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COMPARISON OF WINTERTIME ASPHALT AND CONCRETE PAVEMENT SURFACE TEMPERATURES ON U.S. ROUTE 40 NEAR HEBER, UTAH

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16. Abstract
Asphalt and concrete pavement surface temperatures were compared at a location on U.S. Route 40 in northern Utah where asphalt and concrete meet end to end at the base of the mountain pass. An environmental sensor station was installed to facilitate monitoring of asphalt and concrete pavement surface temperatures, as well as selected climatic variables, at the site. To compare the surface temperatures of the concrete and asphalt pavements during freezing conditions, multivariate regression analyses were performed on data collected during the three winter seasons from 2009 to 2012. Equations were generated for three response variables, including the asphalt surface temperature, concrete surface temperature, and difference in temperatures between the asphalt and concrete surfaces.

The statistical models developed in the analyses show that the surface temperature of both asphalt and concrete pavement increases with increasing air temperature and decreases with increasing relative humidity and wind speed and that the difference in pavement temperatures decreases with decreasing air temperature. For the studied site, the data indicate that concrete pavement will experience freezing before asphalt pavement for all time periods except late afternoon, when the pavement types are predicted to freeze at the same air temperature. Therefore, for material properties and environmental conditions similar to those evaluated in this study, asphalt would require less winter maintenance, on average, than concrete. Due to the interactions among albedo, specific heat, and thermal conductivity, the actual thermal behavior of a given pavement will depend on the material properties and environmental conditions specific to the site.

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UNIT CONVERSION FACTORS

1 meter (m) = 3.28 feet (ft) or 1.09 yards (yd)

1 square meter (m^2) = 10.764 square feet (ft^2) or 1.195 square yards (yd^2)

1 cubic meter (m^3) = 35.314 cubic feet (ft^3) or 1.307 cubic yards (yd^3)

degrees Celsius (ºC) = 5/9·((degrees Farenheit (ºF)) – 32)

1 Joule (J) = 0.7376 foot-pound-force (ft·lbf)

1 watt (W) = 0.7376 foot-pound-force per second (ft·lbf/s)

LIST OF ACRONYMS

CBR	California bearing ratio
DCP	dynamic cone penetrometer
ESS	environmental sensor station
LSM	least squares mean
UDOT	Utah Department of Transportation

EXECUTIVE SUMMARY

Asphalt and concrete pavement surface temperatures were compared at a location on U.S. Route 40 in northern Utah where asphalt and concrete meet end to end at the base of the mountain pass. An environmental sensor station was installed to facilitate monitoring of asphalt and concrete pavement surface temperatures, as well as selected climatic variables, at the site. Data collected during the three winter seasons from 2009 to 2012 were analyzed in this research. In order to focus on the cold-weather pavement surface temperatures, a winter season was defined as the period from November through April, and the data were divided into time periods that were based on sunrise and sunset times to match the solar cycle. To compare the surface temperatures of the concrete and asphalt pavements during freezing conditions, multivariate regression analyses were performed. Equations were generated for three response variables, including the asphalt surface temperature, concrete surface temperature, and difference in temperatures between the asphalt and concrete surfaces.

The statistical models developed in the analyses show that the surface temperature of both asphalt and concrete pavement increases with increasing air temperature and decreases with increasing relative humidity and wind speed and that the difference in pavement temperatures decreases with decreasing air temperature. For the studied site, the data indicate that concrete pavement will experience freezing before asphalt pavement for all time periods except late afternoon, when the pavement types are predicted to freeze at the same air temperature. Therefore, for material properties and environmental conditions similar to those evaluated in this study, asphalt would require less winter maintenance, on average, than concrete.

Due to the interactions among albedo, specific heat, and thermal conductivity, the actual thermal behavior of a given pavement will depend on the material properties and environmental conditions specific to the site. As shown in previous research, concrete pavement can be warmer than asphalt, which is typical of the statewide pavement network, on average, during late morning, evening, night, and early morning. However, the present research clearly shows that, in mountainous regions of northern Utah more typical of canyon areas, engineers may expect asphalt pavement to be warmer than concrete, or equal in temperature to it, during all time periods at sites that receive direct sun exposure, such as the one studied in this research. At such sites, selection of asphalt pavement may facilitate reduced winter maintenance costs; however, though statistically significant, relatively small differences in temperature between asphalt and concrete pavement surfaces may not warrant differences in actual winter maintenance practices; other factors beyond pavement type, such as rutting and surface texture, may more strongly affect winter maintenance and should also be considered.

1.0 INTRODUCTION

1.1 Problem Statement

The Utah Department of Transportation (UDOT) is responsible for winter maintenance of nearly 18,000 lane miles of state highways and removes approximately 65 million tons of snow and ice from these roads annually at an average cost of $22 million for a typical winter season (*1*). Motivated by the high costs of winter maintenance, UDOT engineers were interested in knowing whether asphalt or concrete pavement surfaces require less winter maintenance to determine if pavement surface type should be considered as a factor in the construction of new roads within the state. The criteria currently used by UDOT engineers to select pavement type include traffic volumes, percent trucks, truck speed, subgrade conditions, available construction materials, maintenance requirements, user costs, and roadway location. Regarding roadway location, asphalt pavement is commonly specified by UDOT engineers for use in canyon areas characterized by steep grades and high elevations (*2*). The selection of asphalt pavements for such situations is based on the perception that asphalt pavements are more easily maintained during winter; however, objective data comparing the pavement surface temperatures of asphalt and concrete were desired.

In an earlier study to determine which pavement type has higher surface temperatures in winter, researchers analyzed air temperature data and pavement surface temperature data from 31 environmental sensor stations (ESSs) (22 on asphalt roads and nine on concrete roads) in Utah to create a statistical model for predicting pavement surface temperature given air temperature, time of day, and pavement type (*3*). The statistical analysis predicting pavement surface temperatures showed that, for near-freezing conditions, concrete pavements tend to have warmer surface temperatures during evening, night, early morning, and late morning, while asphalt pavements tend to have warmer surface temperatures during early afternoon and late afternoon. However, the average of all air temperatures corresponding to the freezing point of asphalt pavements was determined to be exactly the same as the average of all air temperatures corresponding to the freezing point of concrete pavements, showing that, although asphalt is better in the afternoon and concrete is better for other times of the day, neither pavement type was better overall across the state. The possibility remains that one pavement type may require more winter maintenance because of rutting, surface texture, or other factors not considered in the analysis; however, from the standpoint of surface temperatures, the previous study indicated that asphalt and concrete pavement surfaces in Utah were equally likely to collect snow or ice and would therefore be expected to require equal amounts of winter maintenance.

1.2 Research Objective and Scope

To supplement the analyses performed in the previous study, which provided useful information about average pavement temperatures across the state, additional analyses of asphalt and concrete pavement surface temperatures were performed for a particular location in a mountainous region of northern Utah more typical of canyon areas. The site, which was selected by UDOT engineers for further study, is positioned on U.S. Route 40 (US-40) where asphalt and concrete meet end to end at the base of the mountain pass leading from Heber to Park City. Specifically, the site elevation, latitude, and longitude are 5,733 ft, 40.56°, and −111.43°, respectively. The landscape in the immediate vicinity is relatively flat with few trees or shrubs, and mountain ranges lie to the east and west of the site. An ESS was installed to facilitate monitoring of asphalt and concrete pavement surface temperatures, as well as selected climatic variables, at the site. Data were collected over three winter seasons from 2009 to 2012.

1.3 Outline of Report

This report consists of five chapters. Chapter 1 presents the problem statement and the objective and scope of the research. Chapter 2 gives background information on the thermal properties of asphalt and concrete materials. Chapter 3 describes the procedures followed in collecting and analyzing the data. Chapter 4 presents the results of the study. Finally, Chapter 5 provides a summary of the findings together with conclusions and recommendations based on the research.

2.0 BACKGROUND

2.1 Overview

This chapter provides a theoretical basis for why asphalt and concrete pavements can have different surface temperatures, based on differing thermal properties of asphalt and concrete materials and daily temperature trends.

2.2 Thermal Properties of Asphalt and Concrete

Engineers have long known that temperature plays an important role in pavement performance. Evidences of this include rutting of asphalt pavements at high temperatures when appropriate grades of asphalt binder are not selected (*4*), cracking due to thermally induced expansion and contraction (*5, 6*), and curling of concrete slabs due to vertical temperature gradients (*7, 8*). Asphalt and concrete behave differently because they each have very different thermal properties. Three important thermal properties, including albedo, specific heat, and thermal conductivity, are discussed in the following sections.

2.2.1 Albedo

Latin for "whiteness," albedo is a measure of how much incoming solar radiation is reflected back into the atmosphere by a given material. An albedo of 0.0 indicates that zero percent of the incoming radiation is reflected back into the atmosphere, while an albedo of 1.0 indicates that 100 percent of the incoming radiation is reflected back. New asphalt pavements have an albedo of 0.04 to 0.05, while asphalt pavements older than 5 years have an average albedo of about 0.12. Concrete pavements have an albedo of about 0.33, which remains relatively constant for the life of the pavement (*9*). Because asphalt has a lower albedo than concrete, it absorbs more solar energy than concrete, leading to differences in temperature.

2.2.2 Specific Heat

Specific heat is a measure of how much energy is necessary to increase the temperature of a given material by one temperature unit as defined in Equation 2.1:

$$c = \frac{Q}{V \cdot \Delta T} \tag{2.1}$$

where: c = specific heat (J m^{-3} °C^{-1})

Q = energy entering the pavement (J)

V = volume of pavement (m^{3})

ΔT = average increase in temperature (°C)

The specific heat of concrete is around 2.07 J cm^{-3} °C^{-1}, while the value for asphalt is 1.42 J cm^{-3} °C^{-1} (*10*). Thus, roughly 1.45 times as much thermal energy is needed to increase the temperature of a concrete sample than is needed to increase the temperature of an equal volume of asphalt by the same amount.

2.2.3 Thermal Conductivity

Thermal conductivity is a measure of how quickly heat is transferred through the material as defined in Equation 2.2:

$$P = k \frac{\Delta T}{\Delta h} A \tag{2.2}$$

where: P = thermal energy transferred from one layer of pavement to the next (W)

k = thermal conductivity (W m^{-1} °C^{-1})

ΔT = difference in temperature across h (°C)

Δh = thickness of layer (m)

A = area of pavement normal to direction of heat flow (m^{2})

The thermal conductivity values for asphalt and concrete are 0.74 W m^{-1} °C^{-1} and 1.69 W m^{-1} °C^{-1}, respectively (*10*). Thus, concrete has approximately 2.3 times the thermal conductivity of asphalt, meaning that heat from the surface of a concrete pavement propagates into the pavement faster than it does through asphalt.

2.3 Daily Temperature Trends

Through the course of a day, the pavement surface temperature is always changing. After the sun rises, incoming solar radiation heats the earth's atmosphere, causing the air temperature to rise. At the same time, solar radiation reaches the pavement surface, causing the surface temperature to increase. Thus, the two main mechanisms for heat transfer into the pavement are convection from the air (a function of thermal conductivity and specific heat) and radiation from the sun and air (a function of albedo and specific heat). Additionally, heat stored from the previous day (a function of thermal conductivity and specific heat) is conducted upwards from the underlying layers. All of these factors combine to determine the current temperature of the pavement.

As the day progresses, the pavement temperature reaches a maximum value a couple of hours after noon and then decreases quickly until nightfall, at which point it continues slowly decreasing until sunrise. Logically, the temperature difference between asphalt and concrete would not be the same at all times of the day because one pavement might heat up faster, leading to a higher high, and cool down faster, leading to a lower low.

2.4 Summary

Differing thermal properties between asphalt and concrete suggest that, for the same environmental conditions, asphalt and concrete pavements will have different temperature profiles. Asphalt typically has a lower albedo than concrete, indicating that asphalt will absorb a larger percentage of incident solar radiation than concrete. Asphalt has a lower specific heat than concrete, meaning that less thermal energy is needed to increase the temperature of asphalt than concrete. Additionally, asphalt has a lower thermal conductivity than concrete, meaning that heat moves more slowly through asphalt pavement than through concrete pavement, all other factors held constant.

Depending on material properties and environmental conditions, asphalt and concrete pavements exhibit changing temperature profiles coinciding to a large degree with the daily solar cycle. In general, a pavement begins heating up shortly after sunrise. As the day progresses, the pavement temperature reaches a maximum a couple of hours after noon and then decreases quickly until nightfall, at which point it continues slowly decreasing until sunrise.

3.0 PROCEDURES

3.1 Overview

This chapter presents the procedures followed in analyzing pavement surface temperatures, performing structural pavement testing, and imaging the pavement surfaces using infrared thermography.

3.2 Pavement Surface Temperatures

Pavement surface temperatures, as well as selected climatic data, were collected through the ESS installed at the research site, which is depicted in Figure 3.1. The measured data were stored on the MesoWest website (*11*). For analysis in this research, all of the data collected during the three winter seasons from 2009 to 2012 were downloaded and compiled into a single file. After the data were downloaded, the approximately 155,000 entries were filtered and sorted, and the data set was further reduced by deleting data points that were not collected on the hour. Presumably because of occasional sensor malfunction, some of the data were invalid and therefore not useable in the research. Consistent with previous research, erroneous rows of data were identified, and subsequently removed, using the following criteria (*3*):

- Missing air temperature
- Missing road temperature
- Air temperature less than −30°F
- Road temperature less than −30°F
- Air temperature or road temperature that stayed constant or nearly constant for at least 12 hours
- Air temperature or road temperature that differed from the previous and following temperatures by more than four times the difference between the previous two temperatures and the following two temperatures (spikes in the data).

In order to focus on the cold-weather pavement surface temperatures, a winter season was defined as the period from November through April, and data recorded from May through October were subsequently deleted from the record, which resulted in a data set of approximately

Figure 3.1 Environmental sensor station at research site.

6,500 entries. The months selected for analysis were chosen based on the number of hours when either the asphalt or concrete pavement surface temperature was at or below the freezing temperature (32°F). Months that had a significant number of entries at or below the freezing temperature were included. For example, during the 2011-2012 season, November had 425 occurrences of freezing temperatures, while October had only 46; similarly, April had 147 occurrences, while May had no freezing temperatures.

Because the times corresponding to maximum temperatures, minimum temperatures, and inflection points vary by month, the data could not be organized by fixed time intervals. Instead, consistent with previous research (*3*), the data were divided into time periods that were based on sunrise and sunset times to match the solar cycle. Table 3.1 shows how the 24-hour day was divided into six time periods for each of the winter months included in the analysis.

To compare the surface temperatures of the concrete and asphalt pavements during freezing conditions, multivariate regression analyses were performed; only data for which the air temperature was less than or equal to 32°F were used in the analyses. Equations were generated for three response variables, including the asphalt surface temperature, concrete surface temperature, and difference in temperatures between the asphalt and concrete surfaces. The possible predictor variables used in the analyses were time period, air temperature, relative

Table 3.1 Time Periods Based on Month for Winter Season

Month	Late Morning	Early Afternoon	Late Afternoon	Evening	Night	Early Morning
November	9:00-11:00	12:00-15:00	16:00-19:00	20:00-23:00	0:00-3:00	4:00-8:00
December	9:00-12:00	13:00-15:00	16:00-19:00	20:00-23:00	0:00-4:00	5:00-8:00
January	9:00-12:00	13:00-15:00	16:00-19:00	20:00-23:00	0:00-4:00	5:00-8:00
February	9:00-12:00	13:00-16:00	17:00-20:00	21:00-23:00	0:00-4:00	5:00-8:00
March	8:00-11:00	12:00-16:00	17:00-20:00	21:00-0:00	1:00-3:00	4:00-7:00
April	7:00-11:00	12:00-16:00	17:00-21:00	21:00-0:00	1:00-3:00	4:00-6:00

humidity, wind speed, wind gust, and dew point. Correlations among these variables were first investigated, and redundant variables were then excluded from the analyses. The remaining predictor variables for which the level of significance, or *p*-value, was less than or equal to 0.15 were included in each regression model. In the development of each model, rows in the data record with missing entries for any of the remaining predictor variables were excluded from the analysis. Least squares means (LSMs) were computed for each time period for each model as a basis for comparing the average surface temperatures of asphalt and concrete pavements when the air temperature was at or below the freezing point.

3.3 Structural Pavement Properties

To examine the subsurface structure of the pavements, dynamic cone penetrometer (DCP) testing was performed on both the asphalt and concrete pavement sections during November 2008. A hole was first drilled through the bound layers using a hammer drill, as shown in Figure 3.2, and then the DCP testing was performed through the hole as shown in Figure 3.3. California bearing ratio (CBR) values were computed from the DCP penetration rates. In addition, in October 2012, cores were removed from each pavement surface layer and the underlying base material to determine layer thicknesses and types. The coring machine is shown in Figure 3.4.

Figure 3.2 Drilling for dynamic cone penetrometer testing.

Figure 3.3 Performing a dynamic cone penetrometer test.

Figure 3.4 Operating the coring machine.

3.4 Pavement Surface Imaging

Infrared thermography was utilized for supplemental investigation of the asphalt and concrete pavement temperatures. Thermal images were taken during January 2014 to enable a visual comparison of the pavement surface temperatures at the research site.

3.5 Summary

Pavement surface temperatures and selected climatic data collected at the research site during the three winter seasons from 2009 to 2012 were downloaded from the MesoWest website and then filtered and sorted for this research. In order to focus on the cold-weather pavement surface temperatures, a winter season was defined as the period from November through April, and the data were divided into time periods that were based on sunrise and sunset times to match the solar cycle. To compare the surface temperatures of the concrete and asphalt pavements during freezing conditions, multivariate regression analyses were performed. Equations were generated for three response variables, including the asphalt surface temperature, concrete surface temperature, and difference in temperatures between the asphalt and concrete surfaces. The possible predictor variables used in the analyses were time period, air temperature, relative humidity, wind speed, wind gust, and dew point.

To examine the subsurface structure of the pavements, DCP testing was performed on both the asphalt and concrete pavement sections, and CBR values were computed from the DCP penetration rates. In addition, cores were removed from each pavement surface layer and the underlying base material to determine layer thicknesses and types.

Finally, infrared thermography was utilized for supplemental investigation of the asphalt and concrete pavement temperatures. Thermal images were taken to enable a visual comparison of the pavement surface temperatures at the research site.

4.0 RESULTS

4.1 Overview

This chapter presents the results of analyzing pavement surface temperatures, performing structural pavement testing, and imaging the pavement surfaces using infrared thermography.

4.2 Pavement Surface Temperatures

Analyses of the pavement surface temperatures resulted in statistical models for the asphalt surface temperature, concrete surface temperature, and difference in temperatures between the asphalt and concrete surfaces. The preliminary statistical analyses showed that dew point and wind gust were highly correlated with air temperature and wind speed, respectively, so the former variables were subsequently excluded from the regression analyses. The remaining predictor variables, including air temperature, relative humidity, and wind speed, all had *p*-values less than or equal to 0.15 and were therefore included in the models. All rows in the data record for which values of these predictor variables were available were used in the analyses; for each regression model, 6,427 rows were used.

The regression model developed for the asphalt pavement surface temperature is given in Equation 4.1:

$$T_{pavement} = 0.7662(T_{air}) - 0.04224(RH) - 0.05928(W) + P \tag{4.1}$$

where: $T_{pavement}$ = asphalt pavement surface temperature (°F)

T_{air} = air temperature (°F)

RH = relative humidity (%)

W = wind speed (mph)

P = adjustment for time period as determined from Table 4.1

This equation predicts the surface temperature for each time period during the winter season when the air temperature is less than or equal to 32°F.

Table 4.1 Adjustment Values by Time Period for Asphalt Pavement

Time Period	*P*
Late Morning	17.0542
Early Afternoon	21.9291
Late Afternoon	14.0393
Evening	12.9467
Night	12.8351
Early Morning	13.2623

The regression model developed for the concrete pavement surface temperature is given in Equation 4.2:

$$T_{pavement} = 0.8063(T_{air}) - 0.02731(RH) - 0.03684(W) + P \tag{4.2}$$

where: $T_{pavement}$ = concrete pavement surface temperature (°F)

T_{air} = air temperature (°F)

RH = relative humidity (%)

W = wind speed (mph)

P = adjustment for time period as determined from Table 4.1

Like Equation 4.1, Equation 4.2 predicts the surface temperature for each time period during the winter season when the air temperature is less than or equal to 32°F.

Table 4.2 Adjustment Values by Time Period for Concrete Pavement

Time Period	*P*
Late Morning	13.4459
Early Afternoon	19.2926
Late Afternoon	11.7138
Evening	10.1191
Night	9.6878
Early Morning	10.0283

The regression model developed for the difference in temperatures between the asphalt and concrete surfaces is given in Equation 4.3:

$$\Delta T_{pavement} = -0.04007(T_{air}) - 0.01493(RH) - 0.02244(W) + P \quad (4.3)$$

where: $\Delta T_{pavement}$ = difference in asphalt and concrete surface temperatures (°F)

T_{air} = air temperature (°F)

RH = relative humidity (%)

W = wind speed (mph)

P = adjustment for time period as determined from Table 4.3

Like Equations 4.1 and 4.2, Equation 4.3 is applicable only to conditions during the winter season when the air temperature is less than or equal to 32°F. In the development of Equation 4.3, the difference in asphalt and concrete surface temperatures was computed by subtracting the concrete surface temperature from the asphalt surface temperature for each row in the data record; therefore, a positive difference indicates that the asphalt temperature is higher than the concrete temperature.

Equations 4.1 and 4.2 show that the predictor variables have similar effects on the surface temperatures of both the asphalt and concrete pavements. That is, the surface temperature of both pavement types increases with increasing air temperature and decreases with increasing relative humidity and wind speed. Equation 4.3 shows that the difference in pavement temperatures decreases with decreasing air temperature, suggesting that differences in winter maintenance requirements diminish with progressively colder conditions.

Table 4.3 Adjustment Values by Time Period for Difference Analysis

Time Period	*P*
Late Morning	3.6083
Early Afternoon	2.6364
Late Afternoon	2.3255
Evening	2.8276
Night	3.1473
Early Morning	3.2340

Displayed in Table 4.4, the LSMs resulting from the statistical analyses show the average surface temperatures of the asphalt and concrete pavements, as well as the differences in temperature between them, when the air temperature was at or below the freezing point. These values indicate that the surface temperatures of the asphalt pavement were consistently higher than those of the concrete pavement, although the magnitude of the temperature difference varies depending on the time period; for the data evaluated at this site, the difference in temperature between the asphalt and concrete pavement surfaces ranges from 0.1 to 1.4°F, where larger temperature differences occur during late morning, night, and early morning, when the sun is setting or rising, and smaller temperature differences occur during late afternoon, when the sun is at its peak.

Table 4.5 presents the number of observations analyzed for each time period. Because only data records for which the air temperature was at or below the freezing point were analyzed, the number of observations for each time period varied. As a result of the lower frequency of cold temperatures during early afternoon and late afternoon compared to late morning, evening, night, and early morning, fewer observations were available during the early afternoon and late afternoon periods.

To determine which pavement type requires less winter maintenance, Equations 4.1 and 4.2 were used to calculate the air temperatures that correspond to a pavement temperature of 32°F for asphalt and concrete, respectively. The average values of relative humidity and wind speed shown in Table 4.6 were used as inputs in the calculations. The predicted air temperatures

Table 4.4 Least Squares Means by Time Period

Time Period	$T_{pavement}$ (°F)		$\Delta T_{pavement}$ (°F)
	Asphalt	Concrete	
Late Morning	30.4	29.0	1.4
Early Afternoon	35.3	34.9	0.5
Late Afternoon	27.4	27.3	0.1
Evening	26.3	25.7	0.6
Night	26.2	25.3	1.0
Early Morning	26.6	25.6	1.1

Table 4.5 Number of Observations Analyzed by Time Period

Time Period	No. of Observations
Late Morning	1093
Early Afternoon	367
Late Afternoon	739
Evening	1108
Night	1578
Early Morning	1542

Table 4.6 Average Environmental Conditions by Time Period

Time Period	Average Air Temperature (°F)	Average Relative Humidity (%)	Average Wind Speed (mph)
Late Morning	24.0	75.5	5.3
Early Afternoon	26.0	62.8	7.8
Late Afternoon	24.6	70.8	5.8
Evening	22.7	79.1	5.0
Night	20.8	83.1	4.5
Early Morning	20.0	84.6	4.5

and the expected differences in air temperatures are displayed in Table 4.7, which indicates that concrete pavement will experience freezing before asphalt pavement for all time periods except late afternoon, when the pavement types are predicted to freeze at the same air temperature. Therefore, for material properties and environmental conditions similar to those evaluated in this study, asphalt would require less winter maintenance, on average, than concrete.

These statistical findings can be explained with reference to the theoretical considerations described in Chapter 2. Because concrete has a higher albedo than asphalt, concrete pavement absorbs less incident solar radiation than asphalt, which is a difference between the two materials that is especially pronounced at sites that receive direct sun exposure, such as the one studied in this research. Also, concrete has a higher specific heat than asphalt, which means that more thermal energy is needed to increase the temperature of concrete compared to asphalt. Although concrete does have a higher thermal conductivity than asphalt, which means that heat propagates more quickly through concrete pavement than asphalt pavement, the magnitude of the thermal

Table 4.7 Air Temperatures Corresponding to Freezing Pavement Surface Temperatures

Time Period	T_{air} at $T_{pavement}$ = 32°F (°F)		ΔT_{air} (°F)	Requires Less Winter Maintenance
	Asphalt	Concrete		
Late Morning	24.1	25.8	-1.7	Asphalt
Early Afternoon	17.2	18.2	-1.0	Asphalt
Late Afternoon	27.8	27.8	0.0	Neither
Evening	29.6	30.0	-0.4	Asphalt
Night	29.9	30.7	-0.8	Asphalt
Early Morning	29.5	30.3	-0.9	Asphalt
Average	26.4	27.2	-0.8	Asphalt

conductivity in relation to the specific heat was not sufficient in this case to generate higher temperatures compared to asphalt in similar environmental conditions; indeed, while a higher thermal conductivity can facilitate more rapid heating, it equally facilitates more rapid cooling, all other factors held constant.

Due to the interactions among albedo, specific heat, and thermal conductivity, the actual thermal behavior of a given pavement will depend on the material properties and environmental conditions specific to the site. As shown in previous research (*3*), concrete pavement can be warmer than asphalt, which is typical of the statewide pavement network, on average, during late morning, evening, night, and early morning. However, though statistically significant, relatively small differences in temperature between asphalt and concrete pavement surfaces may not warrant differences in actual winter maintenance practices; other factors beyond pavement type, such as rutting and surface texture, may more strongly affect winter maintenance and should also be considered (*3*).

4.3 Structural Pavement Properties

A summary of the structural pavement properties is provided in Table 4.8. After the asphalt and concrete cores were removed, the underlying material was examined. A thin, granular layer of aggregate was found immediately beneath the asphalt layer; it appeared to serve as a leveling course above the underlying subbase layer, which was visually determined to be lean concrete or soil-cement. Due to fragmentation of the subbase material under the asphalt, an

Table 4.8 Average Thicknesses of Pavement and Base Materials

Property	Pavement Type	
	Asphalt	Concrete
Surface Thickness (in.)	8.0	10.0
Base Thickness (in.)	2.0	-
Subbase Thickness (in.)	6.0	6.0
Subgrade CBR (%)	140	115

intact core of that layer could not be retrieved from that location; however, a core was successfully removed from beneath the concrete pavement. Because the subbase layer was impenetrable by the DCP, the hole drilled into the surface layer was necessarily extended through the depth of the subbase to facilitate testing of the underlying material. (Although labeled as subgrade in Table 4.8, the layer beneath the lean concrete or soil-cement subbase may actually have been an imported material rather than the natural soil, given the high CBR values; the DCP testing was limited to depths of 36 and 31 in. for the asphalt and concrete pavements, respectively.)

4.4 Pavement Surface Imaging

Infrared pictures of the site taken during the early morning and late morning periods of a freezing winter day were used for visual comparison of the asphalt and concrete pavement temperatures. Figure 4.1 shows the location of the infrared imaging at the joint between the asphalt (right) and concrete (left). Figures 4.2 to 4.9 show the surface temperatures at half-hour intervals from 6:00 a.m. to 10:00 a.m. and clearly illustrate the development of warmer asphalt surface temperatures as the morning progresses.

Figure 4.1 Location of infrared imaging.

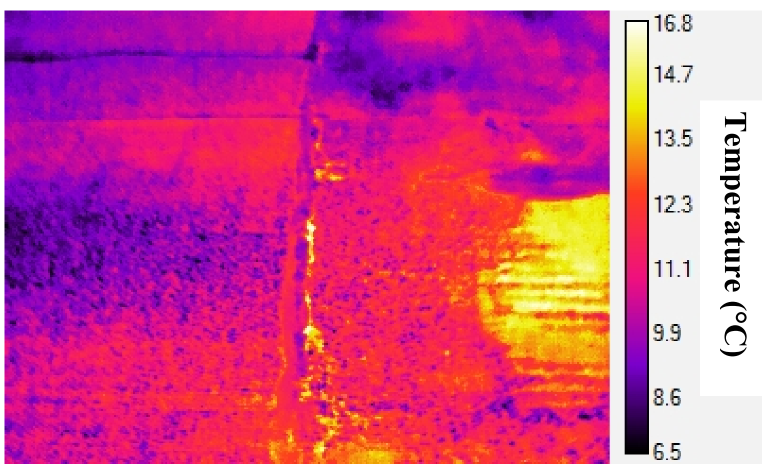

Figure 4.2 Asphalt and concrete pavement surface temperatures at 6:30 a.m.

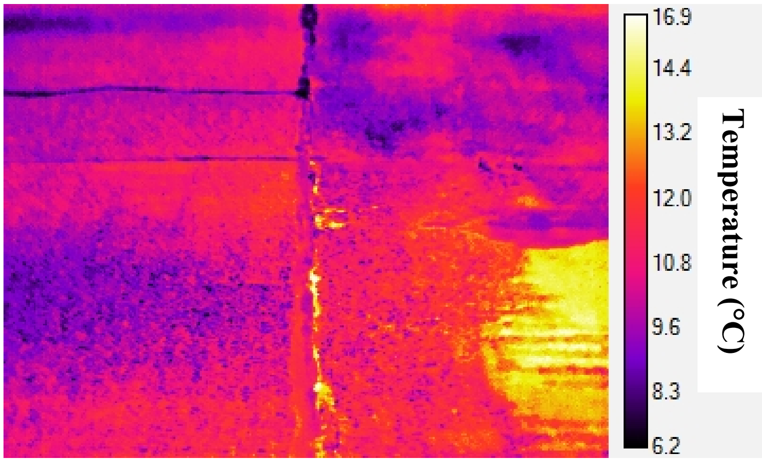

Figure 4.3 Asphalt and concrete pavement surface temperatures at 7:00 a.m.

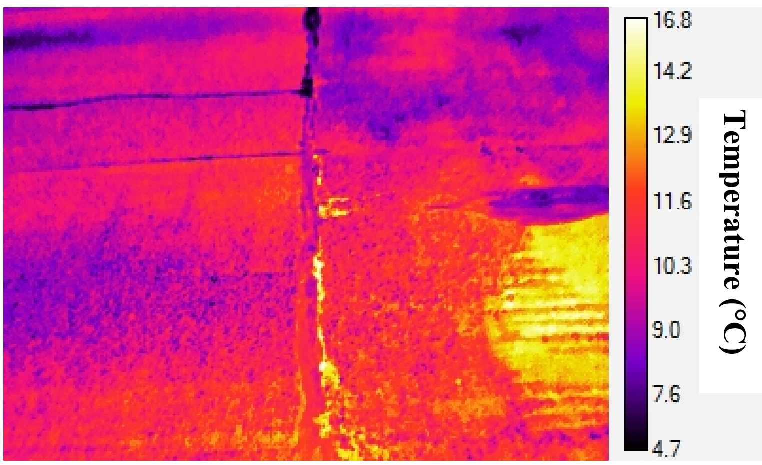

Figure 4.4 Asphalt and concrete pavement surface temperatures at 7:30 a.m.

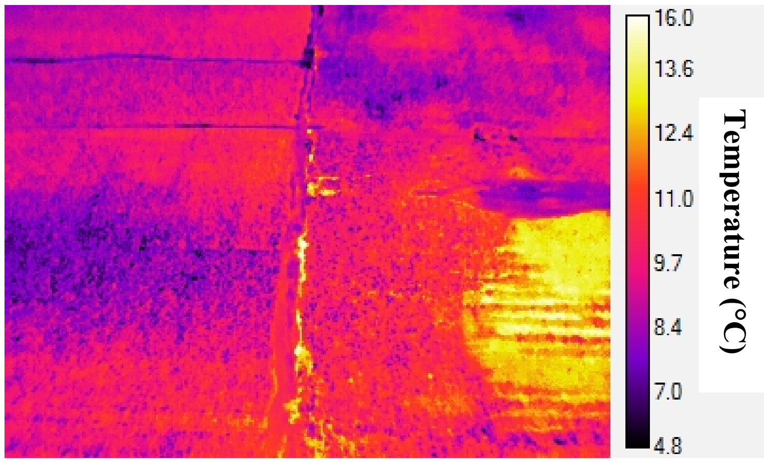

Figure 4.5 Asphalt and concrete pavement surface temperatures at 8:00 a.m.

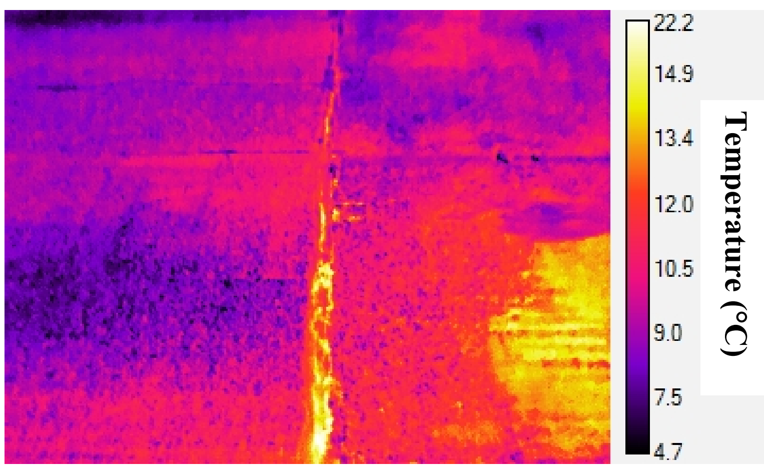

Figure 4.6 Asphalt and concrete pavement surface temperatures at 8:30 a.m.

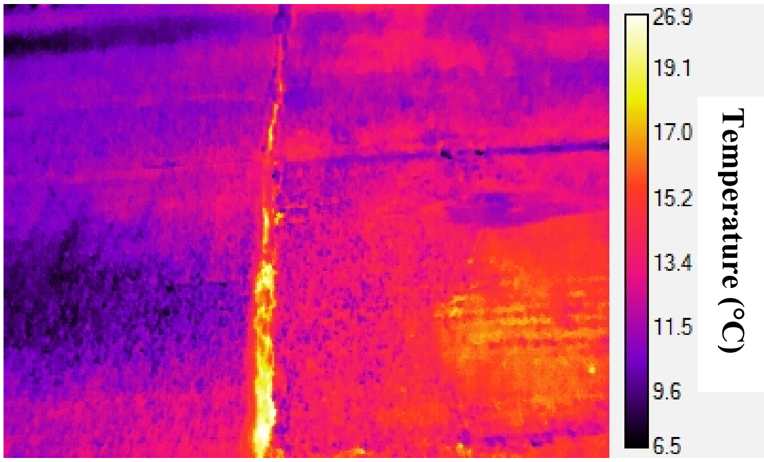

Figure 4.7 Asphalt and concrete pavement surface temperatures at 9:00 a.m.

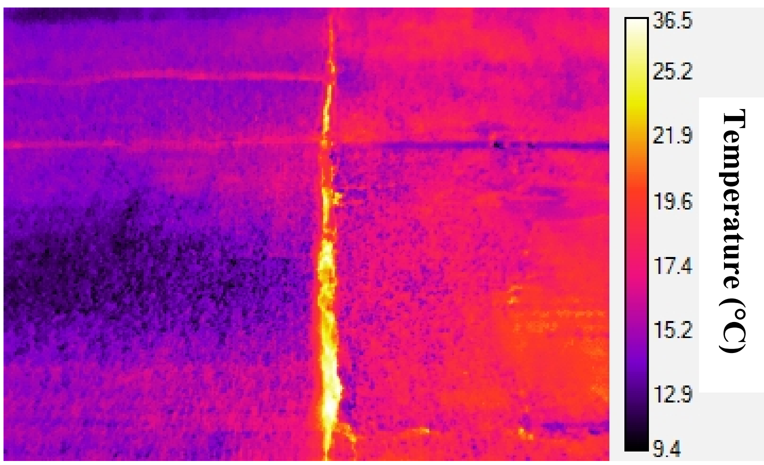

Figure 4.8 Asphalt and concrete pavement surface temperatures at 9:30 a.m.

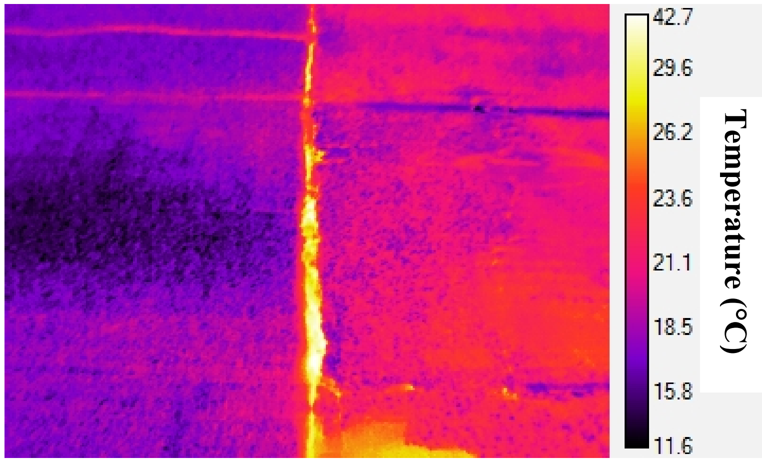

Figure 4.9 Asphalt and concrete pavement surface temperatures at 10:00 a.m.

4.5 Summary

Analyses of the pavement surface temperatures resulted in statistical models for the asphalt surface temperature, concrete surface temperature, and difference in temperatures between the asphalt and concrete surfaces. The three equations developed in the analyses are applicable only to conditions during the winter season when the air temperature is less than or equal to 32°F at the research site. The first two equations show that the surface temperature of both pavement types increases with increasing air temperature and decreases with increasing relative humidity and wind speed. The third equation shows that the difference in pavement temperatures decreases with decreasing air temperature, suggesting that differences in winter maintenance requirements diminish with progressively colder conditions. To determine which pavement type requires less winter maintenance, the air temperatures that correspond to a pavement temperature of 32°F were calculated for asphalt and concrete. For the studied site, the data indicate that concrete pavement will experience freezing before asphalt pavement for all time periods except late afternoon, when the pavement types are predicted to freeze at the same air temperature. Therefore, for material properties and environmental conditions similar to those evaluated in this study, asphalt would require less winter maintenance, on average, than concrete.

For reference, the asphalt and concrete pavement surface thicknesses at the studied site were 8.0 and 10.0 in., respectively, and both were supported by a lean concrete or soil-cement subbase over a subgrade with high CBR values. Infrared pictures of the site taken during the early morning and late morning periods of a freezing winter day were used for visual comparison of the asphalt and concrete pavement temperatures and clearly illustrate the development of warmer asphalt surface temperatures as the morning progresses. These findings can be explained with reference to theoretical considerations of albedo, specific heat, and thermal conductivity.

5.0 CONCLUSION

5.1 Summary

To supplement the analyses performed in a previous study, which provided useful information about average pavement temperatures across the state, additional analyses of asphalt and concrete pavement surface temperatures were performed for a particular location on US-40 in northern Utah where asphalt and concrete meet end to end at the base of the mountain pass leading from Heber to Park City. An ESS was installed to facilitate monitoring of asphalt and concrete pavement surface temperatures, as well as selected climatic variables, at the site. Data collected during the three winter seasons from 2009 to 2012 were downloaded from the MesoWest website and then filtered and sorted for this research. In order to focus on the cold-weather pavement surface temperatures, a winter season was defined as the period from November through April, and the data were divided into time periods that were based on sunrise and sunset times to match the solar cycle. To compare the surface temperatures of the concrete and asphalt pavements during freezing conditions, multivariate regression analyses were performed. Equations were generated for three response variables, including the asphalt surface temperature, concrete surface temperature, and difference in temperatures between the asphalt and concrete surfaces. The possible predictor variables used in the analyses were time period, air temperature, relative humidity, wind speed, wind gust, and dew point. DCP testing, coring, and infrared thermography were also performed on the asphalt and concrete pavements at the research site.

5.2 Findings

The statistical models developed in the analyses show that the surface temperature of both asphalt and concrete pavement increases with increasing air temperature and decreases with increasing relative humidity and wind speed. They also show that the difference in pavement temperatures decreases with decreasing air temperature, suggesting that differences in winter maintenance requirements diminish with progressively colder conditions. To determine which pavement type requires less winter maintenance, the air temperatures that correspond to a pavement temperature of 32°F were calculated for asphalt and concrete. For the studied site, the data indicate that concrete pavement will experience freezing before asphalt pavement for all time periods except late afternoon, when the pavement types are predicted to freeze at the same air temperature. Therefore, for material properties and environmental conditions similar to those evaluated in this study, asphalt would require less winter maintenance, on average, than concrete.

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5.3 Recommendations

Due to the interactions among albedo, specific heat, and thermal conductivity, the actual thermal behavior of a given pavement will depend on the material properties and environmental conditions specific to the site. As shown in previous research, concrete pavement can be warmer than asphalt, which is typical of the statewide pavement network, on average, during late morning, evening, night, and early morning. However, the present research clearly shows that, in mountainous regions of northern Utah more typical of canyon areas, engineers may expect asphalt pavement to be warmer than concrete, or equal in temperature to it, during all time periods at sites that receive direct sun exposure, such as the one studied in this research. At such sites, selection of asphalt pavement may facilitate reduced winter maintenance costs; however, though statistically significant, relatively small differences in temperature between asphalt and concrete pavement surfaces may not warrant differences in actual winter maintenance practices; other factors beyond pavement type, such as rutting and surface texture, may more strongly affect winter maintenance and should also be considered.

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