Title of Design: Application of Phase Change Materials in Airport Runways

Design Challenge addressed: Technical Design Challenges, Airport Operation and Maintenance

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Executive Summary

The purpose of *Application of Phase Change Materials in Airport Runways* was to explore the feasibility of incorporating a Phase Change Material (PCM) into Hot Mix Asphalt (HMA) as a method for reducing damage caused by thermal stresses in airport pavements. The incorporation of the PCM was expected to improve safety by reducing debris from deteriorating pavement, improve the state of the runway by lessening damages, and decrease the amount of time, money and resources needed to maintain runways. PCMs release or absorb heat which makes the material ideal for regulating temperature. The release or absorption of heat occurs during the phase change and can be used to reduce thermal stresses and damage in pavements.

Before mixing with PCM, combustion, absorption, and evaporation tests were conducted to determine how PCM-6 reacted under the high temperatures required for asphalt mixing. Test cubes were constructed with several concentrations of PCM-6 to determine the feasibility of using lightweight aggregate (LWA) as an absorption medium for incorporating PCM-6 into HMA. Next, the thermal properties of the samples were evaluated using a Guarded Longitudinal Calorimeter (GLC), which generated a varying heat flow and measured temperature. After a final mix design was selected, additional samples were produced and subjected to theoretical maximum density tests, bulk specific gravity tests, and an improved GLC test procedure.

Initial testing data indicated it was possible to incorporate up to 2.5% PCM-6 by mass into HMA, but that larger amounts caused samples to lose structural integrity. Thermal tests found PCM slowed the rate of cooling and reduced the extreme temperatures, but did not prevent freezing. Further research could be conducted to investigate alternative PCM incorporation methods, such as encapsulating the PCM in a pellet, to improve structural integrity. The Superpave specification for mix production should be used to confirm that the volumetric properties of the mix are not affected by PCM. Different types of PCMs and thermal cycles should also be tested and developed in order to identify combinations which perform well under different climates.

This team included four seniors from Worcester Polytechnic Institute. The team included two civil and two mechanical engineers, and was supervised by the Civil and Environmental Engineering Department.

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Glossary of Terms

ASTM	American Society for Testing and Materials
BSG	Bulk Specific Gravity
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FOD	Foreign Object Debris
GLC	Guarded Longitudinal Calorimeter
HMA	Hot Mix Asphalt
IQP	Interactive Qualifying Project
LWA	Lightweight Aggregate
MQP	Major Qualifying Project
NWA	Normal Weight Aggregate
PCC	Portland Cement Concrete
PCM	Phase Change Material
PEG	Polyethylene Glycol
TES	Thermal Energy Storage
TMD	Theoretical Maximum Density
VFA	Voids Filled with Asphalt
VMA	Voids in the Mineral Aggregate
VTM	Voids in the Total Mix
WPI	Worcester Polytechnic Institute

Problem Statement

The purpose of this project was to evaluate the effectiveness of utilizing phase change materials (PCMs) as a method for reducing thermal stress in hot mix asphalt (HMA) pavements. The project falls under the Airport Operation and Maintenance Challenges and addresses challenge A. To comply with the specifications of this subcategory, the proposed mixture of PCM and HMA will attempt to demonstrate the ability to improve the service life of a runway and decrease foreign object debris (FOD).

The challenge of incorporating PCM into HMA involves economic, environmental, sustainability, manufacturability, and health and safety constraints. The economic problems of incorporating PCM into HMA include the fact that the savings from reducing the frequency and scale of runway maintenance must exceed the cost of incorporating the PCM. Furthermore, the frequency at which a runway needs to be repaved or sealed has a direct effect on the environment and air quality because harmful chemicals are released during these maintenance processes. Therefore, it is more environmentally friendly to have a pavement that withstands temperature changes and needs to be replaced less routinely. It is also more sustainable to build pavements that do not need to be replaced as often because fewer materials are wasted long-term. Manufacturability was also a constraint in the design process because there were many issues encountered with the incorporation method for the PCM. The PCM should ideally be incorporated in a way or at a ratio which will not compromise the strength of the pavement, and which will not adversely affect the hot mixing process. In terms of health and safety, it is imperative to keep runways free of debris of any size. Failing pavement that chips off of a runway poses a danger to aircraft during both landing and takeoff; therefore, developing a pavement that is less susceptible to thermal damage could keep runways safer. In this way, the design incorporates realistic constraints during the problem solving process.

1 Summary of Literature Review

1.1 Foreign Object Debris (FOD)

One of the major safety concerns of airports is the accumulation of foreign object debris (FOD) on runways and taxiways. The debris consists of unwanted items, such as stones, items that have fallen from planes, baggage pieces, and trash. Every year, FOD at airports causes $12 billion of damage to airplanes and airport infrastructure.[1] A particularly important issue is the danger that debris pose to airport personnel and passengers. In 2000, all 109 passengers and crew, and four people on the ground were killed when Air France Flight 4590 crashed due to FOD.[2] In this particular instance, a small piece of metal from a previous plane cut the tire of Flight 4590 despite the debris being on the runway for less than five minutes.

FOD is removed in various ways depending on the amount and location of the debris. The most common way to remove large amounts of debris from open areas such as runways is to use a FOD sweeper. The FOD sweeper is dragged by a vehicle and forces the small objects into holding sections that are emptied after every few miles of sweeping (Figure 1). Another device is the motor powered vacuum, which is ideal for smaller areas where a FOD sweeper cannot be towed by a vehicle. Other methods include rumble strips which free any debris from an airplane during taxiing. The rumble strips are grooves cut into the pavement and are designed to shake the plane just enough to dislodge any debris clinging to the exterior. Removal of FOD is an important task to ensure safety.[3]

Figure 1: FOD sweepers commonly used at airports.[4]

1.2 Phase Change Materials (PCMs)

In order to minimize the cost associated with the maintenance of airport pavements, governing agencies such as the FAA need to investigate new materials which enhance the performance of a pavement exposed to the environment. Temperature is one of the most important environmental factors affecting this performance, since large temperature changes have the potential to cause significant damage to pavements. Significant improvement in performance, and therefore reduction in maintenance costs, may be possible if the magnitude of these changes in temperature could be decreased. One method is incorporating phase change materials (PCMs) into a pavement mix.

Construction and other commercial industries use PCMs as thermal energy storage (TES) systems. In the past, TES systems have used materials with significant sensible heat storage, or, in other words, heat storage during a change in temperature which does not involve a change in phase. As research into this technology has progressed, materials have been identified which can store more energy as latent heat than previous sensible heat storage materials. PCMs are materials with a high latent heat of fusion (ΔH_f°) which allows large amounts of heat to be absorbed or released during a phase change (Figure 2).[5] There are many families of PCM compounds, each with a range of melting points, which allows for a wide range of applications. Some families of PCMs include organic compounds, such as polyethylene glycol (PEG); saturated hydrocarbons, such as paraffin waxes; inorganic salts and salt hydrates; and eutectic solutions of salts and salt hydrates.[6]

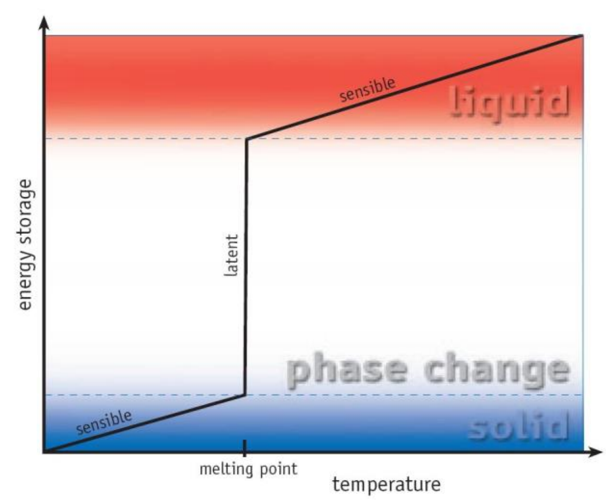

Figure 2: Latent heat versus sensible heat energy storage in a PCM.[6]

PCMs are temperature regulating materials that have the ability to release or absorb heat. The release or absorption of heat occurs during the phase change, which makes the proper selection of a PCM largely dependent on the temperature at which the phase change occurs. For example, PCM-6 (a blend of paraffin waxes), is liquid at room temperature, but as the system temperature lowers to 6 °C (the phase change temperature), the material undergoes an exothermic phase change and solidifies. Conversely, when the system warms, the phase change material undergoes an endothermic reaction and liquefies. Although relatively large amounts of heat are either released or absorbed during these transition periods, the temperature of the surrounding environment remains at the phase change temperature of the PCM. The time during which the temperature remains at this value depends on the value of the latent heat of fusion of the PCM, which means that materials with a high latent heat of fusion (ΔH_f°) can delay a temperature change in their environment for a longer period of time (Figure 3).

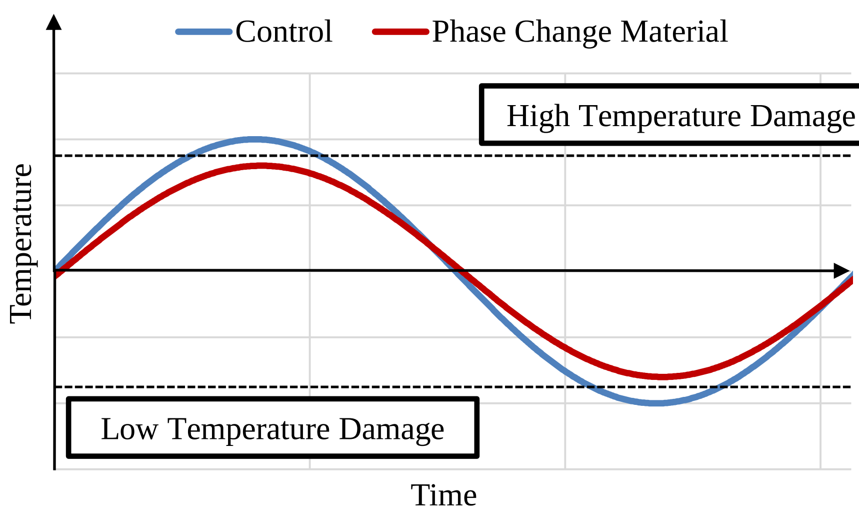

Figure 3: Theoretical illustration of the effect of a PCM on the material temperature profile.

1.3 Rutting and Thermal Cracking in HMA

The properties of PCMs can theoretically be applied to mitigate rutting and thermal cracking in HMA, assuming a proper mix design with adequate strength and other properties can be achieved. Rutting in the HMA can be due to vertical deformations caused by local increases in density when large loads traverse a pavement with a hot surface temperature. The high temperature allows the mix to compress to a state with lower air voids under this extreme condition.[7] A more typical occurrence is deformation or movement of the pavement in both the vertical and horizontal directions due to a shear failure in the pavement. Shear failure occurs when pavements exposed to high temperatures and repeated loads over time lose their binding strength and begin to deform plastically. These deformations often involve a vertical displacement of material under the wheel path, which in turn causes nearby sections of the pavement to move laterally or rise, producing ripples or channels in the pavement surface (Figure 4).[7]

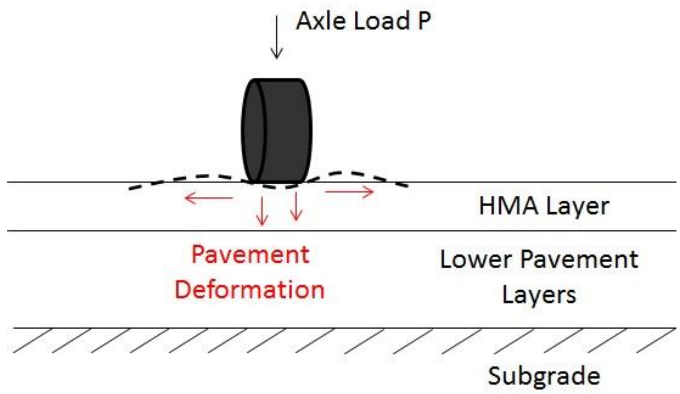

Figure 4: Schematic showing the action of repeated wheel loads over time to create rutting in HMA.

General models to determine rutting in the HMA layer involve the calculation of the vertical plastic strain that the layer undergoes, as stated in the following set of equations[8]:

$$\frac{\varepsilon_p}{\varepsilon_r} = k_1 * a * N^b * T^c \quad (1)$$

$$RD_{HMA} = \varepsilon_p * h_{AC} \quad (2)$$

In Equations 1 and 2, the plastic strain fraction ($\varepsilon_p/\varepsilon_r$) is calculated using the total number of loads (N), the pavement temperature (T, °F), and a non-dimensional depth correction factor (k_1). The data are correlated using several experimental coefficients (a, b, and c), and the total rutting (RD_{HMA}, in) is found by multiplying the plastic strain by the thickness of the HMA layer (h_{AC}, in). The depth correction factor is found using the following experimentally determined equations which are a function of HMA thickness (h_{AC}, in) and depth to computational point (depth, in):

$$k_1 = (C_1 + C_2 * depth) * 0.328196^{depth} \quad (3)$$

$$C_1 = -0.1039 * h_{AC}^2 + 2.4868 * h_{AC} - 17.342 \quad (4)$$

$$C_2 = 0.0172 * h_{AC}^2 - 1.7331 * h_{AC} + 27.428 \quad (5)$$

PCM may be a viable method to reduce the potential for rutting of asphalt pavements in hot climates. For this scenario, a PCM with a melting point significantly above room temperature (70 °F or 20 °C) would be selected and incorporated into the HMA mix design. As the temperature rises, the PCM would melt and absorb heat, thus cooling the overall system.[5] By doing so this would lower the overall temperature values used in Equation 1, thus decreasing the rutting in the HMA layer.

The other distress mechanism which PCMs may be able to reduce is thermal cracking. Thermal cracking can occur as either low temperature cracking or thermal fatigue cracking (Figure 5). In low temperature cracking, the pavement is exposed to extreme low temperatures which cause the pavement to want to contract. However, the pavement is constrained by the base layer in all directions, and it is also constrained in the longitudinal direction by the continuous layer of mix which makes up the lane. High longitudinal stresses build up at the surface of the pavement where the temperature is lowest, and decrease in magnitude within the pavement cross-section.

Figure 5: Transverse cracks caused by thermal cracking in a roadway pavement.[9]

Due to the viscoelastic nature of hot mix asphalt, the initial cooling of the pavement results in a temporary increase in the tensile strength of the HMA (Figure 6). However, once the tensile stresses in the pavement become large, microcracks begin to form and cause local decreases in tensile strength. These cracks form from the surface down because the temperature change is greatest at the surface of the pavement, producing a stress distribution conducive to crack propagation (Figure 7). Some microcracking can heal if the pavement returns to a viscous temperature, but crack propagation and expansion will continue to damage the pavement if temperatures remain low enough to cause continued high tensile stress in the pavement.

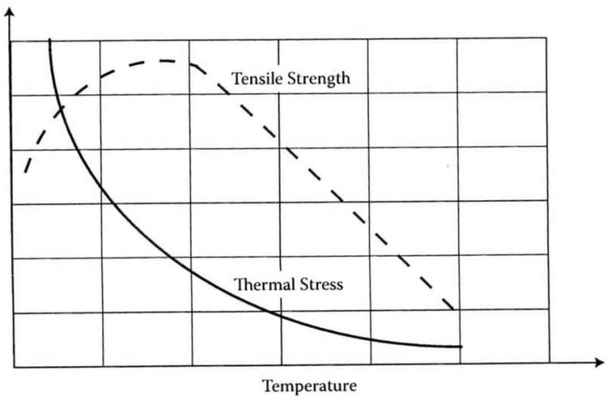

Figure 6: Concept graph of the relationship between tensile strength, thermal stress, and temperature in HMA.[7]

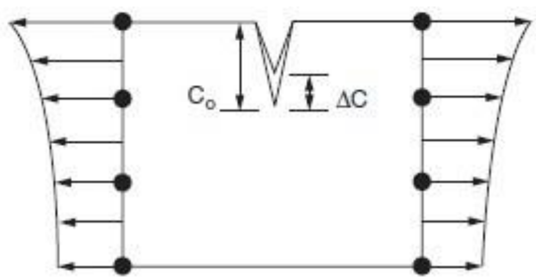

Figure 7: Thermal stress gradient in an HMA layer which causes top-down cracking.[9]

If temperatures remain such that low temperature cracking does not occur because the tensile strength is not exceeded, the HMA will not fail immediately. However, strains may build up after repeated high and low stress cycles produced by temperature fluctuations and traffic loading over time. This could lead to failure in the long term by thermal fatigue cracking.[7] These repeated stress cycles are often inevitable over the lifetime of a pavement. PCMs may be able to reduce a pavement’s susceptibility to thermal fatigue cracking. As the temperature of the pavement decreases, the PCM will freeze and release heat into the matrix keeping the system warmer than the surrounding ambient temperature.[10] If a pavement contained a PCM with a low enough melting point, the PCM could temporarily prevent the pavement from crossing or approaching the operational threshold of the binder, depending on the frequency and intensity of low temperature cycles. In this way the PCM can reduce the extremes of temperature fluctuation and make pavement temperature profiles smoother. This smoother profile may also help to deter freeze-thaw cycling in pavements which have absorbed water. A PCM appropriate for this purpose would need a phase change temperature above the freezing point of water.

2 Interactions Between Airport Operators and Industry Experts

In order to gain specific information on common types of thermal damages to airport pavements, professionals with knowledge of airport pavements were contacted. Questions were geared to each recipient's location and areas of expertise, and were developed in order to gain a range of information. The respondents included John Kirkendall (Jacobs Engineering), Jonathan Neeser (Worcester Airport), and Barry Hammer (FAA Airports Division).

John Kirkendall of Jacobs Engineering responded that he has seen firsthand the effects of thermal distresses at airports in Alaska. He identified frost heave and potholes as the most predominant problems facing airports in that region. According to Mr. Kirkendall, one of the most important ways to prevent airport pavement damage is to repair and prevent cracking, which can allow water to penetrate the asphalt and cause even more damage. Airports in the region use HMA more often than PCC mostly because of the shorter construction time associated with HMA.

Jonathan Neeser of the Worcester Airport stated that although asphalt deterioration does cause FOD at the airport, this is mainly caused by segregation of the HMA and not by thermal distresses. He believes that thermal distresses of the pavements are not predominant at the airport because of the quality of the system used, including proper drainage, and quality mix design and materials. The majority of the damage to the airport pavements is seen near the airplane hangars and not on the runway itself. The HMA at the Worcester Airport is tested for acceptable ranges of stability, flow, air voids, and density.

Barry Hammer with the FAA Airports Division confirmed the importance of FOD safety by noting how loose aggregate, even in the form of a small stone, could have devastating effects if it entered a jet engine intake. He also explained that the most severe freeze-thaw impacts are at airports constructed on frost-susceptible materials, such as clay and silt. However, Mr. Hammer also noted that the conventional wisdom in regards to freeze-thaw is that the adverse impacts of freeze-thaw cycling were a result of this action in the base materials, not within the pavement material itself.

The results of these professional contacts indicate that water penetration of HMA pavements through surface cracks has traditionally been a cause for concern because it allows for pavement deterioration by a variety of failure modes. Specifically, freezing of this water within pavement layers is a concern for airport pavement maintenance. If crack initiation at the surface could be reduced, then this will reduce the total number of entry points for water to enter the pavement. This reduction of entry points will correspond to a reduction in stripping, raveling, cracking, and pothole formation, which will lead to lowered overall maintenance costs for airports. In order to identify possible solutions for surface crack reduction, it was decided to investigate the feasibility of incorporating low-temperature PCM into HMA.

3 Methodology

3.1 Experimental Methods Summary

Before attempting to incorporate PCM-6 into HMA, uncertainties with the behavior of the PCM-6 were investigated. First, a beaker containing 20 mL of PCM-6 was placed in an oven at 150 °C to simulate the conditions of mixing HMA in order to determine if the material would ignite. After determining that the material would not ignite, absorption and evaporation tests were conducted to determine how much PCM-6 was absorbed by the Lightweight Aggregate (LWA) and how much evaporated during the HMA mixing process (Phase 1). Test cubes were then constructed to assess the feasibility of using LWA as a method for incorporating PCM-6 into HMA. Then, the thermal properties of the samples were evaluated using a Guarded Longitudinal Calorimeter (GLC) to determine the thermal impacts of incorporating PCM-6 into HMA (Phase 2). To address the issues with incorporating PCM-6 into test cubes, iterations of mix designs were performed to determine the threshold amount of PCM-6 that could be incorporated without significant loss of material strength. After selecting a final mix design, a final batch of samples was produced and subjected to theoretical maximum density tests, specific gravity tests, and an improved GLC test procedure (Phase 3). The Superpave specification was used throughout the project.[11] The different phases, tests and dimensions/amounts of test specimens are summarized in Table 1.

Table 1: Summary of testing phases.

Phase	Test	Dimensions/Amount
Phase 1 – Absorption and Evaporation Tests		
1	**PCM-6 Heating Test**	20 mL
	Absorption/Evaporation Test	-
Phase 2 – Feasibility of a HMA/PCM Mix		
2	**GLC Testing**	2"x2"x2"
	Control	
	1.25% PCM-6	
	2.5% PCM-6	
Phase 3 - Improved Mix Design		
3a	**GLC Testing**	2"x2"x2"
	Control	
	1.25% PCM-6	
3b	**Theoretical Maximum Density**	2"x2"x2"
	Control	
	1.25% PCM-6	
3c	**Bulk Specific Gravity**	2"x2"x2"
	Control	
	1.25% PCM-6	

3.2 Phase 1: Heating and Evaporation Tests

Before experimenting with incorporating PCM-6 into HMA, an evaporation test was conducted to determine how liquid PCM-6 would behave in conditions similar to those involved in the preparation of HMA. The purposes of this experiment were to investigate whether the material would ignite at high temperatures and to calculate the evaporation rate of liquid PCM-6. To conduct the test, a beaker with 20 mL of PCM-6 was placed in an oven at 150 °C for 1 hour and monitored for combustion. Upon completion, it was determined that the PCM-6 was non-combustible at 150 °C and the final amount of PCM-6 was measured to estimate loss due to evaporation.

After determining that the PCM-6 was safe for mixing, a series of trials were conducted to determine the amount of PCM-6 that would be absorbed by the LWA and the evaporation rate during heating. Three trials of four combinations (12 samples) of LWA were tested: No. 4 sieve, No. 8 sieve, No. 16 sieve, and an equal mixture of each of the aforementioned sieves. The LWA was soaked in PCM-6 for 24 hours before being placed in the oven at 150 °C for 3 hours. After every 30 minutes the amount of PCM-6 was measured and recorded. Since it was found that the PCM-6 evaporated quickly, a second test requiring 12 new samples was conducted for 30 minutes with weights measured at 5 minute intervals.

3.3 Phase 2: Sample Production and Thermal Testing

After investigating the properties of PCM-6, it was possible to begin producing test samples. These samples were designed to act as conceptual samples to determine the feasibility of incorporating PCM-6 into HMA. The samples contained aggregate retained on sieve sizes No. 4 through pan. For these samples, 20% of the aggregate was from a natural sand stockpile and the remaining 80% from a crushed stone stockpile. Since proportions of individual sieve sizes were not used, an initial binder content of 5.5% was increased to 9% by mass to account for binder absorbed by the excess fines present in the mix. The mix design began with a volume of aggregate approximately equal to 8 in^3 (131 cm^3) and a corresponding mass of binder based on the binder content. The PCM-6 was incorporated via absorption into the LWA, which replaces an equivalent volume of normal weight aggregate (NWA) in the mix. To calculate the amount of PCM-6 to add to each sample, the water absorption of LWA was used to back-calculate the theoretical PCM-6 absorption of LWA (13.3%).

3.3.1 Sample Production

Using the results from the PCM-6 absorption and evaporation tests, a mixing procedure was designed and used to construct 2 in (50 mm) cube samples. Exact PCM contents were calculated, but due to losses during the heating and mixing process, approximate target contents are used to identify each mix design. The target concentrations were 0% (control), 1.25%, 2.5%, 5.5% and 10.5% PCM-6 by mass. For the PCM-6 batches, the theoretical amount of absorbable PCM-6 and the LWA were placed in a closed container and agitated every 6 hours over a 24-hour period. Table 2 through Table 6 specifies the proportions used to produce each batch.

Table 2: Mix design for control batch.

Mix Component	Mass (g)
Aggregate (NWA)	**699**
Crushed Stone	556
Natural Sand	143
Binder	**73**

Table 3: Mix design for 1.25% PCM-6 batch.

Mix Component	Mass (g)
NWA	**894**
Crushed Stone	715
Natural Sand	179
LWA	**105**
No. 4	21
No. 8	42
No. 16	42
PCM-6	**14**
Binder	**95**

Table 5: Mix design for 5.5% PCM-6 batch.

Mix Component	Mass (g)
NWA	**427**
Crushed Stone	342
Natural Sand	85
LWA	**420**
No. 4	84
No. 8	168
No. 16	168
PCM-6	**56**
Binder	**95**

Table 4: Mix design for 10.5% PCM-6 batch.

Mix Component	Mass (g)
NWA	**0**
Crushed Stone	0
Natural Sand	0
LWA	**716**
No. 4	143
No. 8	287
No. 16	286
PCM-6	**95**
Binder	**64**

Table 6: Mix design for 2.5% PCM-6 batch.

Mix Component	Mass (g)
NWA	**633**
Crushed Stone	506
Natural Sand	127
LWA	**180**
No. 4	90
No. 8	90
PCM-6	**24**
Binder	**81**

3.3.2 Guarded Longitudinal Calorimeter

The Guarded Longitudinal Calorimeter (GLC) consisted of an insulated cold plate that was used to generate a fluctuating or constant uniaxial heat flow through a sample of material (Figure 8). To measure the heat flow, the sample was placed inside the insulation, which has an opening of 4 in^2 (25.8 cm^2), and six 16-gauge type K thermocouples measured the temperatures within the system. The sample was placed between two glass-ceramic blocks (2 in x 2 in x 1 in) (5.08 cm x 5.08 cm x 2.54 cm) and the thermocouples were held in contact using 1/8 in (0.318 cm) of a thermal transfer media.

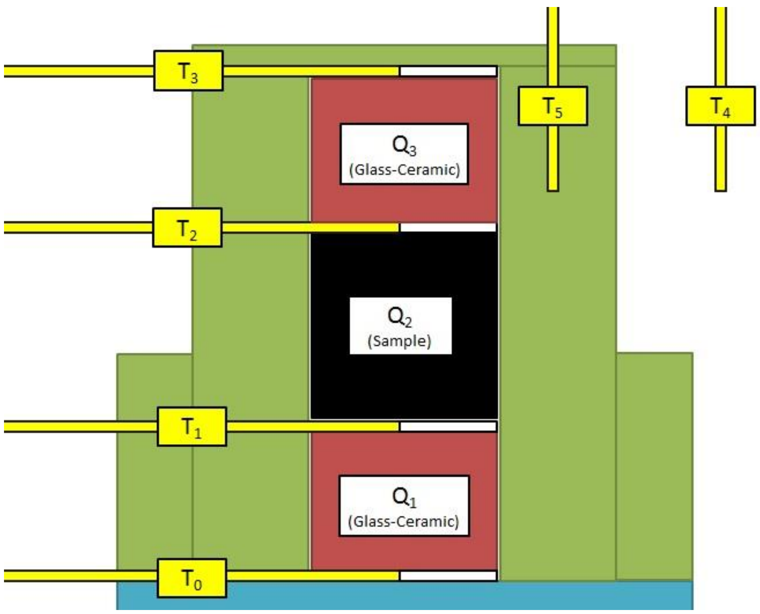

Figure 8: Diagram of the Guarded Longitudinal Calorimeter (GLC) device.

In total, six temperatures were recorded by a data acquisition box and four (T_0, T_1, T_2 and T_3) were used for estimating the heat flow. Temperature T_o is measured at the boundary between the cold plate and a glass-ceramic block, T_1 at the boundary between one of the glass-ceramic blocks and the sample, T_2 at the boundary between the sample and the other glass-ceramic block, and T_3 at the boundary between the glass-ceramic block and the cover of the GLC. Temperature T_4 is the temperature of the ambient air and T_5 is the temperature inside the insulation. To compute the heat flow across the samples, the steady-state conduction equation was utilized, as follows:

$$Q = A_{surface} \cdot \lambda \left(\frac{\Delta T}{\Delta z}\right) \tag{6}$$

Where Q [W] is the heat flow across the sample, $A_{surface}$ (m^2) is the surface area measured in the x-y plane, λ is the thermal conductivity (W/mK) of the sample, and ΔT/Δz (K/m) is the temperature gradient. The temperature gradient is defined as T_n-T_{n+1}, which implies heat flow leaving the sample is positive, and Δz, which is the thickness of the block in the z-direction, was measured experimentally for each sample. For the known glass-ceramics, a thermal conductivity of 4.18 W/mK and Δz of 1 in (2.54 cm) was used. Because the thermal conductivity of the sample was unknown, the heat flow across the sample (Q_2) was found using the following equation:

$$Q_2 = \frac{Q_1 + Q_3}{2} \qquad (7)$$

In order to apply the aforementioned thermodynamic equations, it was assumed the heat flow acted only in the z-direction, conduction was the only form of heat transfer and that the change in temperature was gradual enough to assume steady-state.

3.3.3 GLC Testing in Phase 2

Phase 2 was comprised of testing three samples containing 1.25% of PCM-6, three samples with 2.5% PCM-6, and two control samples (Control 2 was tested twice). The GLC subjected each sample to three cycles of temperatures ranging from 23 to -25 °C (Figure 9).

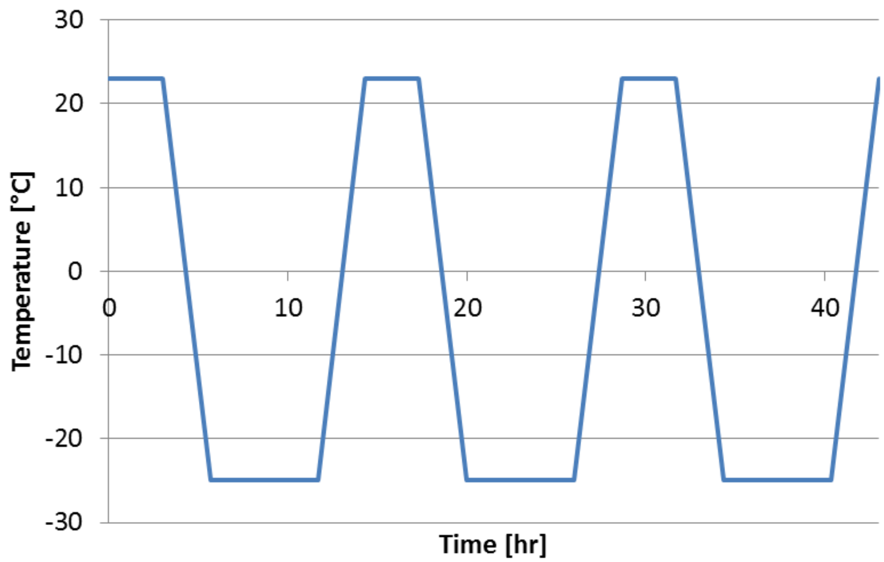

Figure 9: GLC cycle for Phase 2 thermal property testing.

The gradual changes in temperature were used to investigate whether a noticeable change in energy occurred at the phase change temperature (6 °C) for PCM-6. In addition, the temperature plateaus (at 23 °C and 25 °C) were used to determine if the PCM minimized the extreme cold and hot temperatures. The rate of change of the temperature was programmed as 0.3 °C/min.

3.4 Phase 3: Improved Mix Design with Volumetric and Thermal Testing

After establishing the feasibility of incorporating PCM in an HMA mix, tests were performed to evaluate whether an HMA mix utilizing Superpave specifications for airfield pavements could be produced with a HMA/PCM-6 mix. A gradation analysis was performed and a final gradation within the specified limits of the specification was selected. A binder content of 5.5% was used. Theoretical maximum density (TMD) tests were conducted on the control mix, and the TMD of a mix including 1.25% PCM-6 in LWA was back-calculated using the control TMD value. Mix designs were then developed, separately, for each batch of control and PCM based on a target density of 96% of the TMD. Samples were produced and subjected to Bulk Specific Gravity (BSG) testing and thermal testing in the GLC to determine the volumetric and thermal properties of each mix for comparison with the specification.

3.4.1 Aggregate Gradation Analysis

The ASTM C-136 standard was followed to obtain the gradation of the individual aggregate stockpiles used for batching the HMA cubes. For the mix design, a specific gravity of 2.70 and absorption of 1.1% were averages of known properties used for the NWA.[12] Once the gradations were obtained for each stockpile, a linear combination of stockpiles was used to obtain a full aggregate gradation that was within the limits given in the Superpave specification.

3.4.2 Theoretical Maximum Density Test, Sample Mix Design, and Production

Once the aggregate gradation was determined, a trial binder content of 5.5% was selected and a mix was batched for the TMD test. Samples were prepared and cooled to room temperature during a period of continuous mixing. After experimentally determining the TMD of a control batch, the expected TMD of a PCM batch was back-calculated using these results. New mix designs were prepared using these TMD values to produce samples with a target air void content of 4%. Once each mix design was completed, a control batch and a batch of 1.25% PCM-6 were made. Tables 7 and 8 contain the final mix designs developed and implemented for the Phase 3 samples.

Table 7: Mix design for control batch.

Mix Component	Mass (g)
NWA	**840**
Coarse Aggregate	141
Crushed Stone	360
Natural Sand	339
Binder	**48**

Table 8: Mix design for 1.25% PCM-6 batch.

Mix Component	Mass (g)
NWA	**720**
Coarse Aggregate	141
Crushed Stone	360
Natural Sand	219
LWA	**81**
No. 4	81
PCM-6	**11**
Binder	**45**

3.4.3 Bulk Specific Gravity Test and Volumetric Calculations

Once the cubes cooled overnight, the BSG test was conducted on each sample according to ASTM D7063. The BSG values for these samples were used along with the recorded masses of aggregate and binder in each cube to calculate volumetric properties, including the percent voids in total mix (VTM), the percent voids in the mineral aggregate (VMA), and the percent voids filled with asphalt (VFA). These data were compared against each sample and the specifications to determine the effect of the PCM on volumetric properties, as well as, adherence to the Superpave specification.

3.4.4 GLC Testing in Phase 3

Phase 3 utilized three control samples and three samples of 1.25% of PCM-6. Due to time constraints, only one control and two samples of 1.25% PCM-6 were tested. These tests followed the same logic as Phase 2. The main differences were that the Phase 3 testing utilized a more gradual temperature change of 2 °C/hr for cooling and 4 °C/hr for heating, and contained less cycles that ranged from 25 to -25 °C (Figure 10).

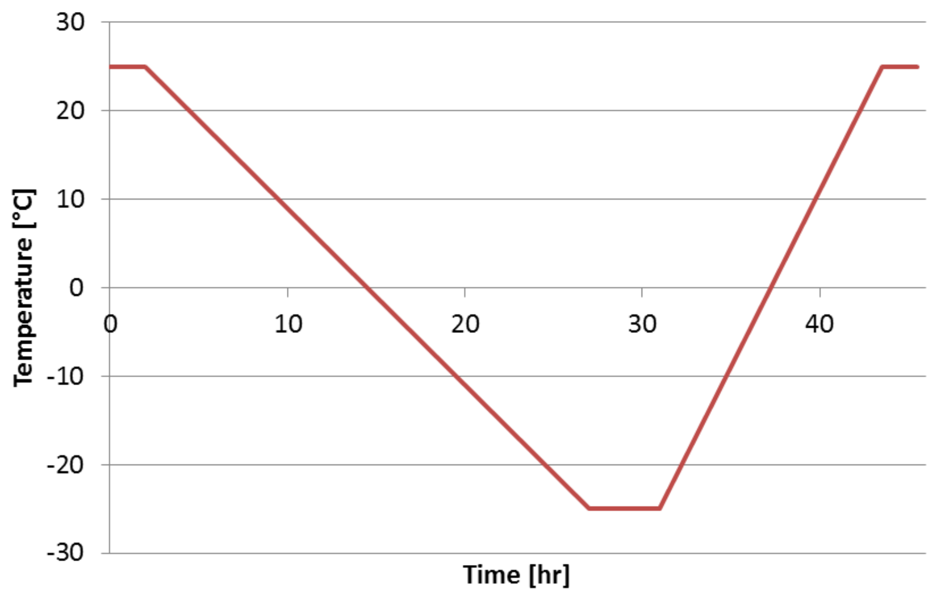

Figure 10: GLC cycle for Phase 3 thermal property testing.

The more gradual temperature change was used because it was expected to produce more consistent temperature measurements near the phase change temperature and allow for more accurate computations of thermal conductivity (Equations 2 and 3).[13]

4 Results and Discussion

4.1 Phase 1: Heating and Evaporation Tests

After exposing the beaker of PCM-6 to 150 ºC temperatures for one hour, no combustion was observed and the pure PCM-6 had lost 6.86% of its mass due to evaporation. The absorption tests produced results centered on the theoretically calculated value of 13.3% (Table 9). In general, the finer LWA material absorbed more PCM-6 than the coarser LWA. This increase may be the result of PCM-6 adhering to the surface of the finer LWA due to the larger surface area per volume.

Table 9: Absorption test data.

Sieve Size	LWA/PCM [%]	Standard Deviation
# 4	10.1	0.509
#8	13.3	0.532
#16	18.1	0.632
Blend	11.9	0.279

Upon completion of the initial evaporation test and analysis of the results, it was found that for each sample over 70% of the PCM-6 had evaporated within the first 30 minutes. Therefore, a second test with shorter, 5 minute time intervals was conducted to obtain more detailed information on the evaporation of PCM-6 from LWA. With the data from this second evaporation test, it was found that after 5 minutes approximately 15% of the PCM-6 would evaporate (Figure 11). Because of these high evaporation rates, the mix design was altered to minimize the exposure of the LWA/PCM-6 mixture to high temperatures.

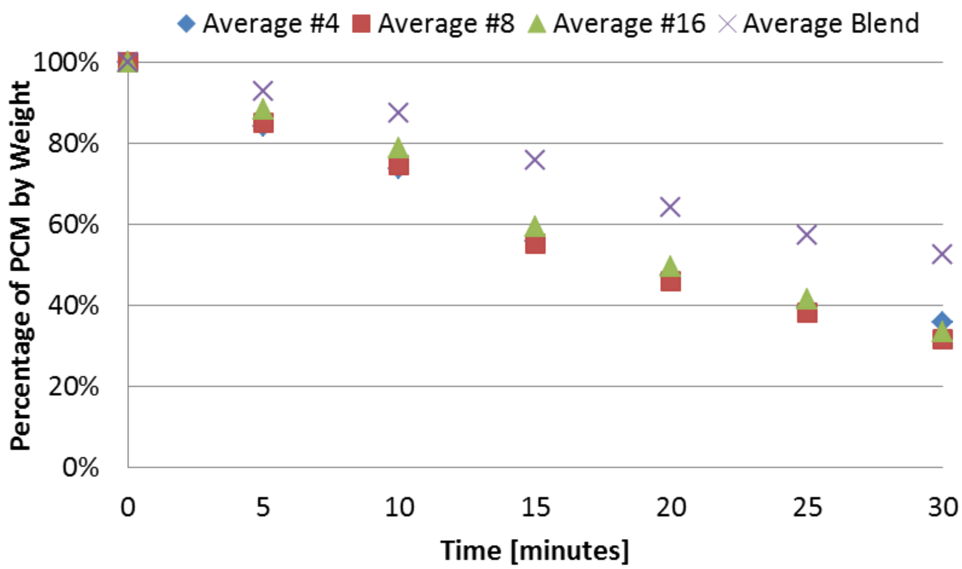

Figure 11: Second PCM-6 evaporation test.

4.2 Phase 2: Sample Production and Thermal Testing

4.2.1 Sample Production and Mix Designs

The first samples produced were control cubes containing no PCM-6. During the mixing process, it was determined that the fines content was too large for the 5.5% binder content, and extra binder was added to give a final content of 10.4% for the control batch. The cubes were compacted and extracted from the molds successfully.

After producing the control cubes, the mix design was altered to use a binder content of 9%. Construction of the 1.25% PCM-6 batch was successful, although the top surface was slightly rougher due to an inadequate amount of soap solution used on the tamp during compaction (Figure 12). However, production of the 10.5% PCM-6 samples was unsuccessful. The degradation of the structural integrity was hypothesized to have been caused by excessive PCM-6, such as from material on the surface of the particle, interfering with the ability of the binder to coat and bond with the aggregate particles.

Figure 12: Compacted HMA samples with 1.25% PCM-6.

To attempt a new maximum PCM batch with 5.5% PCM-6, the mix design was altered to consist of 50% LWA and 50% normalweight aggregate (NWA), and the LWA/PCM-6 mixture was allowed to air dry for 4 hours after the 24 hour soaking period in order to reduce the amount of PCM-6 on the surface of the LWA. However, this resulted in no viable samples for thermal testing and the conclusion that 50% LWA/ 5.5% PCM-6 was still too high to make a feasible mix.

After, a mix was designed to incorporate 2.5% PCM-6. In an attempt to minimize the PCM-binder interaction on the surface of the aggregates, the LWA gradation was changed to eliminate sizes that retained too much PCM on the particle surface. These samples were successfully compacted and extracted from the molds and left to cool overnight to ensure adequate strength. At the end of the Phase 2 mix design and production process, it was found that the maximum feasible PCM content that can be incorporated in an HMA sample using LWA absorption is 2.5%.

4.2.2 GLC Testing in Phase 2

In total, 9 samples with 27 trials (9 cooling/heating cycles) were conducted using the Guarded Longitudinal Calorimeter (GLC) during Phase 2 testing. In order to determine the thermal impacts of incorporating PCM into HMA, two types of graphs were analyzed: average temperature of the sample versus the heat flow across the sample, and the average temperature of the sample as a function of time. The average temperature of the sample was the average of the temperatures measured by thermocouples T_1 and T_2.

The purpose of measuring the average temperature versus heat flow of the sample was to determine if there was an increase or decrease in the heat flow through the sample at the phase change temperature of 6 °C.

When the sample was subjected to freezing, an exothermic reaction was expected and, conversely, when the sample was subjected to thawing, an endothermic reaction was expected. An exothermic reaction, if large enough, would create a negative spike in heat flow, whilst an endothermic reaction would create a positive spike. Each sample was subjected to one trial that included three cooling/heating cycles (Figure 13).

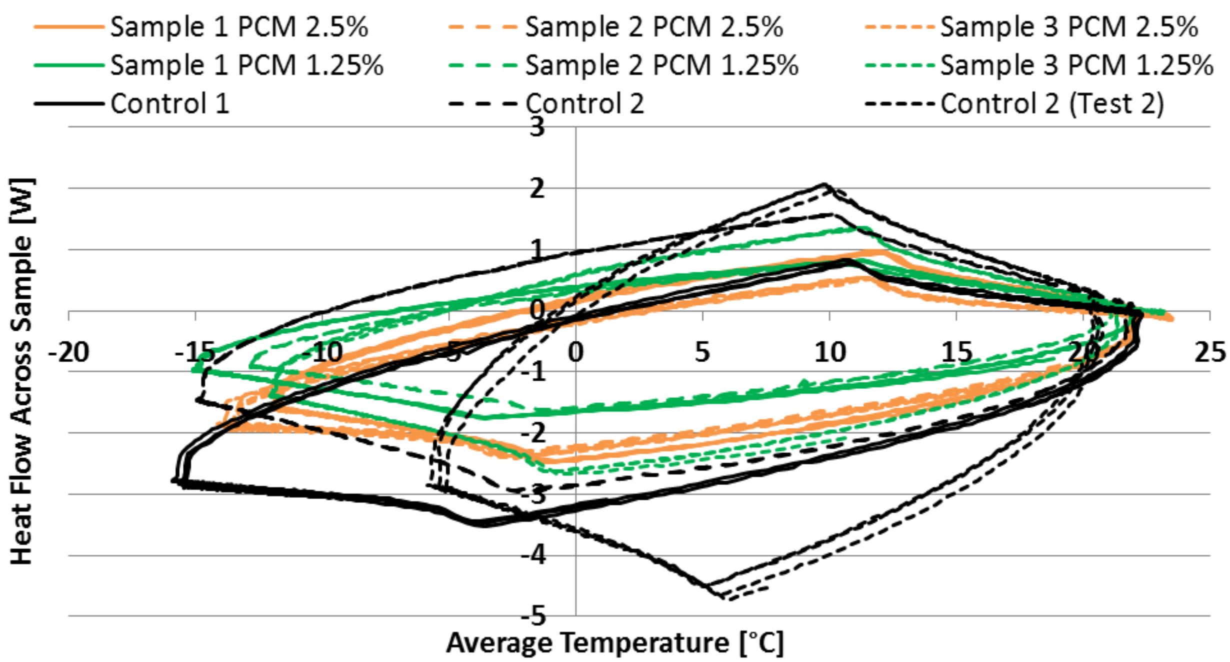

Figure 13: Phase 2 heat flow versus average temperature for samples.

The results from the GLC were mixed, with 2.5% and 1.25% of PCM-6 samples producing relatively centralized data, while the controls produced less consistent results. All samples underwent the same cooling/heating temperature profile and were conducted in approximately the same ambient temperature. Although spikes were seen in the data (quadrants 1 and 3 of Figure 13), the spikes were present for all samples and likely caused by the transition from the constant rate of decreasing/increasing temperature to a constant temperature. Because of the lack of notable spikes, Figure 19 shows no conclusive evidence that endothermic or exothermic reactions occurred during phase change of the PCM-6.

Another method for analyzing the Phase 2 GLC data was to analyze the average temperature versus time (Figure 14). This method measured the time taken for a sample to freeze/thaw and the extreme hot and cold temperature values. Even though the PCM did not produce notable energy changes (Figure 13), the impacts of the PCM may be evident in the reduction of extreme temperatures and decrease of the rate of cooling/heating.

Because the cooling/heating cycles all started at 23 °C, it was possible to normalize all data to the instant the temperature started decreasing by monitoring when the thermocouple nearest to the cold plate (T_o) began decreasing. The normalization of the data refers to the separation of the three cooling/heating trials into separate graphs. Each of the graphs start with the maximum temperature measured before the sample began cooling. For the second and third cycles, the sample never reached exactly 23 °C, so the maximum measured temperature was utilized for normalization. After normalizing all trials, the individual cycles were averaged to create data for overall averages for each sample and control (Figure 14).

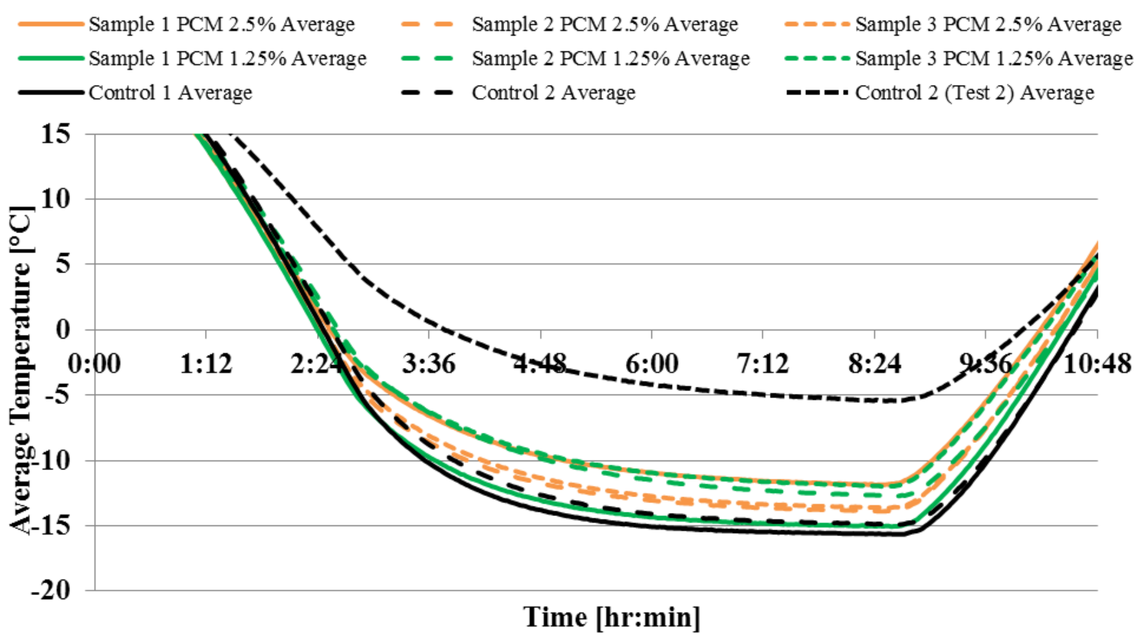

Figure 14: Average temperature versus time for samples averages.

For all samples, the largest temperature deviations occurred after freezing. The thermocouple nearest to the sample (T_o) indicated all samples were subjected to the same programmed cooling/heating cycles in, roughly, the same ambient temperature. Although Control 2 and Control 2 (Test 2) were the same sample, Control 2 (Test 2) produced different results. The most probable explanation for the difference was improper use of the GLC, which could include poor contact between the thermocouples and the sample, which would lead to improper temperature readings, or an inadequate seal between the GLC and the top cover, which would allow ambient air to circulate inside the device. For the following Phase 2 analyses, Control 2 (Test 2) was treated as an outlier.

After assessing the trial averages, overall sample averages and standard deviations were computed for control, 1.25% PCM, and 2.5% PCM to determine the average extreme temperature and average freezing time (Figure 15). The dotted lines represent one standard deviation (σ) and Control 2 (Test 2) was not included in the computations.

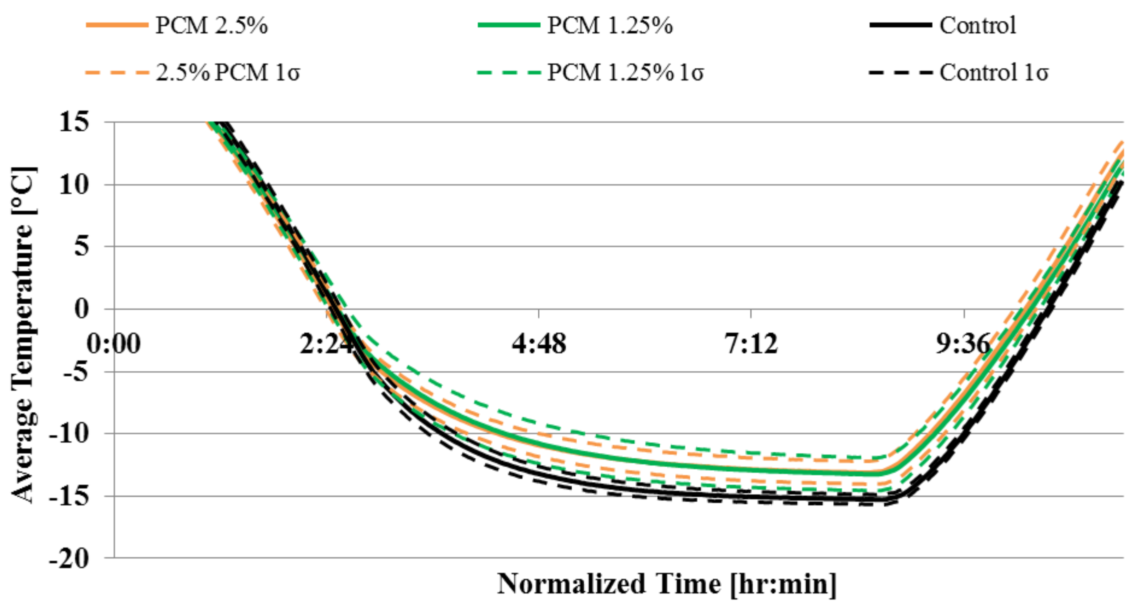

Figure 15: Phase 2 trial average temperature versus normalized time.

The approximate time for a sample to freeze was estimated by the time it took for the average temperature to reach 0 °C. Figure 22 indicates the average samples and controls froze after approximately 2.3 hours into a cycle. Although no PCM sample prevented freezing, a noticeable change in the cooling rate was observed at approximately 30 minutes after the phase change temperature. This reduction in the cooling rate, on average, reduced the average temperature of the PCM samples when compared with the controls. The lowest average temperatures for 2.5% PCM, 1.25% PCM and control were, respectively, -13.11 °C, -13.24 °C and -15.28 °C. Although there is a large deviation of temperature with the control average, the data from 1.25% PCM and 2.5% PCM, even with one standard deviation, indicates PCM may reduce extreme cold temperatures when compared with control.

Although the PCM was chosen specifically to prevent or reduce freezing, the extreme hot temperature of the samples were analyzed (Figure 16). Figure 16 is the same as Figure 15, except the range of data has been modified. Because the first trial was allowed to reach 23 °C without regards to time, only the second and third trials were used in order to keep a consistent time interval. Doing so, the average extreme hot temperatures for 2.5% PCM-6, 1.25% PCM and control were 22.08 °C, 21.62 °C and 21.59 °C, respectively. Another potential benefit of the PCM was that samples may thaw quicker than the controls due to the lower extreme temperature achieved by the sample (Figure 16).

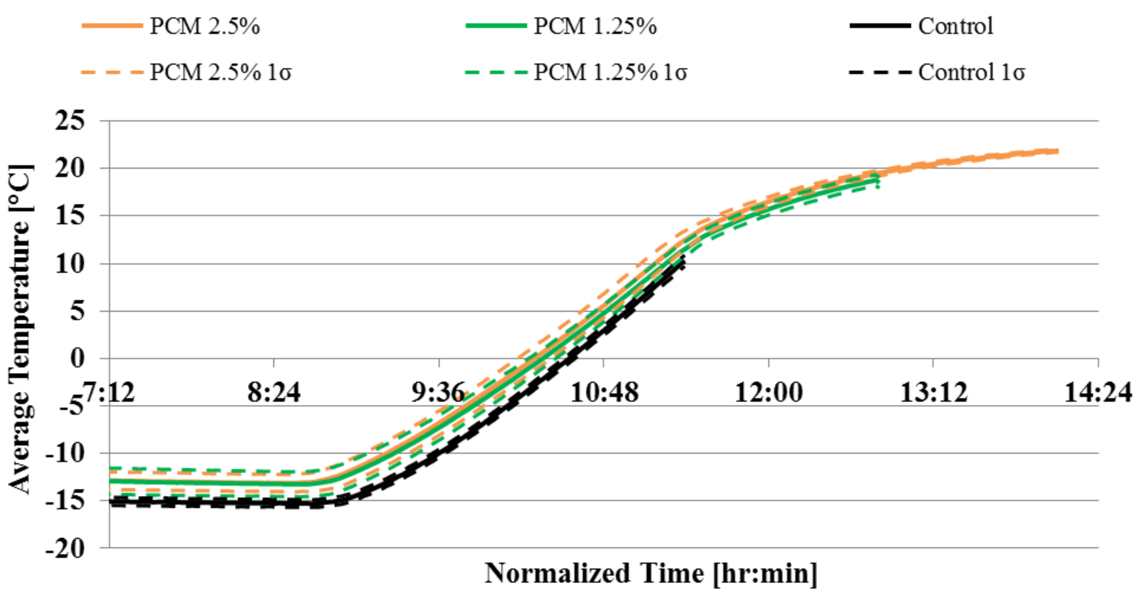

Figure 16: Trial averages at approximate phase change temperature (thawing).

One limitation with measuring the PCM was that each PCM sample was only estimated to contain the designed content, but no tests were conducted to determine how much PCM remained in the sample after mixing. Future tests could be improved if a more accurate amount of PCM could be calculated after mix production. In addition, since there was no uniform mix design, some of the observed thermal differences could be attributed to different binder contents and/or different types and sizes of aggregate. Future tests should be conducted to determine if the thermal properties of aggregate varies greatly in order to reduce uncertainties in the data. Because of the greatly differing results between Control 2 and Control 2 (Test 2), future studies should investigate the consistency and quality of the data produced by the GLC. One method for assessing the GLC would be to subject both controls and samples to multiple cycles on the GLC and assess potential differences.

In conclusion, Phase 2 results provided within one sigma that thermal improvements could be obtained with the incorporation of PCM-6 into HMA. The results show that PCM-6 may reduce the extreme cold temperature of a sample, the rate of cooling, and decrease the time for the sample to thaw. There was no conclusive evidence to support that utilizing PCM-6 reduces the extreme hot temperature. However, in order to have more certainty with the data, future testing would have to be conducted to investigate methods for determining exact PCM content, for producing more consistent GLC data, and to lengthen the steady-state plateau between cycles to reduce data point reduction caused by normalization.

4.3 Phase 3: Improved Mix Design with Volumetric and Thermal Testing

4.3.1 Aggregate Gradation Analysis

Three stockpiles were used to generate an acceptable gradation: 3/8 in coarse aggregate, crushed stone, and natural sand. Two gradations were developed which fell between the Superpave specification limits (Figure 17). The first was a linear combination of the three stockpiles (40%, 20%, and 40%, respectively). The second gradation consisted of the linear combination with some alterations. In order to improve compaction, material retained on or above the 3/8 in sieve was removed from the aggregate gradation and replaced with an equivalent percentage of material retained on the No. 4 sieve.

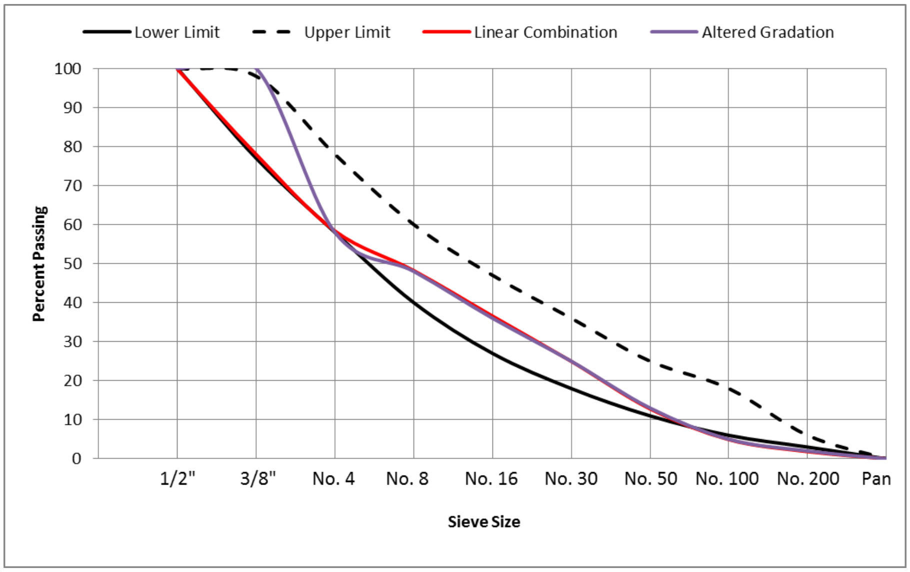

Figure 17: Plot of aggregate gradations for HMA mixes.

The altered gradation was not able to satisfy the Superpave specification due to the high natural sand content (40% versus the normal maximum 20%). Due to the uniformly-graded nature of the 3/8 in coarse aggregate stock, more natural sand and crushed stone stock was needed in order to provide a gradation within the limits of the specification. If this gradation were to be used in practice, it would be more expensive and may impact the properties of the HMA mix. Therefore, the stockpile proportions and alterations used for this gradation were only made in order to facilitate lab operations using the materials available and the non-standard cube samples needed for the GLC tests.

4.3.2 Theoretical Maximum Density Test, Sample Mix Design, and Production

After performing the Theoretical Maximum Density test (TMD) twice on each of three loose material control samples, the average TMD value was reported as 2.34 g/cm^3 with a standard deviation of 0.11 g/cm^3. The back-calculated TMD for the PCM samples was 2.29 g/cm^3.

The first batch of samples produced was the control batch. In order to produce samples with the desired volumetric properties, it was essential to combine all of the material into the mold without losses. As the temperature of the mix dropped below optimal (120-140 °C) during the compaction process, it became more difficult to combine the material. Minor material losses were observed for each sample; however, all samples did compact and extract easily, and were in acceptable shape for volumetric testing.

The final batch of samples produced was the 1.25% PCM-6 batch. Minor material losses were observed in these samples during compaction. The temperature had dropped significantly below the optimal compaction temperature before the final sample was made, so the mold with 2 compacted samples was placed back in the oven for 5 minutes. Although not measured, small losses of PCM-6 were expected. All samples were extracted in good condition and were allowed to cool before volumetric testing.

4.3.3 Bulk Specific Gravity Test and Volumetric Calculations

Average values for the three volumetric properties in question (VTM, VMA, VFA) were calculated using information from the mixing process and the bulk specific gravity test (Table 10). The bulk specific gravities were 84% of the TMD, slightly lower than desired, which was expected due to the material lost during compaction of each sample. The TMD results, however, also impacted the other volumetric properties and were skewed. The voids in the total mix (VTM) were the most notable as they were off by a factor of four.

Table 10: Volumetric properties of HMA samples.

Property	**G_{mb}**		**VTM (%)**		**VMA (%)**		**VFA (%)**	
Sample Group	**Average**	**St. Dev**	**Average**	**St. Dev**	**Average**	**St Dev**	**Average**	**St. Dev**
Target	Control 2.25 / PCM-6 2.20		4		15		65-78	
Control	1.97	0.11	16.0	4.8	31.1	4.1	49.3	8.3
PCM-6	1.92	0.01	16.2	0.5	32.7	0.4	50.5	1.0

Although the properties were not in line with the specification, the average properties for the controls and the PCM samples were approximately the same, suggesting that the PCM may not have a large effect on the volumetric properties of the HMA. Also, the standard deviation among PCM samples was low, indicating that there was high precision in these results. The relatively higher standard deviation among the controls could be due to the first sample tested, which developed a leak and had to be re-tested after drying.

4.3.4 GLC Testing in Phase 3

Phase 3 thermal testing utilized an improved mix design and slower GLC cooling/heating cycle. Because of time constraints, one control and two samples of PCM-6 1.25% were tested. Each sample was subjected to one cooling/heating cycle in the GLC. In total, three samples of PCM 1.25% and Control were mixed. The heat flow across the sample was plotted as a function of the average temperature (Figure 18).

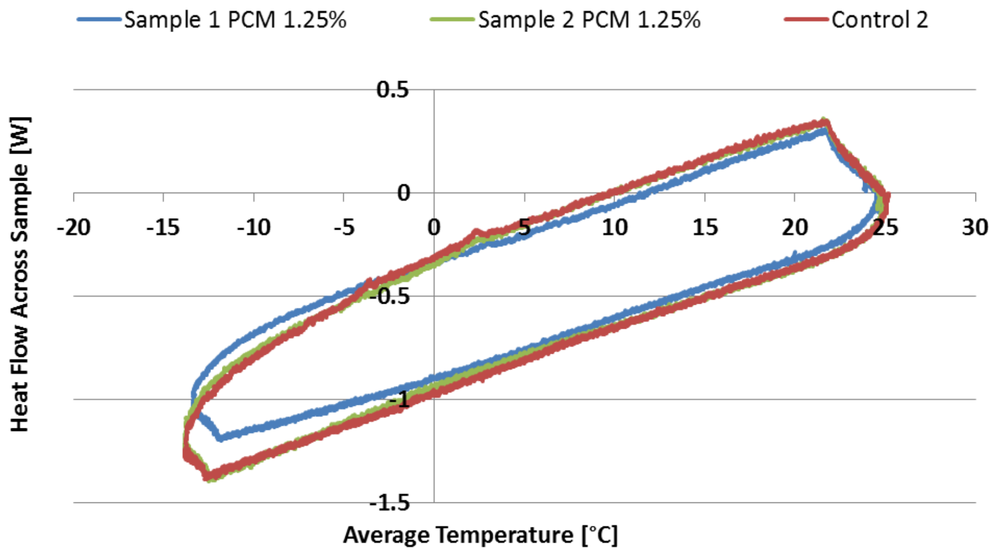

Figure 18: Phase 3 heat flow versus average temperature for samples.

Figure 18 shows no signs of endothermic or exothermic reactions at the phase change temperature. Although a small spike was observed at 2.5 °C for Control 2, no spike was observed for any of the PCM samples. In addition, Sample 2 PCM 1.25% and Control 2 produce a similar curve, while Sample 1 PCM 1.25% produced a smaller shape. After, the average temperature was then plotted as a function of time. The graph allows for analysis of the rate of cooling/heating, freezing/thawing times, and the computation of maximum temperatures (Figure 19).

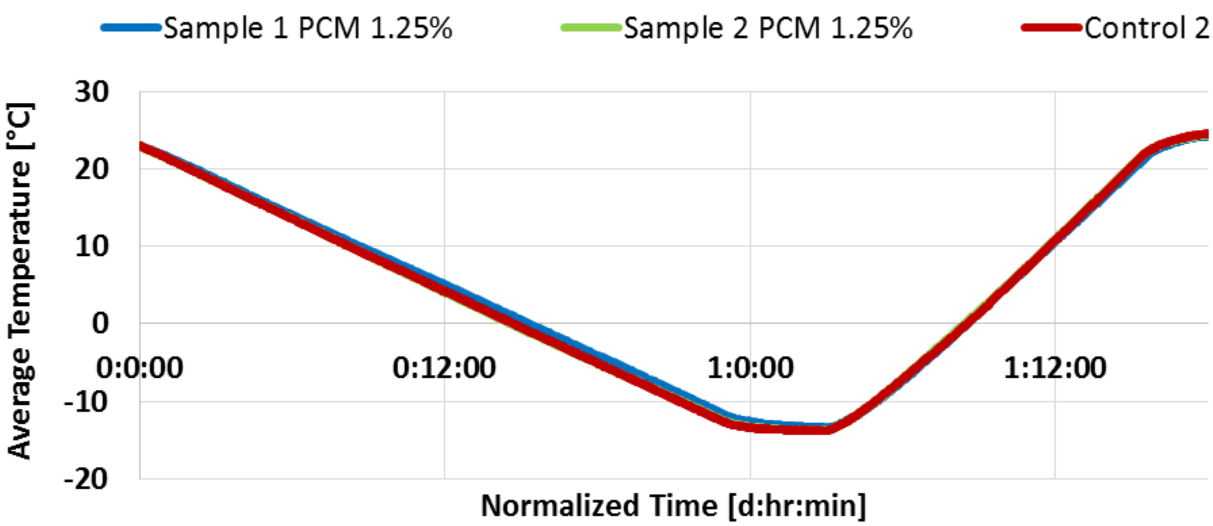

Figure 19: Phase 3 trial average temperature versus normalized time.

As was the case in Figure 18, Sample 2 and Control 2 produced almost identical temperature profiles, while Sample 1 showed a decrease in the freezing rate. A summary of the cooling/heating rate, extreme temperatures and thermal conductivity are shown (Table 11):

Table 11: Phase 3 extreme temperatures, freezing/thawing times and thermal conductivity.

	Sample 1 PCM 1.25%	Sample 2 PCM 1.25%	Control 2
Maximum Temperature [°C]	24.8	24.8	24.9
Minimum Temperature [°C]	-13.4	-13.8	-13.8
Thermal Conductivity [W/mK]	0.65 (+/- 0.07)	0.83 (+/- 0.11)	0.83 (+/- 0.11)
Freezing Time [d:hr:min]	0:15:17:10	0:14:35:10	0:14:41:40
Thawing Time [d:hr:min]	1:8:31:30	1:8:24:40	1:8:31:40

All samples had approximately the same extreme temperatures, and thawing time, but the rate of cooling was reduced for Sample 1. It was expected that all samples would reach the approximate same maximum and minimum temperatures because of the length of the test. Sample 1 remained above freezing for approximately 35 minutes longer than Control 2. It is important to note that during Phase 3 testing, the GLC changed temperature every hour, whilst during Phase 2 the GLC changed temperature every minute. In addition, the duration and cycling between cooling/heating also cause Phase 2 results to appear more substantial than Phase 3. In addition, the HNA/PCM for Sample 1 had an average thermal conductivity of 0.65 W/mK, which was lower than Control 2 and Sample 2. A lower conductivity reduces the rate of heat flow through a sample which reduces the rate of cooling and heating. Although the reduction in heating rate could potentially increase the time it takes for a sample to thaw, the sample could still thaw quicker (Sample 1) or on par with a control (Sample 2) if the PCM reduced the extreme cold temperature. Because Control 2 and Sample 2 exhibited roughly the same results, future analysis should be conducted to determine if any PCM was integrated into Sample 2 or if the GLC recorded inaccurate results. Although more tests will need to be conducted to be certain of the effects of PCM, these initial results provide additional indications that HMA incorporated with PCM reduces cooling rates and, potentially, extreme cold temperatures.

One issue with utilizing a slower cooling/heating temperature profile was that the temperature inside the sample varied. This variance meant PCM located closer to the cold plate would have changed phase sooner than

PCM located near the top of the sample. This difference in activation time would diminish the collective ability of the PCM to warm or cool the sample. For example, the temperature profile of Sample 1 PCM 1.25% (Phase 3) is shown (Figure 20).

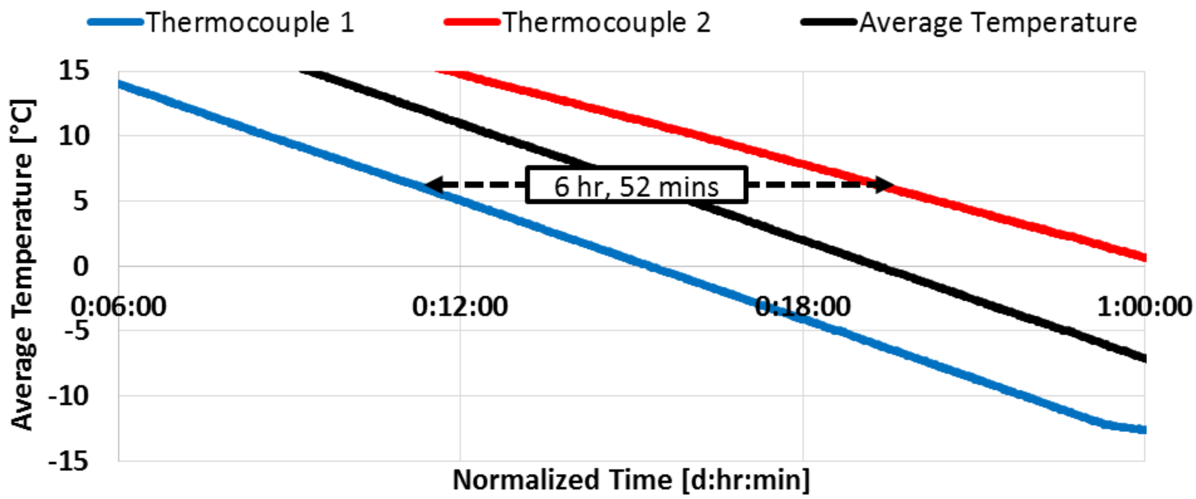

Figure 20: Temperature profile of sample 1 PCM 1.25% (Phase 3).

The figure illustrates that by the time thermocouple 2 (T_2) indicated 6 °C, thermocouple 1 (T_1) had reached 6 °C almost 7 hours earlier. In addition, by the time all of the PCM, theoretically, had changed, portions of the sample would have already frozen. In comparison with Phase 3, the Phase 2 sample, theoretically, completed its phase change in approximately 5 hours. Although the amount of PCM, and particle size and amount was different between the two phases, a portion of the different temperature profiles was caused by the rate of PCM activation. In the future, endothermic and exothermic reactions may be more observable if the temperature decreased/increased more quickly so that the PCM would phase change in a shorter amount of time, thus releasing more energy.

5 Risk Assessment

Ideally, the safety protocols required for maintaining a PCM/HMA runway would be almost equivalent to those required for a normal HMA runway. In accordance with Advisory Circular AC 150/5200-37, a gap analysis would have to be conducted to determine if PCM runways would require additional safety management systems (SMS). In addition to regular maintenance and sweeping for foreign object debris (FOD), analyses should be conducted on the environmental impacts and life-cycle.

The method used for incorporating PCM into HMA using LWA is currently not feasible for direct use in airport runways. If utilizing LWA becomes a feasible method for incorporating PCM, then additional risks associated with the mixing process may arise. Because PCM evaporates quickly when subjected to temperatures required for mixing HMA, the LWA soaked with PCM should be added to the mix as late as possible to reduce evaporation losses. Still, during the mixing process there may be risks caused by the PCM evaporating or leaking into the environment. Further work would be required to develop an environmentally-friendly method for mixing the LWA into the HMA and to determine the impacts of PCM leaking into the environment. Additionally, other methods for incorporating PCM into HMA, such as by using pellets, could be investigated to avoid issues with evaporation.

For a PCM/HMA mixture to become practical, further research must be conducted to determine a method for incorporating the PCM without compromising structural integrity of the mix. If future PCM mixes are weaker than standard HMA, but still sufficient for runway use, then further analysis would be required to accurately determine how PCM impacts the overall life-cycle of the HMA. Assessment of other failure mechanisms, such as failure caused by cyclic loading, should be evaluated to determine if other mechanisms would cause failure before failure from thermal stresses. For areas that are subjected to frequent temperature fluctuations, PCM/HMA mixtures may be more beneficial than in areas that are at relatively constant temperatures.

6 Conclusions and Future Work

The incorporation of PCM-6 into HMA using LWA was shown to be possible, but was not yet feasible for use in airports. The data showed that the incorporation of PCM altered the thermal properties of the samples, but at the cost of a reduction in their strength; many of them were easily damaged during testing and handling. Further research should be conducted to determine the effects of LWA on the mechanical properties of the HMA and to determine the interaction between the PCM and the binder. Other methods of introducing PCMs into HMA that isolate the PCM from the binder should be investigated. Encapsulating the PCM in a pellet may be a viable option, for instance, because it isolates the PCM from the binder while still dispersing it throughout the matrix of the HMA. In addition, the volumetric property testing completed in Phase 3 indicated that PCM-6 does not have an adverse effect on volumetric properties, such as air voids, when compared to a control sample. However, this should be verified using the proper Superpave mix production instead of the hand-compaction methods used in this study. Testing for both volumetric and thermal properties of individual samples would be possible if the GLC was designed for cylindrical samples.

The data showed that PCM reduced the extreme low temperature of a sample, reduced the rate of cooling, and decreased the time for the sample to thaw, but did not prevent free-thaw cycling. Since samples behaved differently when subjected to different rates of cooling/heating, varying cooling/heating cycles and testing different types of PCM could help to better understand how PCMs respond and which PCM might be suited for the given conditions. For instance, one experiment might test a PCM sample with a gradual cooling rate that reaches extreme cold temperatures, while another might explore a quick cooling rate that reaches a less-extreme cold temperature. Potentially, composite samples comprised of multiple types of PCM could be designed in order to contend with different temperature fluctuations. Thus, there is a need for further research on this topic in order to improve the feasibility of incorporating PCM into HMA for use in airport runways.

Appendices

Appendix A: Contact Information

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Appendix B: Description of University

Worcester Polytechnic Institute (WPI) is a privately owned technological institution located in Worcester, Massachusetts. Founded in 1865, WPI was one of first universities in the United States to focus on engineering and technology. Today, WPI offers more than 50 undergraduate and graduate degree programs in areas such as science, engineering, technology, and management, and according to U.S. News & World Report, WPI consistently ranks in the top 25% of universities. WPI is characterized by rigorous 7-week terms in which students take 3-4 classes each of the 4 terms of the academic year. WPI is also unique in terms of its project-based learning in which undergraduates are required to complete a Sufficiency in the Liberal Arts, an Interactive Qualifying Project (IQP), and a Major Qualifying Project (MQP). IQP is described as a "project which relates technology and science to society or human needs" and can optionally be completed during a term abroad. The MQP is similar to a senior capstone design and assesses students' knowledge in their field of study through independent research and design. The MQP also has the option to be completed abroad. The pillars of a WPI education are theory and practice and the university's goal is that "graduates emerge ready to take on critical challenges in science and technology, knowing how their work can impact society and improve quality of life."

Appendix C: Non-University Partners

N/A

Appendix E: Educational Experience

Student Response

1. **Did the FAA Design Competition provide a meaningful learning experience for you? Why or why not?**

   The FAA Design Competition provided our group with a meaningful and hands-on project that allowed us to investigate and attempt to remedy issues with our Nation's infrastructure in a multi-disciplinary team. Through this project, we were able to develop our skills as engineers by immersing ourselves in a project where each person learned something new. In general, we learned about thermodynamics, heat transfer and material science.

2. **What challenges did you and/or your team encounter in undertaking the Competition? How did you overcome them?**

   Because incorporating PCM into HMA has never been attempted, we faced issues at most corners due to a lack of literature. To overcome many of these issues, we either sought council from our advisors or attempted to find our own solutions. For instance, when attempting to find a reasonable mix design, we started with a rough estimate from our advisors then iterated through many failures until we found a workable design. Although some issues were not solved, we did provide additional hypotheses for our failures. We concluded the project with many routes for future work that could potentially make the whole PCM/HMA incorporation more feasible.

3. **Describe the process you or your team used for developing your hypothesis.**

   Initially, we started with an EPA project proposal that focused on using PCM to prevent freeze-thaw cycling in roads. We based that project off the work our advisor had done with using PCM to prevent water from freezing in Portland cement concrete bridge decks. After our EPA project was rejected, we shifted gears to the FAA Design Competition. Although we focused on low-temperature effects in runways, we also investigated how PCMs might help prevent low-temperature cracking, thermal fatigue cracking, and the freezing of water in pavements which can lead to cracking due to frost expansion.

4. **Was participation by industry in the project appropriate, meaningful and useful? Why or why not?**

Industry contacts were useful in determining which failure mechanisms were prevalent in airport runways. Our contact at Logan Airport helped us reach out to a broad range of individuals with a broad range of experience. Answers from these contacts enabled us to narrow the focus of our project to an area which would have the best foreseeable applicability to the current problems seen in the national airport infrastructure.

5. **What did you learn? Did this project help you with skills and knowledge you need to be successful for entry in the workforce or to pursue further study? Why or why not?**

Paul R. Bender:

As a civil engineering major, this project provided me with a wealth of new knowledge. I have focused on transportation engineering within my major, but WPI offers limited coursework in the area of hot mix asphalt when compared to concrete. As such, I gained firsthand experience in designing and testing hot mix asphalt pavements. I also developed many skills and concepts related to thermodynamics and materials science which will be beneficial going forward into the workforce.

Sarah A. Cote:

As a civil engineering major preparing for graduate studies, this project was a great opportunity to gain experience conducting research and carrying out hands-on lab work. This project also expanded my knowledge in areas outside of civil engineering by allowing me to gain insight into material science and thermal properties of materials.

Rachel A. Lewis:

Through the processes of designing and completing this project I have learned the importance of teamwork and time management. As a mechanical engineering major, it was very interesting to work on a project outside of my major. This project allowed me to experience one of the numerous applications of mechanical engineering into another field of engineering, and learn that collaboration between people with different strengths is key.

Bryan J. Manning:

Although I am entering into a purely mechanical career after graduation, this project was useful because it strengthened my skills in collecting data, troubleshooting testing apparatus and analyzing large amounts of data. Although I will probably never mix asphalt in the future, many of the skills I learned/developed are applicable to general engineering.

Faculty Response

1. **Describe the value of the educational experience for your student(s) participating in this Competition submission.**

   The FAA competition helped to provide a larger context for research being carried out by the student team. They were interested in the thermal properties of asphalt and how to prevent thermal deterioration; the FAA contest helped them to focus on the specific area of airport pavements. As such, they learned a great deal about the specific deterioration mechanisms of airport pavements and the needs of airport management. This context provided extra depth to which they would not have otherwise been exposed.

2. **Was the learning experience appropriate to the course level or context in which the competition was undertaken?**

   The students were participating in the FAA design competition as part of their capstone senior design project (called an "MQP" at WPI.) Competing in the FAA competition helped the students to meet several of the learning outcomes of the project-oriented educational system at WPI. Specifically, focusing on the FAA competition added an interdisciplinary component to the research; provided a social context of the technical issues that were addressed; provided an outlet for communicating their results to external groups, developing writing and oral communication skills as appropriate; and linked their research to a specific technical issue.

3. **What challenges did the students face and overcome?**

   The students faced a number of challenges based on the nature of their research. First, the idea of incorporating PCM in asphalt systems has not been tried before, to our knowledge, and as such the literature on this subject is extremely limited. Methodologies had to be developed by the group, and a number of initial attempts at sample production were unsuccessful. Finally, the GLC is a device that is not widely used, and the methodologies for its successful use were not immediately clear. The team overcame these hurdles by looking at generally similar experiments in the literature, and developing their own methodologies by refining the process over time. This showed significant devotion to the project and entailed a great deal of work.

4. **Would you use this Competition as an educational vehicle in the future? Why or why not?**

   If students were interested in airport operations, I would not hesitate to recommend this competition to them. It provided an excellent context for the research that the students were carrying out. It was also useful to help them interact with professional airport personnel.

5. **Are there changes to the Competition that you would suggest for future years?**

   Most of the difficulties that we encountered with the competition were a result of the scientific research that we were carrying out, and not related specifically to the competition. As such, I would not recommend any changes to the competition.

Appendix F: References

[1] Bargar, C., Langford, W., Prescott, J., & Stone, N. (2012, April 25). FODHippo an automated debris collection trend for airport runways.

[2] Chen, W., Xu, Q., Ning, H., Wang, T., & Li, J. (2011). Foreign object debris surveillance network for runway security.*Emerald*, *83*(4).

[3] Bachtel, B. (1998). Foreign object debris and damage prevention. Aero Magazine, 1,1.

[4] Aerosweep. Airfield FOD sweeper - The FOD*BOSS. Retrieved from airport-technology.com. n.d. Web. 10 Oct. 2013.

[5] Sakulich, A.R. & D.P. Bentz. (2012). *Incorporation of phase change materials in cementitious systems via fine lightweight aggregate*. Construction and Building Materials, 35 (2012) 483-490.

[6] Joint Implementation Network. (n.d.). *Energy storage: Phase change materials for thermal energy storage.* Climate Tech Wiki: A Clean Technology Platform. Retrieved from http://climatetechwiki.org/technology/jiqweb-pcm-0.

[7] Mallick, Rajib B. & Tahar El-Korchi. (2009). *Pavement engineering: Principles and practice*. Boca Raton, FL: CRC Press.

[8] Tannoury, G.A. (2007). *Laboratory evaluation of hot mix asphalt mixtures for Nevada's intersections-Phase II.* University of Nevada, Reno- Civil Engineering. ProQuest.

[9] Lin, S. (2011). *Evaluation of HMA fracture mechanics-based thermal cracking model*. Unpublished Master's Thesis, Royal Institute of Technology, Stockholm, Sweden.

[10] Sakulich, A.R. & D.P. Bentz. (2012). *Increasing the service life of bridge decks by incorporating phase-change materials to reduce freeze-thaw cycles*. Journal of Materials in Civil Engineering, 24 (2012) 1034-1042.

[11] Cooley, A.L. Jr., et al. (2009). *Implementation of superpave mix design for airfield pavements*. Burns Cooley Dennis, Inc. Vols 1-3. Airfield Asphalt Pavement Technology Program.

[12] El-Korchi, Tahar. Personal interview. 25 Nov. 2013.

[13] Farnam, Y., Bentz, D., Sakulich, A., Flynn, D., and Weiss, J. *Measuring Freeze and Thaw Damage in Mortars Containing Deicing Salt Using a Low Temperature Longitudinal Guarded Comparative Calorimeter and Acoustic Emission (AE-LGCC)*. Accepted for Publication in Journal of Advances in Civil Engineering Materials (ASTM).