ABSTRACT

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Title: Environmentally Tuning Asphalt Pavements Using Phase Change Materials: Benefits, Design, and Challenges
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The vulnerability of highway infrastructure to changes in environmental conditions is becoming a topic of concern, and the effects of climate on pavement performance need to be better mitigated. Abrupt environmental fluctuations can detrimentally affect pavement performance and service conditions. Moreover, noticeable temperature fluctuations, coupled with heavy vehicles and ample rainfall and snow precipitations, can cause pavements to reach their limiting performance criteria rapidly.

Asphalt materials must balance the need for thermal management with mechanical resistance to maximize pavement performance in such unpredictable environments. The ability to endow asphalt pavements with thermal energy storage capacities based on environmental conditions will enhance their life cycle performance. Phase Change Materials (PCMs) have demonstrated ideal characteristics as thermoregulating agents for various engineering applications. PCMs are substances that absorb and release thermal energy as they liquify and solidify, depending on pavement temperature. Accordingly, this study investigates the environmental tuning of asphalt pavements using PCMs. This dissertation presents four thematic research efforts that intend to: (1) reveal the benefits of modifying asphalt pavements with PCMs to lessen the appearance of low and high temperatures in roads, (2) develop characterization and design techniques to aid the tuning of asphalt pavements with Microencapsulated PCMs (μPCMs), (3) illustrate the challenges of implementing new paving technologies, and (4) propose a statistical approach to predict the volumetric, mechanical, and thermal properties of asphalt mixtures simultaneously.

The findings of this dissertation corroborate through experimental and computational results that, indeed, PCMs can enhance the thermal response of asphalt pavements to adverse freezing temperatures, leading to a considerable reduction in snow accumulation and ice formation at the pavement's surface. A prototype PCM asphalt pavement slab shows that, over a year and across 100 locations in the United States, the exposure of asphalt pavements to freezing temperatures could be reduced up to 29.1% by taking advantage of the thermal effect of PCMs.

Additionally, μPCM modified asphalt mixtures demonstrate that high temperatures (above 43°C) in asphalt pavements could be alleviated, reducing the contributions of roads to the urban heat island effect.

Thermal cycling results suggest that μPCM tuned asphalt mixture specimens can experience temperature reductions between 1.8 and 10.3°C, as compared to non-μPCM modified asphalt mixture specimens subjected to the same ambient temperatures. However, this outcome depends on the amount and characteristics of μPCMs, asphalt mixture materials, ambient temperature, phase change transition (liquification or solidification), depth from the pavement surface, and density of the compacted asphalt mixture specimens. Thus, to systematize this tuning effect, a portion of this study focuses on developing a rheological approach for identifying the μPCM latent heat effect and a design approach for reproducing asphalt mixtures with μPCM in large quantities. A Complex Shear Modulus (G*) Change Rate emerges as one of the most interesting findings of this dissertation and as a novel parameter to detect the μPCM latent heat effect using rheological measurements. The G* Change Rate links well with the Differential Scanning Calorimetry results of μPCM modified asphalt binders and thermal response of μPCM modified asphalt mixtures.

Although the design of μPCM modified asphalt mixtures is successfully demonstrated, mechanical testing results reveal that there are still several challenges to be addressed in the implementation of μPCM tuned asphalt pavements. As such, this dissertation presents a field demonstration project accompanied by a thorough statistical analysis that could assist in implementing asphalt pavements with PCMs. The proposed statistical approach could help adjust the volumetric, mechanical, and thermal properties of μPCM modified asphalt mixtures. Overall, the findings of this dissertation are worth further exploration to promote the adaptability of asphalt pavements to the environment through the utilization of thermal energy storage systems.