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The mechanism of different thermoregulation types of composite shape-stabilized phase change materials used in asphalt pavement

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HIGHLIGHTS

- Temperature thermoregulations were proposed to solve pavement temperature problems.
- Appropriate phase change temperature values were determined.
- Analyzed mechanism of the three thermoregulations phase change materials.
- Recommended composites mass proportion and corresponding enthalpy values.

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ABSTRACT

Considered the temperature distress forms and the impacts of temperature on asphalt pavement, three temperature thermoregulations were proposed to solve the asphalt pavement temperature problems initiatively. Based on the properties of phase change thermoregulation agent, thermoregulation types of composite phase change materials (CPCMS) were studied and the values of appropriate phase change temperature were determined by differential scanning calorimetric (DSC) test. Results show that for high temperature thermoregulation, the phase change temperature range is 35–50 °C, in which with the 58# paraffin proportion increasing, the phase change enthalpy increases linearly and the phase change temperature grows exponentially. As for the low temperature thermoregulation, the phase change temperature range is −5 °C to 5 °C, in which with the Tetradecane proportion increasing, the phase change enthalpy grows linearly, while phase change temperature increases exponentially. In terms of the mixing temperature thermoregulation, the phase change temperature range is 5–35 °C, in which when Tetradecane mass ratio are fixed as 30%, 40%, and 50%, with the 58# paraffin proportion increasing, high temperature enthalpy grows and phase change temperature increases linearly; when 58# paraffin mass ratio are fixed as 30%, 40%, and 50%, with the Tetradecane proportion increasing, low temperature enthalpy grows approximate linearly, exothermic (endothermic) high phase change temperature decreases (grows) slight linearly. Finally, this paper recommends composites mass proportion to different thermoregulations types and the corresponding enthalpy values, which intends to solve the worldwide problem of temperature distresses in asphalt pavement in the future.

1. Introduction

Asphalt mixture, which is one of the time and temperature sensitive mixtures, meets with different temperature impacts during its life cycle [1,2]. Asphalt mixture presents elasticity in low temperature and shows viscosity in high temperature, which has the viscoelastic characteristic [1,2]. Temperature and moisture are two main environmental factors that play a key role in affecting the mixture performance [3]. Freeze–thaw cycles have significant impact on pavement performance, the resilient modulus of asphalt mixture as well as pavement structure capacity declined under freeze–thaw cycles [4]. Rapid temperature change leads to severe cyclical freeze/thaw of surface layers in winter or cold region. During summer or in hot region, the heating/cooling process hardens the binder and then the pavement occurs fatigue damage.

Due to temperature sensitivity, asphalt pavement generates various distresses. These distresses aggravate pavement performance, decrease transportation safety, shorten pavement life cycle, and increase both the agency and user's cost. In many cases,

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environmental factors enlarge the traffic loads distresses [1]. Numerous investigations have found out that environmental factors, especially temperature, affect asphalt pavement performance significantly [1,2,5]. As asphalt pavement crack at low temperature and deform at high temperature easily, the functional performance and driving security reduce significantly [1,2]. Distresses caused by temperature are the broadest and the most important problems in the worldwide at yet. Simultaneously, snow, frost and ice that under frozen climate reduce pavement anti-sliding performance, which produce frequent traffic accidents, and then cause traffic jams even highway closure. All these influences caused by temperature reduce the investment profit as well as decrease the highway transportation efficient, and affect the transportation safety severely.

Nowadays, a large number of researches have conducted on the solutions for asphalt pavement temperature distresses, such as modifying asphalt, adding fiber and additives, optimizing gradations, and manufacture methods. However, these actions are passive, and furthermore, these solutions could only solve the special temperature distresses of a certain road, a certain area or were only effective in a certain period of highway lifecycle. However, for different asphalt pavements, the materials, construction levels, climate conditions, traffic loads, and temperature distresses are different, so the above passive methods will be not effective and have no representativeness. Concerned with these problems, exploring new measures to improve the adaptability of asphalt pavement to environment is urgent [6]. Therefore, the main objective of this research is to find a solution that actively adjusts asphalt pavement temperature by asphalt mixtures itself, and maintains pavement temperature in a suitable range. Hence the temperature influence on asphalt pavement can be mitigated.

Phase change material (PCM), also named as latent thermal energy storage material, is capable of storing and releasing large amounts of thermal energy [7]. During the phase change process, PCM can regulate mismatch of energy demand by absorbing or releasing heat [8]. Nowadays, PCM has been used in many applications such as exploiting solar energy, electric "shifting peak and filling valley", civil buildings heating and refrigeration [9]. Simultaneously, there have been a great number of studies on using PCM into asphalt mixture. Ma and Wang analyzed and evaluated the PCM's temperature regulation effect on asphalt pavement by heat transfer theory and simulation test [6]. Zhang et al. tested and analyzed the energy storage capacities of various PCMs and the effect of these PCMs on asphalt pavement performance [10]. Ma and Li have carried out numerous studies about mixing organic solid–liquid PCM into asphalt mixture, the results showed that organic solid–liquid PCM had positive influence on asphalt pavement temperature in a way, but it had gone against pavement service performance [4]. PCMs that added in asphalt mixture could adjust its working temperature with damping effect, which would enhance the temperature resistance capacity of asphalt mixture and improve asphalt mixture's adaptability to the changing environment actively [7]. Therefore, method of applying PCMs into asphalt pavement is active, inspirational and valuable, and it may solve the worldwide temperature stress problems.

Based on further studies [6–9], the organic PCM may soften asphalt binder for it would dissolve when mixed into asphalt binder. Although silicon dioxide (SiO_2) was used as supporting material to prevent PCM from dissolving, the temperature during asphalt mixture mixing process was very high (higher than 140 °C), so that solid PCM absorbed overmuch heat and became liquid, and then leaked out from the supporting material mostly [6]. To improve the form-stability of PCMs, lots of studies on using encapsulation method to synthesize composite phase change material (CPCM) have been done. CPCM was consisted of PCM and encapsulation medium, as the existence of encapsulation medium, the PCM will not leak out during solid–liquid or liquid–solid phase change process. There are many preparation methods of CPCM, such as direct immersion method, melt blending method and graft copolymerization. Based on the capillary effect, direct immersion method immerges liquid PCM into porous supporting material directly to synthesize CPCM. Lee et al. prepared phase change concrete by utilizing this method, and compared energy storage capacity between common concrete and phase change concrete [11]. Direct immersion method is easy to carry out, but the PCM's thermophysical properties will decline and PCM may leak out after multiple thermal cycling [12]. Melt blending method is carried out by melting PCM and supporting material firstly, then blending them together to synthesize CPCM. Ahmet prepared two kinds of paraffin/high density polyethylene composites by using melt blending method [13]. Melt blending method is simple and easy to operate, but phase separation may occur easily and PCM may leak out from the CPCM [15]. Graft copolymerization is a process in which side chain grafts are covalently attached to a main chain of polymer backbone to form branched copolymer [14]. Ahmet et al. synthesized a series of polystyrene graft palmitic acid (PA) copolymers as novel polymeric solid–solid phase change materials (PCMs) via graft copolymerization [15]. The drawback of graft copolymerization is that the prepared composites have low latent heat [12]. Ren and Ma et al. studied four different kinds of CPCMs, which were prepared by using pure PCM, silica powder adsorbed PCM, floating bead adsorbed PCM and activated carbon adsorbed PCM as raw materials through sol–gel method [12]. And their coating effectiveness and latent heat storage capacities were analyzed by scanning electron microscope (SEM) and differential scanning calorimetry (DSC) [12].

The French National Group Bitumen pointed out that a difference of 5 °C can delay or accelerate the risk of cracking for three years or so [16]. Therefore, how to initiatively control critical temperature (temperature at which distresses begin to occur) of pavement at an accept level, or delay its appearance time (shorten the duration of critical temperature on pavement) is a novel solution to mitigate asphalt pavement temperature distresses. There have been a great number of studies on PCMs thermoregulation. Salaün et al. manufactured a thermoregulation textile fabric through incorporating melamine–formaldehyde microcapsules that containing n-alkane mixture, achieved that the thermoregulation response depended on the surface deposited weight and the mass ratio binder to microcapsules and the suitable mass ratio binder to micro PCMs taken was between 1:2 and 1:4 [17]. Izzo Renzi et al. coated micro PCMs onto the fibrous substrate by polymer binder, and then used DSC and infrared vision camera (IRT) to evaluate the samples thermoregulation properties [18].

Nowadays, researches about PCM used in asphalt mixture are mainly focused on PCM properties, preparation mechanism, preparation technology, and effect of tempering, however, researches about phase change materials on tempering range and operating temperature are poor. Therefore, aimed at the temperature distresses and its impact on asphalt pavement, based on PCMs properties, different thermoregulation types of CPCMs were studied, and the critical temperature values corresponding to thermoregulation types were determined. The objectives of this research is to analyze the proposed three different thermoregulation types of CPCMs and the influence of Tetradecane and 58# paraffin on phase change thermostat agent, to recommend composite phase change materials and the corresponding mass ratio. The aim of this project is to propose a suitable and effective CPCMs and corresponding composites, which intend to solve the temperature distresses in asphalt pavement.