Temperature field numerical analysis of asphalt pavement

Zhu Dengyuan[1, a]
[1]School of Civil Engineering and Architecture, Linyi University, China
[a]zdy320@163.com

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Abstract. Aimed at the problems of asphalt pavement temperature shrinkage cracks, numerical simulation method is applied to study the spatial-temporal distribution of asphalt pavement temperature field caused by periodically varying temperature and continuous cooling. Based on permanent asphalt pavement temperature field observations of Shandong Province, 24h temperature changes of each pavement layers during summer and winter is studied. The pavement temperature changes with substantial cooling in summer afternoon and continuous cooling in autumn are also studied. The results demonstrate the spatial and temporal variations of asphalt pavement temperature field distribution, and lay a foundation for the research to the cracks of pavement temperature shrinkage.

Introduction

The design mechanical state of the pavement structure on continuous medium theory does not match the real mechanical state under load with cracks. Particularly, the water in cracks accelerates the damage to the pavement structure, and the actual service life is shorter than expected. The causes of cracks in asphalt pavement are complex, in which temperature shrinkage is the main reason [1-7]. The temporal and spatial variation of temperature field is the basis of researching asphalt pavement shrinkage cracks. Studies have been done to the asphalt pavement temperature conditions using on-site observation, theoretical analysis and numerical simulation method [8-9]. Based on temperature field observations of Shandong permanent asphalt pavement, 24h temperature changes of each pavement layers during summer and winter is studied. The pavement temperature changes with substantial cooling in summer afternoon and continuous cooling in autumn are also studied. The results demonstrate the spatial and temporal variations of asphalt pavement temperature field distribution, and lay a foundation for the research to the cracks of pavement temperature shrinkage.

ANALYSIS MODEL

Abaqus finite element method is used to simulate the temperature field of asphalt pavement under the condition of daily periodic temperature change and continuous cooling. The model is 20m in length and 3.78m in height, and the temperature field is analyzed by plane strain DC2D8 (8 node quadrilateral heat conduction element).

Calculation Parameters

Typical pavement structure and temperature field analysis parameters are shown in Table 1.

Table 1. Typical pavement structure and temperature field analysis parameters

Pavement structure layers	materials	thickness (cm)	density (kg/m³)	thermal conductivity (J/m·h·℃)	heat capacity (J/kg·℃)
surface	Asphalt concrete(AC20)	18	2100	4680	924.9
base	Cement stabilized base(CTB)	30	2300	5616	911.7
Sub-base	Lime and fly-ash stabilized base(LFS)	30	1900	5148	942.9
subgrade	Compacted Soil(CS)	300	1800	5616	1040.0

Temperature Boundaries

Assuming that the temperature gradient in the horizontal direction of the pavement structure is zero, the top surface of the pavement is the main boundary and the infinite depth is the secondary boundary. According to the different pavement characteristics, the road boundary condition is divided into three boundary conditions. The first boundary condition is the function of known road surface temperature change; the second boundary condition is the function of known road surface heat flux; the third boundary condition is the function of medium temperature variation contacted with the road surface.

In the numerical analysis model, the interaction model is used to define the second boundary and the effective radiation of the pavement. The first boundary is defined in the load, and the second and third bounds are changed by the FORTRAN subroutine. The detailed temperature boundary conditions are as follows:

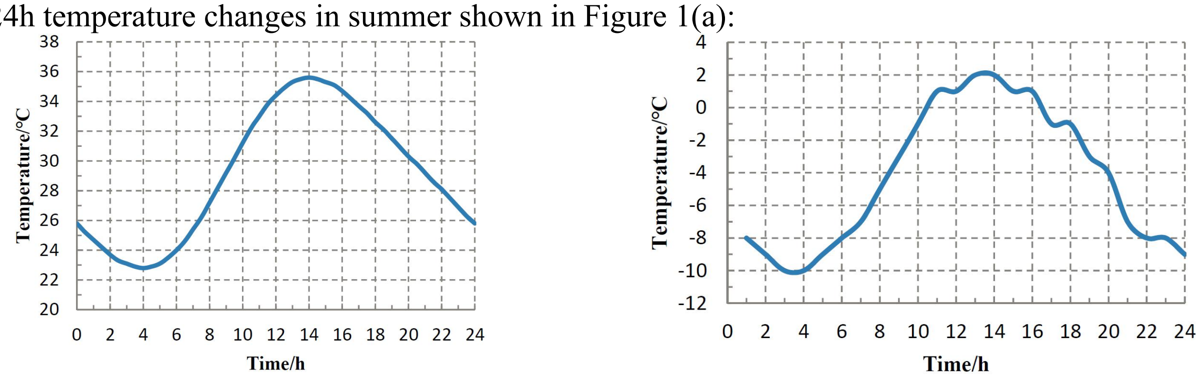
(1) 24h/day temperature in summer

The 24 hours/day representative temperature of Shandong in typical high temperature season as shown in Table 2, the maximum temperature is 35.6 ℃, occurred in the afternoon 2:00; the minimum temperature is 23.1 ℃, occurred in the morning 5AM.

Table 2. The 24 hours/day representative temperature in typical high temperature season（$\overline{T}_a$=29 ℃, ΔT=12.8℃,v=2.6m/s,Q_0=26.3MJ/m2）

time	temperature (℃)	time	temperature (℃)	time	temperature (℃)	time	temperature (℃)
1	24.7	7	25.4	13	35.3	19	31.5
2	23.7	8	27.2	14	35.6	20	30.3
3	23.1	9	29.2	15	35.3	21	29.2
4	22.8	10	31.2	16	34.7	22	28.1
5	23.1	11	33	17	33.7	23	26.9
6	24	12	34.4	18	32.6	24	25.8

24h temperature changes in summer shown in Figure 1(a):



(a) summer (b) winter

FIG.1. 24h temperature changes in summer and winter

(2) 24h/day temperature in winter

The 24 hours/day representative temperature of Shandong in typical low temperature season as shown in Table 3, representing the winter temperature, maximum temperature 2 ℃, occurred in the afternoon 2PM;

Table 3. The 24 hours/day representative temperature in typical low temperature season
($\overline{T}_a$=-4.3℃, ΔT=12℃, v=4.6m/s, Q_0=20.3MJ/m2)

time	temperature (℃)	time	temperature (℃)	time	temperature (℃)	time	temperature (℃)
1	-8	7	-7	13	2	19	-3
2	-9	8	-5	14	2	20	-4
3	-10	9	-3	15	1	21	-7
4	-10	10	-1	16	1	22	-8
5	-9	11	1	17	-1	23	-8
6	-8	12	1	18	-1	24	-9

24h temperature changes in winter shown in Figure 1(b).

(3) Substantial continuous cooling in afternoon of summer

Continuous cooling generally occurs in the high temperature summer weather in storm, pavement structure temperature field changes greatly. Table 4 for the continuous cooling temperature 24h distribution, temperature drop down 18.6 ℃.

Table 4. The 24 hours/day temperature change in the afternoon of summer

time	temperature (℃)	time	temperature (℃)	time	temperature (℃)	time	temperature (℃)
1	24.7	7	25.4	13	35.3	19	17
2	23.7	8	27.2	14	35.6	20	17
3	23.1	9	29.2	15	32	21	17
4	22.8	10	31.2	16	25	22	17
5	23.1	11	33	17	18	23	17
6	24	12	34.4	18	17	24	17

The temperature changes during the afternoon in summer are shown in Fig.2 (a). The linear combination of two sine functions is used before 14:00, and Boltzmann function is used to simulate the diurnal variation process of temperature. The expression of the segmented function is (1). The function graphs are continuous and smooth, and are suitable for numerical calculation.

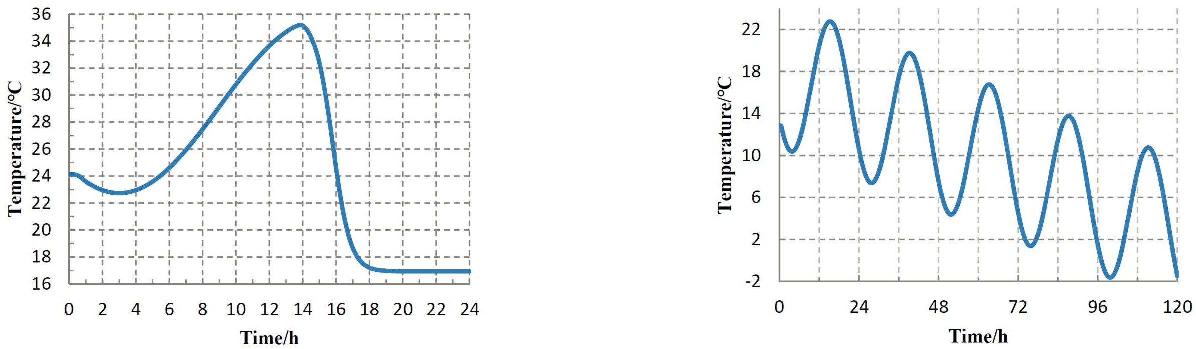
$$T_a = \begin{cases} \overline{T}_a + T_m\left[0.96\sin\omega(t-t_0) + 0.146\sin 2\omega(t-t_0)\right] & t < 14 \\ A_2 + \dfrac{(A_1 - A_2)}{1+\exp(\dfrac{t-A_3}{A_4})} & t \geq 14 \end{cases}$$ * MERGEFORMAT (1)

Where: A_1, A_2, A_3, A_4 are fitted constants.

$\overline{T}_a$ – Daily average temperature

T_m – Daily variation of temperature

t_0 – Initial phase



(a) continuous cooling in afternoon of summer (b) Temperature fall for five days continuously in winter season

FIG.2. Temperature change in afternoon of summer and fall for five days continuously

(4) Temperature fall for 5 days continuously in winter season

5 days cooling in autumn and winter is as shown in Figure 2 (b), using two linear combination of sine function + linear function to simulate a continuous five days of daily temperature changes.

$$T_a = T_0 + T_m \sin\omega(t-t_0)\text{-}k(t-t_0) \quad \text{* MERGEFORMAT (2)}$$

RESULT ANALYSIS

Comparison of measured and simulated

The temperature comparison results at 2-cm below top surface between the simulation and measurement of the Shandong permanent pavement is shown in Fig.3.

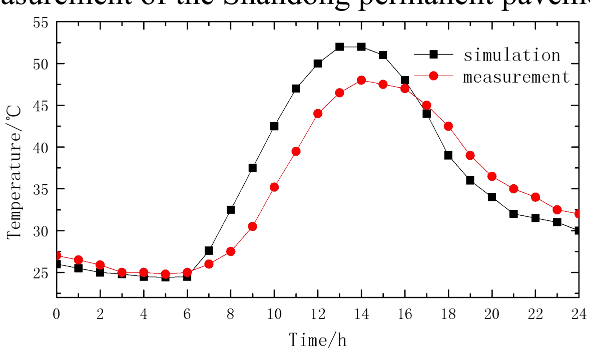


FIG.3. the temperature comparison between the simulation and measurement results

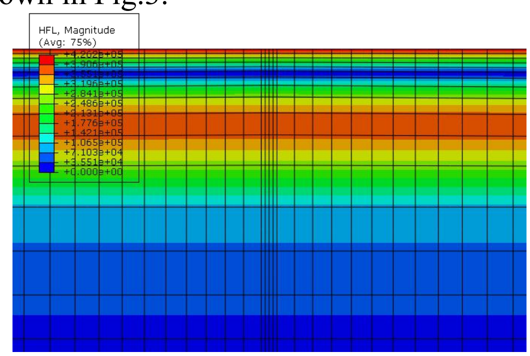


FIG.4. HFL in the pavement structure (t=17.5h)

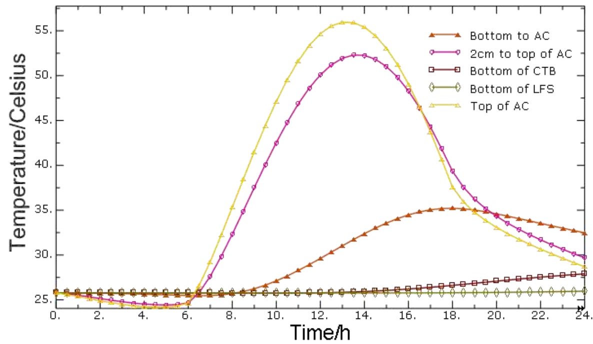
The temperature changes are basically consistent between measured and simulated results. Because of complication of the actual weather conditions, the measured peak temperature will be slightly lower than the simulation, and the time slightly behind, but the overall law is consistent. The simulation results reflect the actual temperature field changes of the pavement structure.

Heat flux analysis

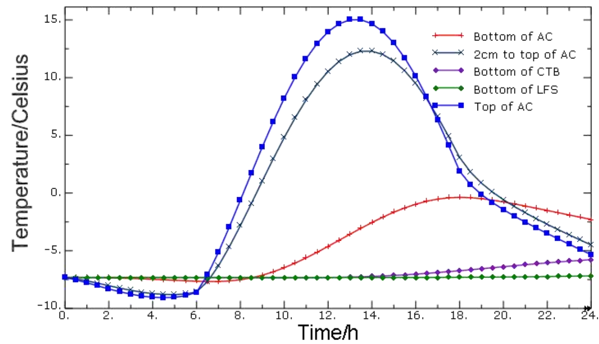
The distribution of heat flux (HFL) in the pavement structure at t=17.5h is shown in Fig.6. It shows that the heat flux is distributed differently along the pavement thickness at the same time. In the pavement structure, there is a hysteresis effect between the maximum HFL and the maximum temperatures.

Temperature field analysis of pavement structure with periodic temperature change

Fig. 5(a) is the 24h temperature change of pavement structure in high temperature summer season, and Fig. 5(b) is the temperature change pattern of pavement structure in low temperature winter season. The temperature curves of the two maps are basically the same, indicating that the value of road surface temperature is proportional to the daily average temperature. The maximum road surface temperature is greater than the maximum atmospheric temperature, indicating that the road pavement absorb a large number of solar radiation energy.



summer (average atmospheric temperature 29˚C,daily range temperature12.8˚C) (a)



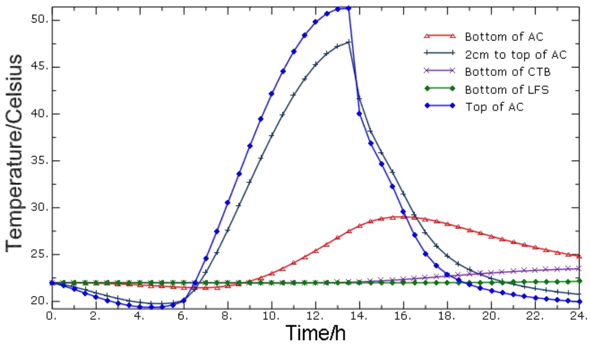
winter (average atmospheric temperature -4.3˚C,daily range temperature12˚C)(b)

FIG.5. 24h temperature changes of pavement structure

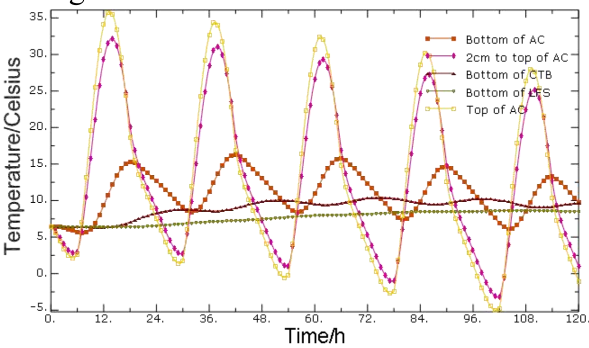
As showed in Fig. 5, the heating and cooling of the pavement structure are both fast. The temperature of the top asphalt layer AC is significantly affected by environmental factors such as air temperature and radiation, but the temperature amplitude of the base and the subbase is not changed much. The analysis of temperature stress field focused on asphalt pavement layers is enough, and asphalt pavement temperature cracking problem can only take a limited pavement thickness. The base and subbase are in the state of continuous warming, which indicates that the ground temperature is rising continuously in the same weather cycle. The road heating process is short (about 7h), while the cooling process is long. The time at which the highest temperature occur at any position below the surface layer is always lag behind the time on the top surface, the farther the distance from the road surface, the longer the lag time. There is a tendency to cross the top surface temperature line for the characteristic temperature line and the bottom layer temperature line, it is indicating that the upper part of the asphalt layer is cooled and the lower part is heated, accompanied by a long cooling process, the road surface prone to temperature fatigue cracks.

Temperature field analysis of continuous cooling

Fig. 6 (a) shows the temperature changes of the pavement structure caused by the abrupt cooling of the wind and rainstorm in the summer afternoon.



(a) abrupt cooling of the wind and rainstorm in the summer afternoon



(b) Continuous cooling for 5 days in autumn and winter

FIG.6. The temperature variation of every asphalt pavement structure layers due to continuous cooling

The temperature variation of the asphalt surface layer is larger and the bottom layer is smaller, pavement temperature difference up to 30 ˚C or more in 6h, shrinkage cracks may be caused by the sudden cooling process. Top of AC temperature line and 2cm to top of AC line intersect at 14h, indicating that the road surface temperature is lower than the bottom temperature; it will exacerbate asphalt pavement surface shrinkage cracks occurred in a short period of rapid cooling.

Fig.6 (b) shows the temperature variation of every pavement structural layers due to air temperature fall down for 5 days continuously in winter season. Continuous cooling for 5 days in autumn and winter has little effect to base and sub-base layers, but AC asphalt layer shows a general trend of continuous cooling, and the temperature difference between the road surface temperature changes greatly. The temperature gradient caused by the continuous cooling is also an important reason for the asphalt layer cracking.

CONCLUSIONS

(1) The numerical simulation of asphalt pavement space-time temperature field distribution of Shandong is consistent to field tracking test results;

(2) The results of periodic temperature change and continuous cooling show that the temperature field of asphalt pavement has a lagging effect to air temperature change; Asphalt layers of the pavement structure affected significantly by the air temperature, radiation and other environmental factors, but little effect to base layers. Taking a limited road surface thickness is enough to study asphalt pavement temperature cracking problem.

(3) A large temperature gradient in asphalt pavement layers is produced by continuous cooling, and it is an important reason for the cracking of asphalt pavement.

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