Construction and Building Materials 164 (2018) 419–432

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Performance analysis of incorporating phase change materials in asphalt concrete pavements

Bhagya Athukorallage [a,*], Tharanga Dissanayaka [b], Sanjaya Senadheera [b], Darryl James [a]

[a] Department of Mechanical Engineering, Whitacre College of Engineering, Texas Tech University, Lubbock, TX 79409, USA
[b] Department of Civil, Environmental, and Construction Engineering, Whitacre College of Engineering, Texas Tech University, Lubbock, TX 79409, USA

HIGHLIGHTS

- The evolution of the latent heat of the PCM is accounted for using an enthalpy formulation with phase dependent properties.
- The maximum surface temperature was higher for a layered PCM pavement system than for one without PCM.
- A critical φ value exists for a PCM embedded ac-layer below which the maximum surface temperature was lower than a non-PCM system.
- The critical φ value is 60% for the boundary conditions used in the simulations.
- The effective thermal conductivity of the PCM-embedded ac-layer plays a key role in the heat transfer through the pavement.

ARTICLE INFO

Article history:
Received 24 April 2016
Received in revised form 20 December 2017
Accepted 28 December 2017

Keywords:
Phase change materials
Heat transfer
Asphalt pavement systems
Effective thermal conductivity
Phase dependent properties

ABSTRACT

The use of phase change materials (PCMs) in asphalt pavement mixtures has the potential to be an effective method of regulating extreme temperatures. In this article, the primary objective is to understand conditions for which PCMs mitigate extreme temperatures in a flexible pavement system. The volume-averaged energy equation with phase dependent thermal properties is used to analyze the heat transfer process in the integrated PCM pavement system. Our results show that (i) a pavement system consisting of a layer of PCM that is directly below the asphalt-concrete (ac)-layer yields higher surface temperatures than a system without the PCM layer and (ii) a pavement system in which PCM is embedded in the ac-layer with varying volume fraction has lower surface temperature values than that of the pavement without PCM when the PCM volume fraction is below a critical volume fraction, 60% for the conditions used; otherwise higher surface temperature values exist. Finally, we show the effective thermal conductivity has a strong effect on the temperature distribution throughout the surface layer of PCM-embedded pavement system.

1. Introduction

According to the Federal Highway Administration, America has approximately 953,000 miles of paved roads, which is approximately one-fourth of the public road available in the US. Among these paved roads, 83% are asphalt and the remaining are concrete. Asphalt mixtures are used to pave highways, roads, parking lots, and airports among others. The main advantages of asphalt pavements are ease of maintenance, time to construct, and safety and smoothness of ride. Another important advantage of using asphalt mixtures in the nation's transportation network, as indicated by the National Asphalt Pavement Association, is its recyclability and reusability.

There are many performance distresses over the life period of asphalt pavements. The two main distresses are thermally-induced rutting at high temperature conditions and cracking at low temperature conditions (Ma et al. [1,2]). Rutting is the load-induced permanent deformation of the pavements layers (Zhang et al. [3], Xu and Huang [4]) that negatively affects the performance of the roads and reduces the service life. Further, rutting may lead to structural failures and affect the safety of highway users (Xu and Huang [4]). The major causes for rutting are environmental factors, such as temperature and moisture (Si et al. [5]) coupled with heavy traffic loads (Zhang et al. [3]).

---

* Corresponding author.
E-mail addresses: bhagya.athukorala@ttu.edu (B. Athukorallage), tharanga.dissanayaka@ttu.edu (T. Dissanayaka), sanjaya.senadheera@ttu.edu (S. Senadheera), darryl.james@ttu.edu (D. James).

https://doi.org/10.1016/j.conbuildmat.2017.12.226
0950-0618/

Nomenclature

$\dot{\mathcal{Q}}(t)$	direct normal solar insolation ($\mathrm{W/m^2}$)
$\mathcal{F}_l, \mathcal{F}_s$	liquid and solid volume fractions of PCM
h_{eff}	convection heat transfer coefficient ($\mathrm{W/(m^2 \cdot K)}$)
L_f	latent heat of fusion (kJ/kg)
T	temperature (K)
t	time (s)
α	absorptivity of asphalt
α_{eff}	effective thermal diffusivity ($\mathrm{m^2/s}$)
ρ	density ($\mathrm{kg/m^3}$)
τ	dimensionless time
θ	dimensionless temperature
φ	volume fraction of PCM
Bi	Biot number
c_p	specific heat capacity ($\mathrm{J/(kg \cdot K)}$)

Fo	thermal Fourier number
k	thermal conductivity ($\mathrm{W/(m \cdot K)}$)
Ste	Stefan number
T_i	initial temperature (°C)
T_m	melting temperature of PCM (°C)

Subscripts

eff	effective
ref	reference
ac	asphalt-concrete layer
base	base layer
l	liquid phase
s	solid phase

Several research studies have been performed to address the rutting problem in pavements. Modifying the asphalt binder, adding fibers and additives, and optimizing mineral aggregate gradation are examples of measures investigated. Arslan et al. [6] looked at the effect of chemically synthesized materials (diethylene glycol based polyboron compound (DEGPC) and monoethylene glycol based polyboron compound (MEGPC)) that were used as additives for the bitumen. Marshall Stability (MS) test of these samples indicated both additives enhanced the stability of the mixtures, and the Dynamic Shear Rheometer (DSR) test results of this study revealed that the binder with the DEGPC additive increased the rutting resistance at all test temperatures. A review article by Yildirim [7] reported that the asphalt binder modified with natural rubber increased the rutting resistance, and the binder, which had been modified with styrene–butadiene–styrene (SBS) improved its elastic recovery. Serin et al. [8] added steel fibers to asphalt-concrete mixtures and evaluated the stability of the samples using the MS test. Based on the test results, stability enhancement occurred when the sample contained 0.75% steel fibers by mass.

Phase change materials (PCMs) may be incorporated into asphalt mixtures to reduce temperature extremes possibly reducing thermally-induced rutting (He et al. [9], Guan et al. [10], Sakulich and Bentz [11], Manning et al. [12], Ma et al. [13], Chen et al. [14], Leng et al.[15]). The addition of PCMs with appropriate thermal characteristics may help to regulate extreme temperatures and reduce thermally-induced rutting and urban heat island effect (Guan et al. [10]). PCMs absorb and release energy at a constant temperature or narrow temperature range as it changes phase; hence, it can be considered an additive for pavement materials to be used in regions where extreme temperature variations occur (Ma et al. [1], Dave et al. [2]). For asphalt pavement systems paraffin-based PCMs are widely available and possess favorable characteristics such as being noncorrosive and nontoxic, and are compatible with mixing materials (Sharma et al. [16], Bing et al. [17]).

The experimental work by Ma et al. [13] and Guan et al. [10] utilized a composite organic solid–liquid PCM with phase change temperature 8°C–25°C in an asphalt mixture. The composite PCM was prepared employing a microporous absorption process to prevent the leakage of PCM. Silica powder ($\rho = 2.65\ \mathrm{g/cm^3}$ and particle size = 50 μm) was used as the carrier matrix due to its high phase transition temperature and good thermal conductivity, which helped to enhance thermal transport and control temperature within the asphalt. Temperature control performance of a mixture that contained 20%of PCM by weight was studied and temperature variations of doped and non-doped specimens were measured as the samples were kept in a constant temperature oven at 60°C. In both samples, temperatures increased rapidly at first and then gradually stabilized to about 60°C. Results showed that the sample with PCM took a longer period of time to reach 60°C because the initial rate of temperature increase was lower than that of the control sample (non-PCM). The maximum temperature difference between the samples was approximately 19.7°C, and it occurred after approximately 45 min of heating. For the cooling process, the sample with PCM showed slightly higher temperatures due to a slightly lower cooling rate as compared to the non-doped sample.

Manning et al. [12] reported that the incorporation of *PCM-6* (phase change temperature 6°C) in hot-mix asphalt could possibly delay, or prevent, freezing and reduce low temperature extremes. Here, a porous lightweight aggregate (LWA), which can absorb and hold PCM by capillary action, was used as a medium for incorporating *PCM-6* in hot-mix asphalt. The hot mix asphalt samples with PCM contained 80% of normal-weight aggregates, 9.4% light-weight aggregates, 8.5% of asphalt binder, and 1.25% of PCM-6 by mass. The samples were subjected to thermal cycles with maximum and minimum temperatures of 23°C and −25°C, respectively. These experimental results showed that the low temperature extreme was 2°C warmer for the samples with the embedded PCM. Furthermore, a reduction in the cooling rate was observed with the PCM embedded samples.

Chen et al. [18] evaluated the thermal and mechanical properties of asphalt mixtures with and without PCMs. In this study, two types of composite shape-stabilized PCMs (*PCM-L* and *PCM-Z*) were used in the experiments with a phase change temperature of 45°C and 50°C, respectively. Asphalt-PCM samples with 5% PCMs by weight of the aggregate were prepared using the Marshall mix design procedure and were subjected to the wheeling rutting test, the indirect tensile strength test, and the three-point bending test. Using the data obtained from the wheeling rutting test, the dynamic stability values were calculated for the specimens. Results showed that both samples had a lower resistance to permanent deformation than the control sample. However, the sample with *PCM-Z* had a higher dynamic stability value than that of the sample with *PCM-L* and hence, possessed a high temperature stability.

In a numerical investigation of concrete specimen containing PCMs, Shari et al. [19] developed a one-dimensional heat transfer computational model of a PCM-impregnated asphalt concrete sample that utilized the effective heat capacity method to model the phase change process. The boundary conditions imposed on the simulations represent a time-dependent temperature function on one end and convection and radiation heat losses on the other end. Further, effective thermophysical properties were calculated by assuming a parallel configuration for the two composite med-