s) \\ q_c &= h_c(T_a - T_s) \end{aligned} \tag{2.2}$$

where I is solar radiation incident on the surface, and α' is the absorptivity coefficient of surface materials, ε is emissivity, σ is the Stefan-Boltzman constant ($5.67 \cdot 10^{-8}$ W/(m^{2}K^4)), T_a is atmospheric temperature, T_s is pavement surface temperature, h_t is the thermal radiation coefficient, h_c is the convection coefficient.

2.2. Model dimension, meshing and boundary conditions

Previous studies showed that proper characterization of the interlayer bonding conditions between every layer was very crucial to predict the critical responses and service life of the synthetic sports track accurately (Chun *et al.*, 2015). However, some previous studies considered two extreme interlay bonding conditions which were full-bonding (i.e. no sliding) and no-bonding conditions (i.e. sliding). All those were impractical assumptions for the actual sports track (Chun *et al.*, 2015; Kim *et al.*, 2011). In the study, the partial bonding conditions were used to simulate the actual interlayer behavior. The synthetic track model is established by using the commercial finite element software Ansys to evaluate the critical response characteristics of the synthetic track in different interlayer bonding conditions.

The finite element model was simulated following some assumptions in the study. Every layer of the sports track was uniform, elastic and completely isotropic. The temperature of each layer fluctuated evenly along the vertical direction. The contact between every layer, including the interlayer between the synthetic surfaces and the asphalt layer, was close. And the heat flux and temperature were completely continuous. The heat resistance of the contact was not considered. It was sunny and unclouded day. The composite heat transfer coefficient was constant with time. The athletic track temperature achieved the balance at 6 o'clock. The initial body temperature, which was just the environmental temperature of 19.5°C, was applied to the athletic track.

2.2.1. Model dimension and meshing

It is necessary to determine the proper size, mesh and boundary conditions of the simulated model due to the nature of finite element analysis (Chun *et al.*, 2015). To reduce the influence from boundary constraints, the horizontal expansion was 400 cm. And a 48.4 cm vertical depth was used. In the vertical direction, there were five layers from the top to bottom. Three 4-node plane elements were used to generate the finite model. PLANE55 was applied to a 2D steady state or transient thermal analysis. SURF151 was used for surface effect applications. In the structural analysis, PLANE55 was converted to PLANE182 which is used for 2D modeling of solid structures. The total number of elements was 75528.

Proper simulation of the interlayer bonding conditions is crucial to predict structural responses of the synthetic sports track accurately. A special bonding interlayer whose thickness was only 1mm was used to model the interlayer between the synthetic sports surfaces layer and the asphalt layer. Different bonding conditions between the synthetic surface and asphalt layer were simulated by changing the interlayer physical parameters. When these parameters were the same as those of the asphalt layer, the full-bonding status was modeled. It meant nearly a no-bonding status between the two layers, and the elastic modulus of the interlayer was close to $0.2300 \cdot 10^{-10}$ MPa. The larger the elastic modulus of the interlayer was, the closer was the bonding between the synthetic surface and asphalt layer. The thermal response trend of the synthetic sports track was simulated in a transient thermal analysis. And thermal loads were applied to the body of the whole synthetic sports track after the thermal response. The structural response was analyzed. The relevant parameters of the athletic track are listed in Table 1 (Chun *et al.*, 2015; Xue *et al.*, 2013; Hassn *et al.*, 2016; Mulungye *et al.*, 2007).

Table 1. Material parameters

Layer	Thick-ness [mm]	Elastic modulus [MPa]	Poisson's ratio	Thermal expansion factor [10^{-5}]	Thermal conduct-ivity [W/(m °C)]	Specific heat capacity [J/(kg °C)]	Density [kg/m^3]
Synthetic surface	13	100	0.45	8	0.13	2010	1100
Interlayer	1	Instructions	0.3	2.1	1.16	963.7	2371.67
Asphalt layer	70	2300	0.3	2.1	1.16	963.7	2371.67
Base	200	1500	0.2	1.2	1.31	1084	2500
Subbase	200	300	0.2	1.2	1.5	1069	2500

Instructions: Test 1 – 2300 MPa; Test 2 – $2300 \cdot 10^{-4}$ MPa; Test 3 – $2300 \cdot 10^{-6}$ MPa; Test 4 – $2300 \cdot 10^{-8}$ MPa; Test 5 – $2300 \cdot 10^{-9}$ MPa; Test 6 – $2300 \cdot 10^{-10}$ MPa

2.2.2. Boundary conditions

There are three types of boundary conditions covering the thermal analysis, including heat flow and surface convection on the synthetic surface, and the radiant energy between the surface and its surrounding environment. The heat flux of the surface node is given as (Barber, 1957)

$$q = q_s + q_t + q_c = \alpha_\beta I_s + h(T_a - T_s) \tag{2.3}$$

where I_s is the solar radiation incident on the pavement surface, and α_β is the absorptivity coefficient for the pavement mixes, and $h = h_t + h_c$ is the multiplex coefficient of heat transfer, which is related to the wind velocity v.

Figure 2 shows the finite element node network and boundary conditions. Typical meteorological weather data was applied in the model as given in Table 2 (Wu, 1995). In the thermal analysis, other boundaries were all adiabatic except for the surface boundary which was the heat flux boundary. In the structural analysis, the bottom nodes were fully constrained (Mulungye *et al.*, 2007). The transient thermal analysis was used to simulate the thermal response for one day. The structural response was analyzed by temperature load from the thermal response. Finally, the temperature stress and strain of the athletic track in the day were indicated.

Table 2. Weather data

T_{max} [°C]	T_{min} [°C]	Q_r [MJ/m^2]	v [m/s]	c [h]
29.6	18.5	29.06	0.8	13.2

In Table 2, T_{max} is the maximum temperature, T_{min} is the minimum temperature, Q_r is the total solar radiation, v is the wind velocity, and c is the sun exposure time.

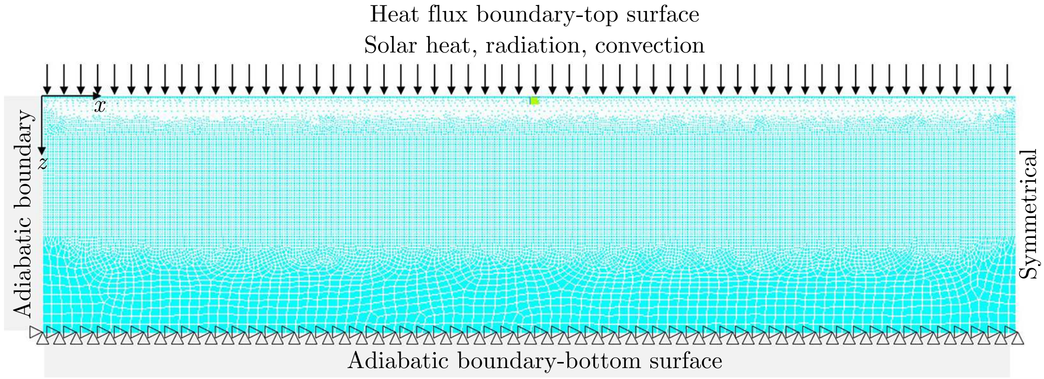

Fig. 2. Finite element node network

3. Results and discussion

3.1. Temperature and temperature gradient fluctuations of one day

Figure 3 presents temperature distributions of the synthetic athletic track at different longitudinal depths in one day when every layer had the full-bonding status. The maximum temperatures became decreasing with an increase of depths obviously. Especially, the maximum temperatures varied from 41.8°C down to 30.6°C when the depths varied from the top of the synthetic sports layer to its bottom at 13:00. The temperature differences between the top and the bottom of the synthetic layer were larger from 6 o'clock to 18 o'clock than in other times. Compared with thermal conductivity of asphalt concrete, that of the synthetic material was lower, and the temperature could not transmit from the top to bottom more easily. Therefore, the synthetic sports layer was just like a hot film covering the bottom layer. In hot weather, the underwater vapor would be concentrated between the synthetic sports layer and the asphalt layer when the special hot film was covered on the asphalt layer. All those could cause layer separation or affect the service life of the synthetic sports track if there was not enough bonding between the asphalt layer and the synthetic sports layer.

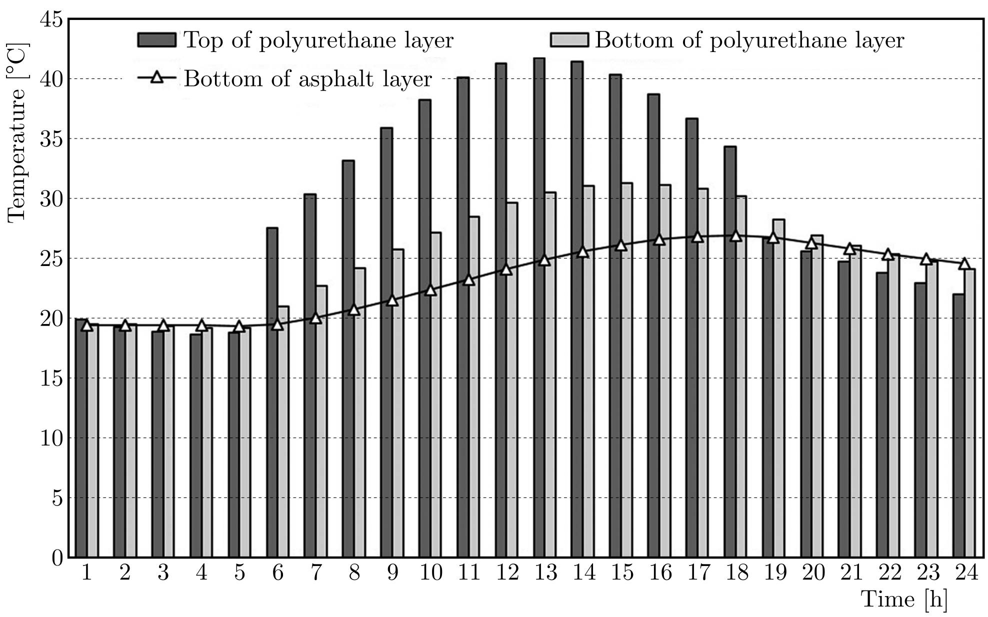

Fig. 3. Temperature distribution of every layer in a day

The corresponding temperature gradient fluctuation of every layer is shown in Fig. 4. The synthetic surfaces show a positive gradient when temperature of the top was higher than the bottom one in the synthetic sports layer. Similarly, a negative gradient occurred when the top temperature was lower than the bottom one. It indicated that the synthetic sports surfaces had suffered the largest temperature fluctuation. However, the asphalt base layer had almost no temperature gradient. Finally, the large temperature gradient might affect the mechanical performance of the synthetic sports layer.

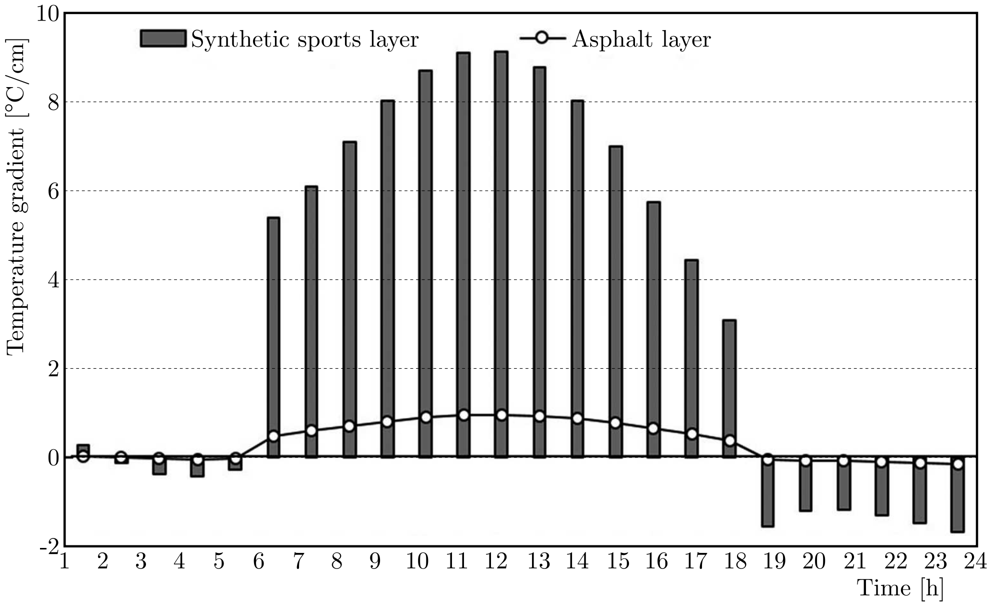

Fig. 4. Temperature gradient fluctuation of every layer in a day

3.2. Effects of the bonding condition on temperature stress of the synthetic sports layer

The temperature stress effects of bonding conditions on the top of the synthetic sports layer are given in Fig. 5. Whether the interlayer bonding was continuous or not, the top of the synthetic sports layer was in the compressive status from 6:00 to 18:00. The result indicated that the more continuous the interlayer bonding was, the greater was compressive strength of the synthetic sports surfaces. In other words, the surface of the synthetic sports track was suffering compressive stress obviously from 6:00 to 18:00. At other times, the track surface withstood weak tensile stress which was far less than the national standard calibration value of 0.4 MPa (General Administration of Quality Supervision, 2011). Especially, the maximum compressive strength at the top of the synthetic sports track had a logarithmic relationship with the modulus of interlayer bonding in the study, which is shown in Fig. 6.

Different bonding conditions of the interlayer had also a larger effect on temperature stress of the bottom of the synthetic sports layer. Figure 7 shows the temperature stress effect of the bonding conditions on the bottom of the synthetic surface layer. When the interlayer bonding was completely continuous, the bottom of the synthetic sports layer was basically in a full compressive condition starting from 8 o'clock. However, when the interlayer bonding began to become discontinuous, the bottom of the synthetic sports layer was slightly in a tensile condition from 5 o'clock to 19 o'clock. In the part-bonding status between the synthetic sports layer and the asphalt layer, the tensile strength of the layer bottom was decreasing when the bonding became closed. The continuous bonding between the layers would provide fixing to the synthetic sports layer, which was 13 cm in thickness; hence the bottom of the synthetic sports track was compressed.

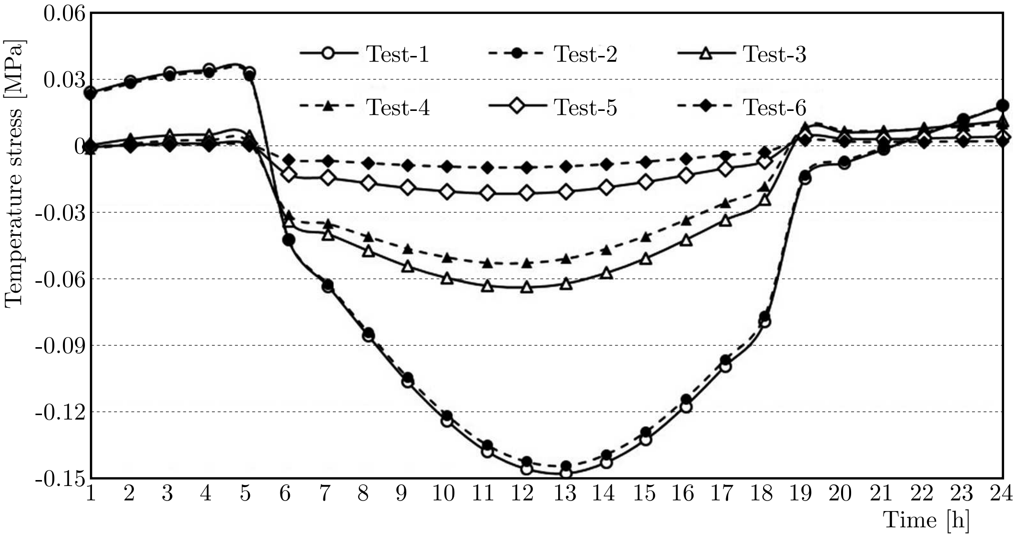

Fig. 5. Effect of the interlayer bonding condition on temperature stress of the top of the synthetic layer

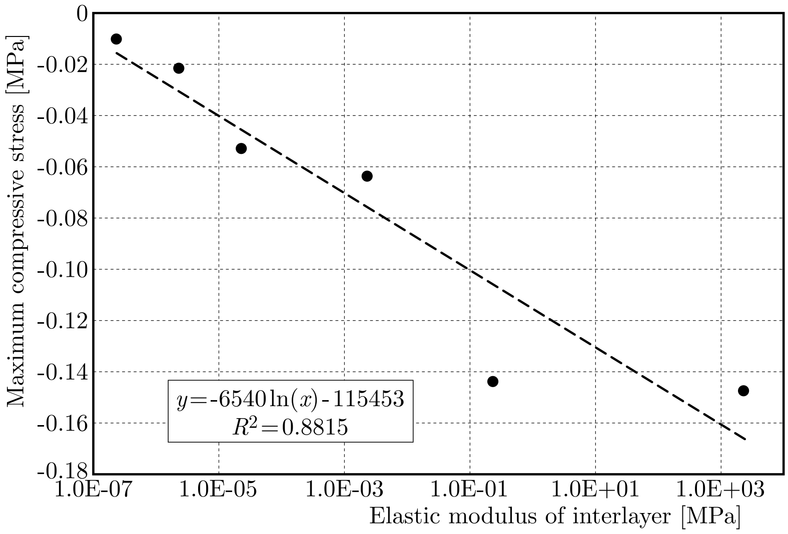

Fig. 6. Relation between the top maximum compressive stress and bonding condition

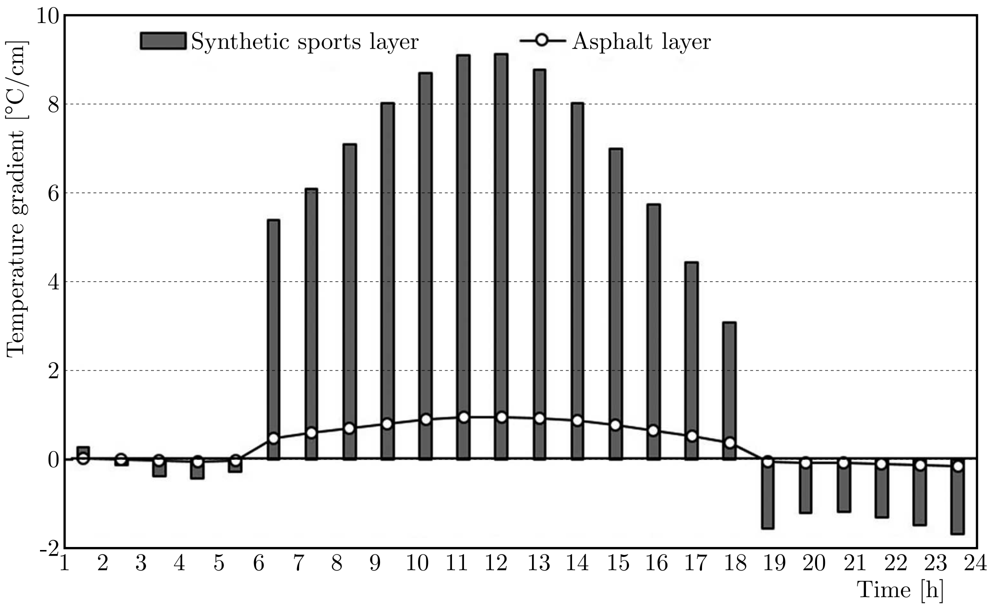

Fig. 7. Effect of interlayer bonding on temperature stress of the bottom of the synthetic layer

3.3. Effects of bonding conditions on temperature strain of the synthetic sports layer

The temperature strain difference in different bonding conditions with time between the top and bottom of the synthetic sports layer is shown in Fig. 8. Figure 9 presents the maximum

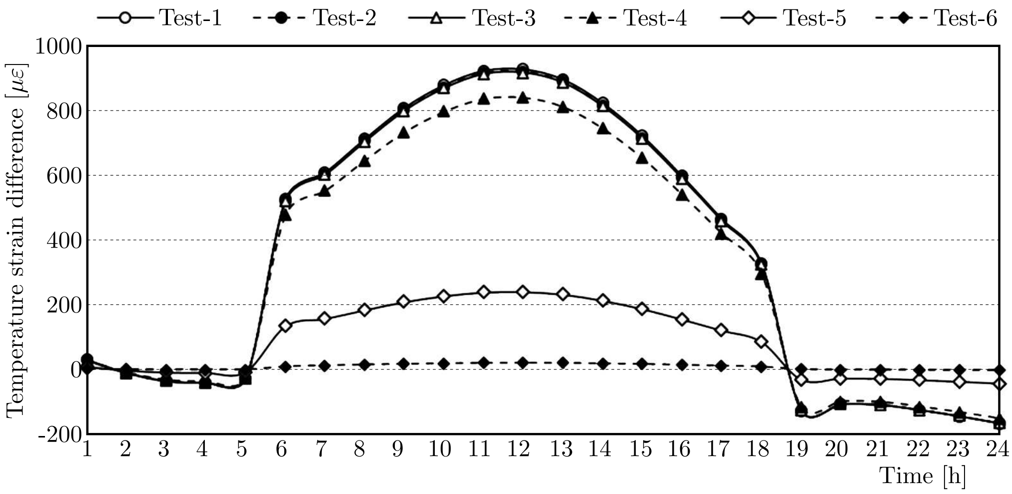

Fig. 8. Effect of interlayer bonding on temperature strain difference of the synthetic layer

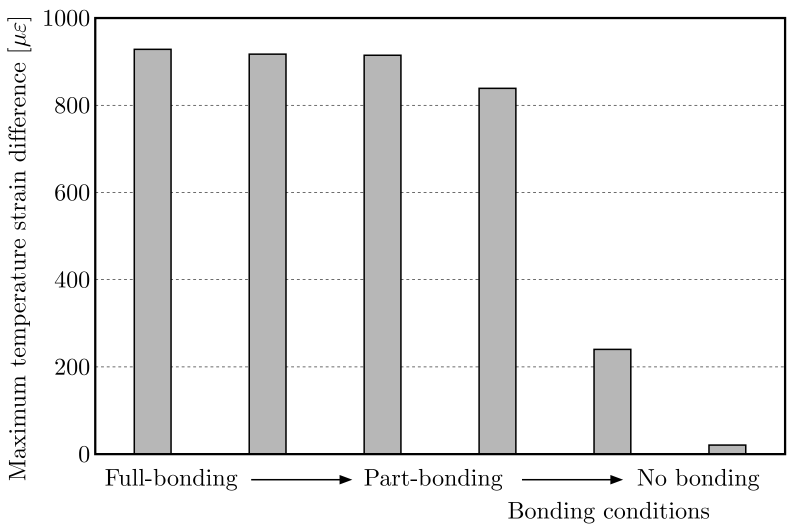

Fig. 9. Temperature difference in different interlayer bonding at 12:00

temperature strain difference in different bonding conditions at noon. The results indicated that the closer the bonding between the synthetic sports layer and the asphalt base layer was, the greater was the temperature strain difference between the top and bottom of the synthetic sports layer. When the bonding was hardly completely continuous, the temperature strain difference between the top and bottom of the track was almost 0. The synthetic sports track was constrained by the asphalt base layer when the bonding condition was completely continuous. Hence the bottom of the synthetic sports track was compressed, as indicated in Fig. 8. When the bonding was closed between the layers, the temperature strain difference between the top and bottom of the synthetic sports layer was obvious. The bonding strength would become weak at the repeated action of temperature load with time. When the bonding strength became smaller and smaller, the synthetic sports layer began to lack adequate constraints. All those caused that the surface layer had almost no strain difference. In other words, the synthetic sports layer had lost its role as a real track layer because it had been completely separated from the synthetic sports track. Therefore, the synthetic sports track began to be destroyed quickly and lost its normal function once the synthetic sports layer separated from the asphalt base layer.

4. Conclusions and recommendations for future research

The deeper the depth along the vertical direction was, the lower was the maximum temperature of the layer. The temperature change of the synthetic surface was larger than in other layers because the surface material had lower thermal conductivity, and the temperature could not transmit from the top to bottom easily. The synthetic sports surfaces were like a special hot film that covered the asphalt base layer. At the same time, during the day, the synthetic sports surfaces suffered the largest temperature fluctuation, which would produce thermal stress and strain in the surface. All those could cause layer separation or affect the service life of the synthetic sports track if there was not enough bonding between the asphalt layer and the synthetic sports layer. The more continuous the interlayer bonding was, the greater was the compressive strength of the synthetic sports surfaces. The maximum compressive strength at the top of the synthetic sports track had a logarithmic relationship with the modulus of the interlayer bonding condition. The closer the bonding between the asphalt layer and the synthetic sports layer was, the greater was the temperature strain difference between the top and bottom of the synthetic sports track. When the bonding strength became smaller and smaller, the synthetic sports track began to be destroyed quickly and lost its normal function once the synthetic sports layer separated from the asphalt base layer. The suggested simulation model would be expected to predict the influence of the bonding layer materials on the mechanical performance of the synthetic sports track in different environmental temperatures. However, all physical parameters were all from some references in FE models. In the future research, some experiments on physical parameters need to be done. Especially, the actual constitutive relations of the synthetic sports track should be considered. At the same time, the ground reaction forces collected during forefoot running should be considered when the mechanical performance of the synthetic sports layer is simulated.

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