Permeable Pavement for Road Salt Reduction

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16. Abstract (Limit: 250 words)

Road salt and particularly sodium chloride is used for de-icing roadways during winter months in cold climates but can have a negative impact on the environment. This report describes research that investigated the use of permeable pavements that are not treated with road salt as an alternative to impermeable pavement surfaces that are treated with road salt. Various methods were used to quantify the snow and ice cover on impermeable and permeable pavements under near-identical but various environmental conditions. It must be noted, however, that impermeable pavements including the ones in this study are typically managed with road salt while permeable pavements are not. However, the following conclusions can be drawn from previous research and data collected during this project: 1) permeable pavements and the porous subbase beneath them function as thermal insulators, preventing heat transfer from the surface to below and vice versa; 2) permeable pavements that are clogged due to sediment accumulation or collapsed pores provide no benefit compared to impermeable pavement; 3) more sites with impermeable pavement had more friction than sites with permeable pavement; 4) more sites with impermeable pavement had less snow and/or ice cover than sites with permeable pavements; and 5) more sites with impermeable pavement had pooled water than sites with permeable pavements. This demonstrates the primary winter benefit of permeable pavements: meltwater can infiltrate through permeable pavements and prevent refreezing. Refreezing of meltwater on impermeable pavements creates dangerously slippery conditions which can be avoided with functional permeable pavements.

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PERMEABLE PAVEMENT FOR ROAD SALT REDUCTION

FINAL REPORT

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EXECUTIVE SUMMARY

Road salt and particularly sodium chloride is used for de-icing roadways during winter months in cold climates but can have a negative impact on the environment. Chloride in our streams, lakes and groundwater has caused lake and stream impairments in many locations throughout the Twin Cities metropolitan area of Minnesota, and investigations will likely result in similar notifications in all Minnesota cities. The primary cause is salt from roadways that is added to provide safe roads for drivers. To save our lakes and rivers, and to have drinking water that can be consumed, we need to reduce or eliminate the salt that we place on our roads. There are indications that permeable pavement can accomplish the reduction or elimination of salt addition while still providing a relatively safe driving surface. In addition, permeable pavements have the ability to infiltrate meltwater compared to impermeable pavements in which meltwater likely refreezes on the surface when air temperature decreases below freezing.

This report describes research that investigated the use of permeable pavements that are not treated with road salt as an alternative to impermeable pavement surfaces that are treated with road salt. The primary research question is this: Do unsalted permeable pavements have more, the same, or less snow and ice than salted impermeable pavements during winter conditions in cold climates? To answer this question, the research project included a review of the existing literature to identify methods in which snow and ice could be quantifiably and repeatably measured on various pavement surfaces. Then, various methods were used to quantify the snow and ice cover on permeable pavements under various conditions and compare the results to snow and ice cover on impermeable pavement surfaces under near-identical environmental conditions. The methods employed included photographic, temperature (air, surface, and in-pavement), and surface friction measurements.

Research data prior to the current project by Wenck (2014) were evaluated and the following conclusions about permeable and impermeable pavements during mid-winter (e.g., January or February) were observed:

- When the pavement surface temperature is warmer than the subbase temperature (e.g., at 18"), the permeable pavement surface is warmer than the impermeable pavement surface. Conversely, when the pavement surface temperature is colder than the subbase temperature (e.g., at 18"), the permeable pavement surface is colder than the impermeable pavement surface.
- The difference in temperature between the surface and approximately 18" below the surface is greater in the permeable pavement compared to the impermeable pavement, regardless of the pavement surface temperature. In addition, the subbase temperature at 18" below the surface is warmer in the permeable pavement compared to the impermeable pavement. This suggests that permeable pavements and the porous subbase beneath them function as thermal insulators, preventing heat transfer from the surface to below and vice versa.

During the current research project, photographic methods determined that the presence of snow could be easily identified, and time lapse comparisons could demonstrate when impermeable pavements had

snow and permeable pavements did not, or vice versa. Unfortunately, photographic methods were not able to distinguish between ice and water on the pavement, and thus were not adequate for determining if the pavement surface was slippery.

The air temperature, pavement surface temperature, and in-pavement temperature profiles were measured for a number of sites for the purpose of predicting surface conditions without other technology. As identified in the literature, a difference between the air temperature, surface temperature, and in-pavement temperature can be used to predict the pavement surface conditions. We found that a comparison of temperature alone was not sufficient or consistent to predict whether the surface was covered or what covered the pavement (e.g., snow, ice, water, etc.).

Finally, surface friction was measured on various pavement types for various conditions and determined to be the most reliable method for comparing the surface conditions. While other methods could determine when snow and/or ice were present on the surface, only surface friction could quantifiably determine if the surface was slippery and unsafe for travel. In several cases (see Chapter 3), snow and/or ice were present on the pavement surface, but the friction was such that pedestrian traffic was recommended as cautious or safe.

A survey was conducted in January 2018 of local municipalities and at least 44 locations around the Twin Cities metro area were identified as possible permeable pavement measurement sites, including locations of permeable asphalt, permeable concrete, and permeable block pavers. These sites were evaluated and 22 were found to be suitable for data collection during winter 2019-2020 (Year 4). Of the 22 sites in which friction and surface temperature were measured, 13 sites (59%) had more friction on the impermeable pavement compared to the permeable pavement; 7 sites (32%) had similar friction (typically bare pavement); and 2 sites (9%) had less friction on the impermeable pavement compared to the permeable. This suggests that under typical mid-late winter conditions, more sites of impermeable pavement had more friction than permeable pavements.

Of the 22 sites, 12 sites (55%) had warmer surface temperatures on the impermeable pavement compared to the permeable pavement; 4 sites (18%) had similar temperatures ($\Delta T < -0.5°C$); and 6 sites (27%) had cooler surface temperatures on the impermeable pavement compared to the permeable pavement. Similar to surface friction, more sites of impermeable pavement had warmer surface temperatures compared to permeable pavements. In contrast to the friction data, however, more permeable pavement sites had warmer temperatures (n = 6) compared to the permeable pavement sites with more friction (n = 2). All six of these measurements occurred when the pavement surface temperature was above but near freezing temperature. If precipitation or snowmelt occurred at the time of measurement, the warmer permeable pavement could infiltrate the precipitation before the air (and pavement) temperature decreased enough to freeze the precipitation to the surface. If the same precipitation fell or snowmelt ran onto an impermeable pavement, it's possible that it would not runoff and thus be susceptible to freezing when the ambient air (and surface temperature) decreased below freezing. Thus, permeable pavements may have more potential to melt snow and ice than unsalted impermeable pavements.

Of the 22 sites, 13 sites (59%) had less snow and/or ice cover on the impermeable pavement compared to the permeable pavement; 9 sites (41%) had similar snow/ice cover on both pavements; and none of the sites had more snow/ice on the permeable pavement compared to the impermeable pavement. Visual observations mimicked the friction measurements described above in that the same number of sites (n = 13) had more friction and less snow on the impermeable compared to the permeable. The sites that had more friction, however, did not correspond exactly with the sites that had less snow.

Of the 22 sites, 8 sites (36%) had more pooled water on the impermeable pavement compared to the permeable pavement; 14 sites (64%) had similar or no pooled water on both pavements; and none of the sites had less pooled water on the impermeable pavement compared to the permeable pavement. This demonstrated the primary winter benefit of permeable pavements: Meltwater can infiltrate through permeable pavements and prevent refreezing. Refreezing of meltwater on impermeable pavements can create dangerously slippery conditions, but can be avoided with functional permeable pavements.

It must be noted, however, that impermeable pavements are typically managed with road salt and permeable pavements are not. Therefore, this evaluation is likely comparing salted impermeable pavements to unsalted permeable pavements. Regardless, the following conclusions can be drawn from previous research and data collected during this project:

- Permeable pavements provide warm weather hydrologic and water quality benefits.
- Permeable pavements that are clogged due to sediment accumulation or collapsed pores provide no benefit.
- Snow and ice cover are sensitive to the weather conditions (temperature, sunlight, etc.), surface albedo, snow removal, and traffic.
- Meltwater on impermeable pavement can refreeze into ice, whereas permeable pavements infiltrate meltwater.
- Permeable pavements insulate and "spread the heat" less than impermeable pavements.
  - Patches of bare pavement on impermeable asphalt can spread quickly as snow/ice melts (but can refreeze).
  - Block pavers can be slow to melt snow and ice, but may benefit from flexible plow blade edges or brushes.

CHAPTER 1: LITERATURE REVIEW

1.1 INTRODUCTION

Road salt and particularly sodium chloride is used for de-icing roadways during winter months in cold climates but can have a negative impact on the environment. Chloride in our streams, lakes and groundwater has caused lake and stream impairments in many locations throughout the Twin Cities metropolitan area of Minnesota, and investigations will likely result in similar notifications in all Minnesota cities. The primary cause is salt from roadways that is added to provide safe roads for drivers. To save our lakes and rivers, and to have drinking water that can be consumed, we need to reduce or eliminate the salt that we place on our roads. There are indications that permeable pavement can accomplish the reduction or elimination of salt addition while still providing a relatively safe driving surface. In addition, permeable pavements have the ability to infiltrate meltwater compared to impermeable pavements in which meltwater likely refreezes on the surface when air temperature decreases below freezing. Another benefit to Minnesota will be the safety increment that permeable pavement has over unsalted impermeable pavement. Research has commenced that will document the winter performance of permeable pavement as a safe driving surface without the addition of salt, and result in:

- *Reduced environmental impacts* – Every permeable pavement road replacement that is installed as a result of the project will help reduce the chloride load to our receiving water bodies.
- *Improved road safety* – A permeable pavement road without salt may be safer than a traditional pavement road without salt in cold Minnesota conditions.
- *Reduced risk* – If permeable pavement is successful at reducing required salt additions, there will be a reduced risk to aquatic life and to traffic on the road during winter months.

Research has also commenced to investigate the reduction in road salt application during winter months that can be attained with implementation of permeable pavements, while still providing for acceptable road safety. Several studies have used various methods to evaluate pavement surface conditions, including dry, wet, snowy, and icy. We will take lessons learned from these studies to compare pavement surface conditions on permeable and impermeable pavements in Minnesota winters. Some previous research in Robbinsdale, MN, has suggested that road salt application can be substantially reduced, even eliminated, with permeable pavement systems because less snow and ice were found to be present when compared to impermeable pavements. Current research will expand on this foundation to quantify the differences and investigate the fundamental mechanisms behind these differences.

1.2 WINTER ROAD SURFACE CONDITION EVALUATION

In general, there are four methods in the scientific literature for evaluating winter road surface conditions: acoustic, imagery, albedo (light reflection), and friction. By far the most widely studied method is imagery analysis, though some studies using sound are equally successful. Studies using these methods are described in the following sections.

1.3 ACOUSTIC DETECTION

Within a discussion of Artificial Neural Network (ANN) technologies, McFall (2000) showed that simple analysis of sound data could be used to distinguish dry, wet, snow, and ice-covered pavements. He used a Sony portable DAT recorder with an AKG C414 B-ULS microphone (max frequency = 20 kHz). The results from his analysis are shown in Figure 1.1.
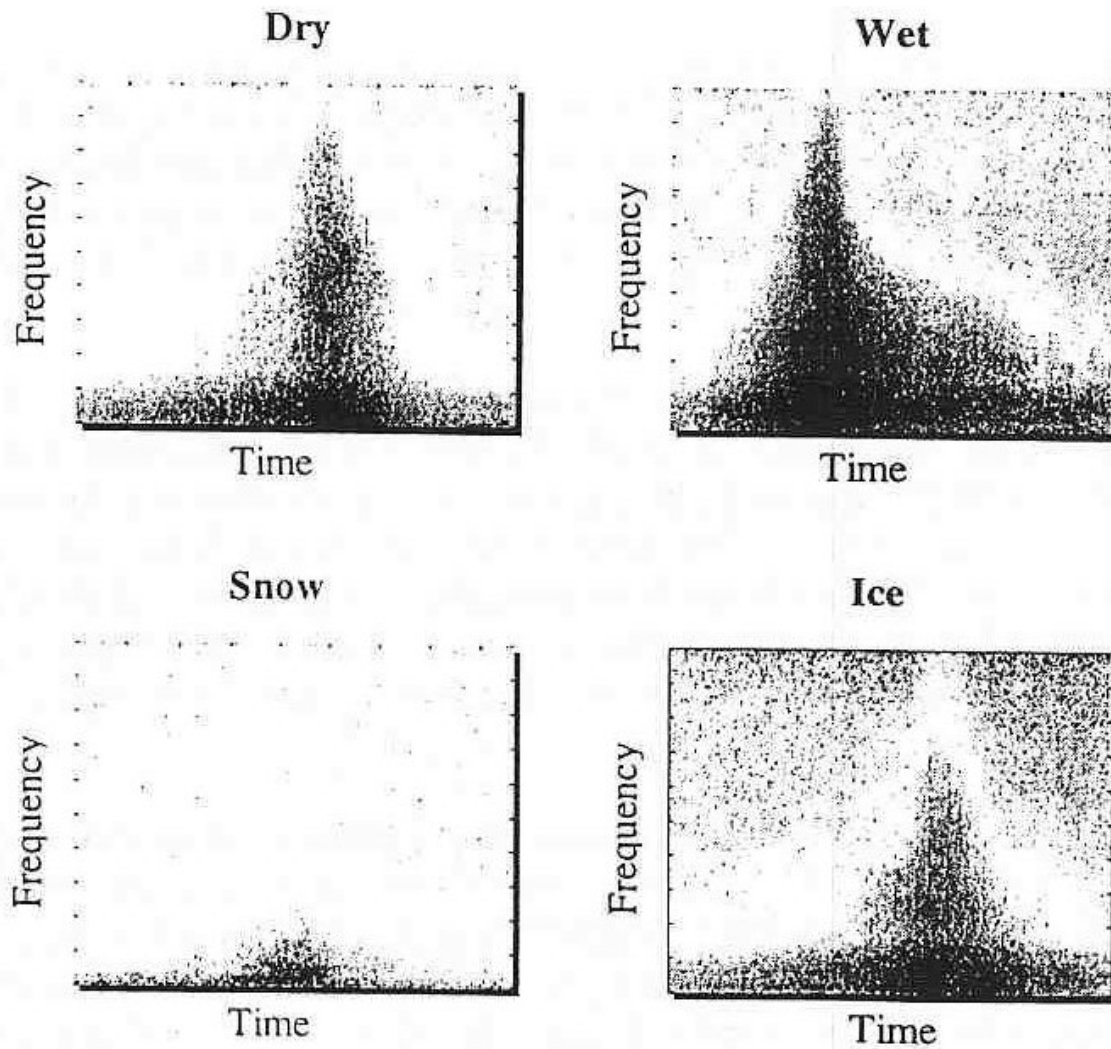
Figure 1.1 Spectrograms of typical signals for four road classes. (from McFall 2000).

McFall and Niittula (2002) expanded on previous work by McFall (2000) by testing a system that combined visual images and sound to determine road surface conditions of dry, icy, snowy, or wet. They used an analog high-resolution grayscale Sony SPT-M124 video camera and a Matrox Meteor II frame grabber card to capture image data. They used a Larson/Davis microphone, designed specifically for outdoor use, connected to a Digital Audio Labs Deluxe sound card to capture acoustic data. No external illumination was added, so only images captured during daylight hours were used. After training the ANN and using a confidence routine to remove input data that is unlikely to classify correctly (poor image or sound quality), the authors achieved over 90% correct classification for snowy, icy, and wet days. Dry conditions, however, were only correctly classified for 50% or less of the dry days.

Kongrattanaprasert et al. (2010) distinguished dry, wet, slushy, and snowy road conditions using acoustic signals and artificial neural network. In addition to peak frequency, the authors analyzed the

cumulative distribution of frequencies and autocorrelation of frequencies, as shown in Figure 1.2. Classification of road surface conditions were verified visually by the authors, and their process recognized snowy conditions with 98% accuracy, 68% accurate for slushy conditions, 94% accuracy for wet conditions, and 91% accuracy for dry conditions. Overall accuracy was 90%.
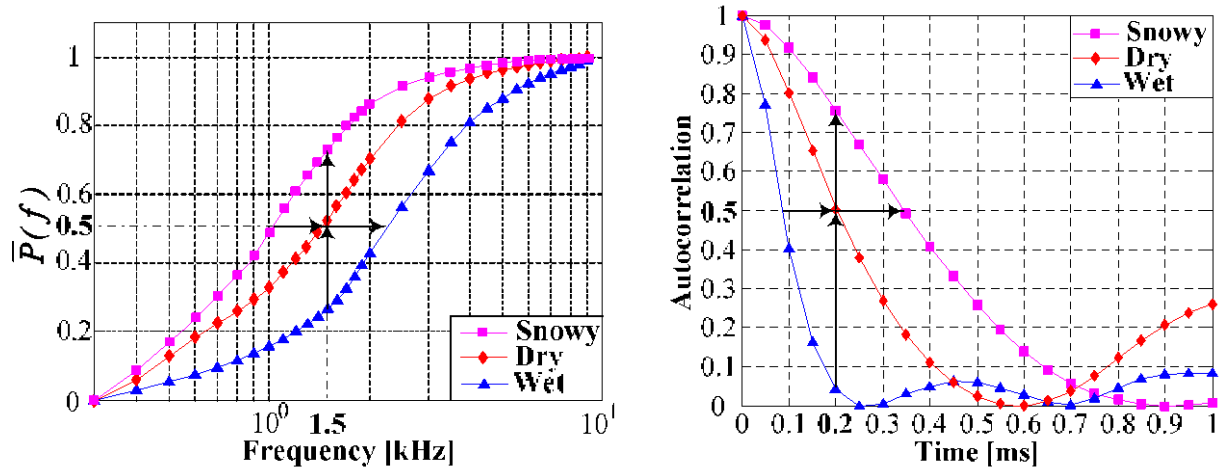
Figure 1.2 Typical cumulative curves of the power spectrum of tire noises for five minutes (left) and Autocorrelation curves for five minutes (right). (from Kongrattanaprasert et al., 2010)

Alonso et al. (2014) evaluated acoustic measurements from a vehicle-mounted microphone and successfully distinguished dry from wet pavement.

1.4 PHOTO/VIDEO ANALYSIS

Luengo (2013) provides a summary of research on automatic road condition determination and provides recommendations to Trafikverket on the use of Sweden's extensive road camera system for road condition detection. Many of the references discussed by Luengo (2013) are also provided here, with more detail.

Kuehnle and Burghout (1998) found limited success (40 - 50% accuracy) distinguishing dry, wet, snowy, icy, and snowy with tracks road surface conditions when analyzing video imagery for various photographic features: red level, blue level, green level, gray level, standard deviation of each color, and ratios thereof. They analyzed a total of 69 color images from a handheld Hi-8 camcorder and listed several factors that reduced the accuracy, including: limited data, assigning a single condition (e.g., wet, dry, snow) to a road surface, and limited algorithm development and training, among others.

Yamada et al. (2001) distinguished dry, wet, slushy, icy, and snowy pavement conditions from analysis of image data. Wet conditions were distinguished using comparison of vertical and horizontal polarization. Snowy conditions were distinguished by analyzing "coarseness of texture" as the standard deviation of the grey level, and directionality of texture as the co-occurrence matrix (i.e., comparing neighboring

pixels). Yamada et al. (2001) also considered air temperature in the analysis of data. The authors used 337 feature data points for training, and analyzed over 9000 images for verification, achieving over 80% accuracy as shown in Table 1.1.

Table 1.1 Results of Discriminant Analysis (top) and Verification Results (bottom). (from Yamada et al., 2001)

RESULTS OF DISCRIMINANT ANALYSIS

	Discrimination results			Items of discrimination				
Road Condition	Number of samples	Number of correct discrimination	Accuracy rate [%]	Snowy	Icy	Slushy	Wet	Dry
Snowy	44	44	100	44	0	0	0	0
Icy	85	85	100	0	85	0	0	0
Slushy	75	65	86.7	0	0	65	10	0
Wet	82	77	93.9	0	0	5	77	0
Dry	51	51	100	0	0	0	0	51

VERIFICATION RESULTS

	Discrimination results			Items of discrimination				
Road Condition	Number of samples	Number of correct discrimination	Accuracy rate [%]	Snowy	Icy	Slushy	Wet	Dry
Snowy	1037	1023	98.6	1023	14	0	0	0
Icy	1489	1248	83.8	176	1248	67	0	0
Slushy	1122	958	85.4	0	23	958	141	0
Wet	4482	4325	96.5	0	0	19	4325	138
Dry	1358	1317	97.0	0	0	0	41	1317

Yamada et al. (2003) distinguished wet and dry pavement by using two TV cameras with polarizing filters that are attached to the rearview mirror inside a vehicle to record images of the roadway. By comparing the ratio of the filtered images, wet and dry conditions were distinguished as shown in Figure 1.3.

(a) Vertical polarization

(b) Horizontal polarization

Wet

Dry

Ratio

(c) Polarization ratio
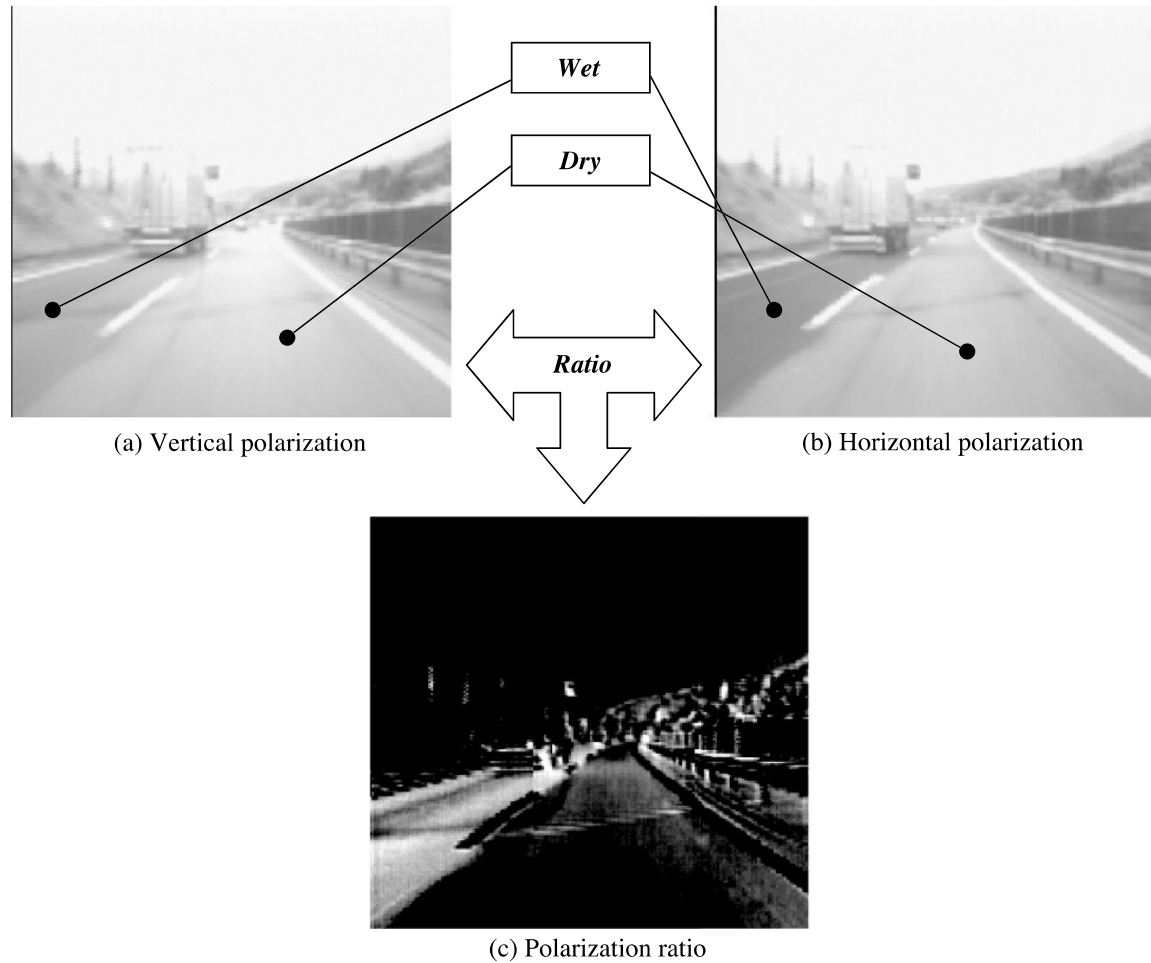
Figure 1.3 Detection of wet condition by the property of polarization. (from Yamada et al., 2003)

Kutila et al. (2008) tested dual cameras with vertical and horizontal polarization and surface graininess to distinguish snow, ice, and dry asphalt. They used a Xenics XEVA-USB 320 camera with a 900–1700 nm range and a Peltier-cooled InGaAs array detector with 320 x 256 pixels. An example of images captured with this setup and polarizing filters is shown in Figure 1.4.

Figure 1.4 The captured test samples. Left-hand image is captured with a horizontal polarization filter and the right–side image with a vertically polarized component. (from Kutila et al. 2008)

When comparing the difference between the vertical and horizontal polarized images, Kutila et al. (2008) distinguished snow, ice, and dry road surface conditions as shown in Figure 1.5. When comparing graininess, Kutila et al. (2008) showed that ice produces less graininess than dry asphalt (i.e., ice is smoother than bare pavement), as shown in Figure 1.6. Though successful, the authors state that the XENICS camera system is expensive and proposed developing a similar system using "low-price" CMOS cameras, and estimated the prototype cost would be approximately $4000 (in 2008).
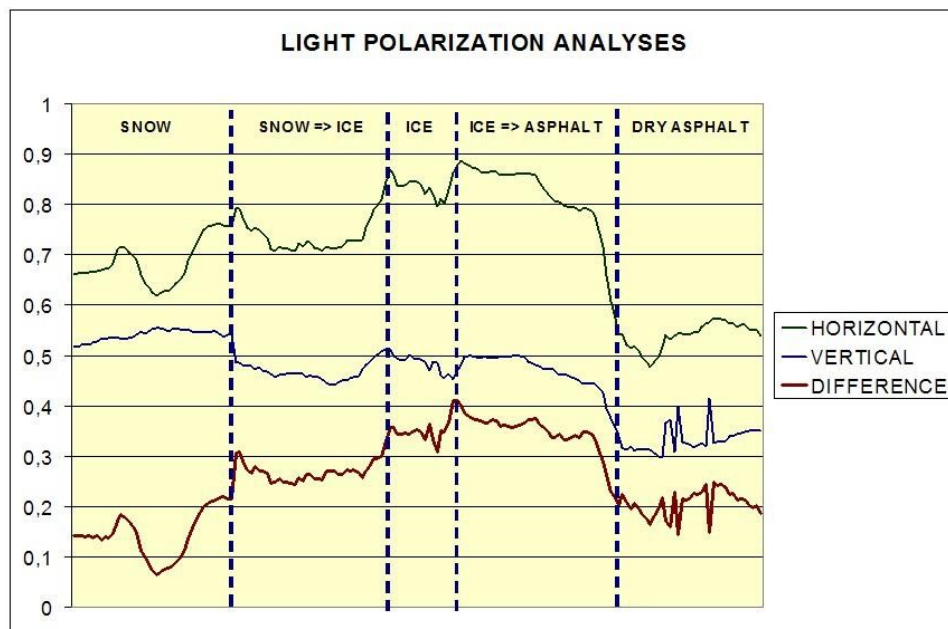
Figure 1.5 Light polarization analysis in an asphalt road. Vertical axis is the intensity in the region-of-interest scaled to range [0... 1]. The average differences between the tested road conditions are: SNOW = 0.14; ICE = 0.35; ASPHALT = 0.21. (from Kutila et al. 2008)
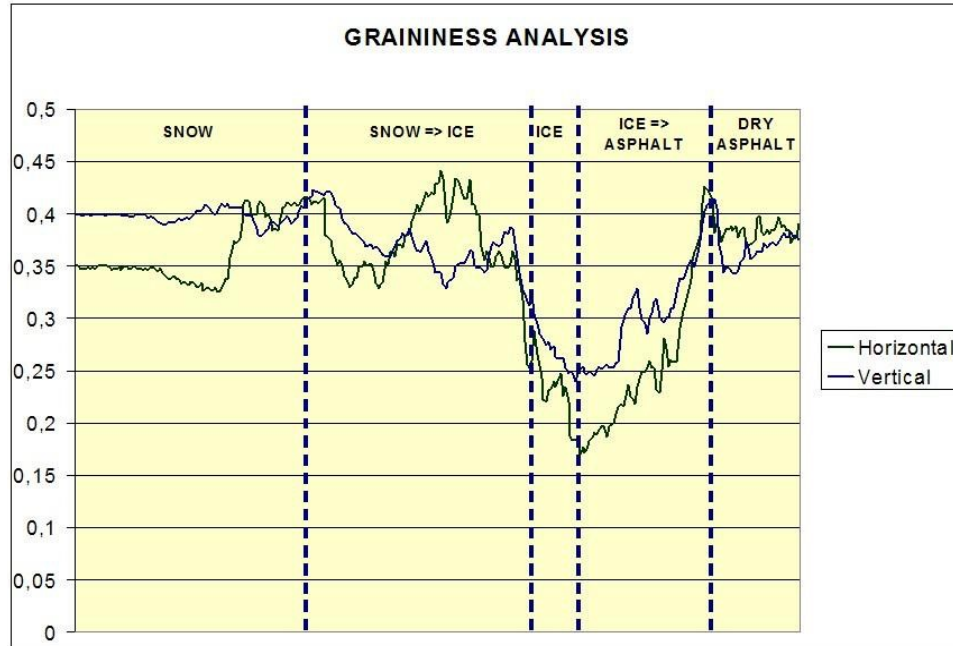
Figure 1.6 Graininess measures against different road surfaces. The horizontal and vertical diagrams refer to the direction of the used polarization filter. The average graininess values for different conditions are: SNOW = 0.378; ICE = 0.254; ASPHALT = 0.376. (from Kutila et al. 2008)

Kutila et al. (2009) also tested a dual camera system with vertical and horizontal polarization and surface graininess to distinguish icy, wet, snowy or dry asphalt. They used CMOS type cameras (containing the Micron MT9V032 imager element), which acquire monochrome images with 640 x 480 pixels. The authors then tested the system on cold winter roads in Sweden and sunny summer dry roads in Germany. In winter, the method distinguished between snowy, icy, and wet road surface conditions as shown in Figure 1.7.
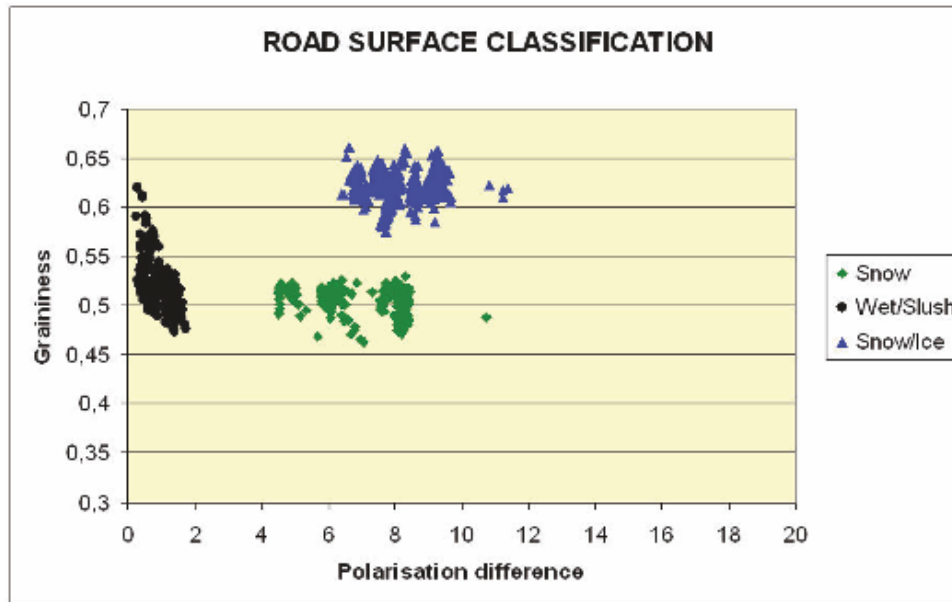
Figure 1.7 Detection of snowy, wet, or icy road surface conditions in winter conditions using dual polarized cameras and graininess measurements. (from Kutila et al. 2009)

Kutila et al. (2009) report, however, that distinguishing between icy/snowy and dry pavement or between wet and dry pavement were not as successful. Both the graininess and polarization results overlap, presenting a challenge when attempting to determine different road surface conditions, as shown in Figure 1.8. The system cost approximately $6400 (in 2009).
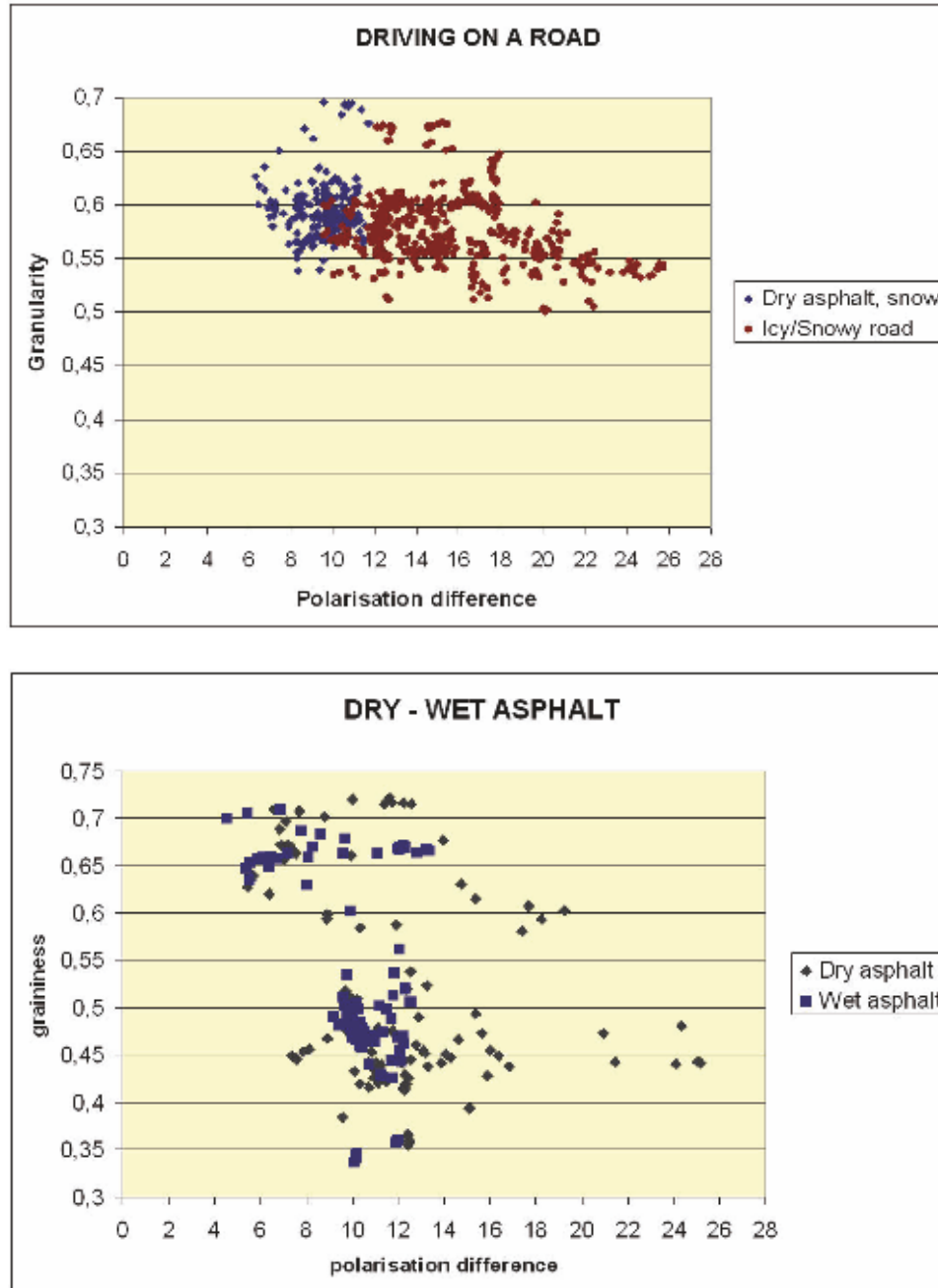
Figure 1.8 Detection of snowy, wet, icy, and dry road surface conditions in winter conditions (top) and summer conditions (bottom). (from Kutila et al. 2009)

Jokela et al. (2009) tested a dual-camera system with a vertical polarizing filter on one camera and a horizontal polarizing filter on the other. The cameras took simultaneous pictures of the same portion of the roadway, and the difference in reflection and refraction captured by the images is used to determine the road surface conditions. In addition, the authors also analyzed the graininess of the images as a measure of the surface roughness, with the intent of further improving the accuracy. For

verification, the authors also collected data using two Vaisala CSC111 camera systems. The authors' dual-camera system distinguished snow from ice but could not distinguish ice from water on the roadway (see Figures 1.9 & 1.10). While the graininess showed differences between roadway types (asphalt, sand, and gravel), it did not improve the distinction of surface conditions (snow, ice, water). The authors suggest the cost of their dual-camera system is approximately $2800, compared to the Vaisala system which is approximately $31,000 (in 2009).
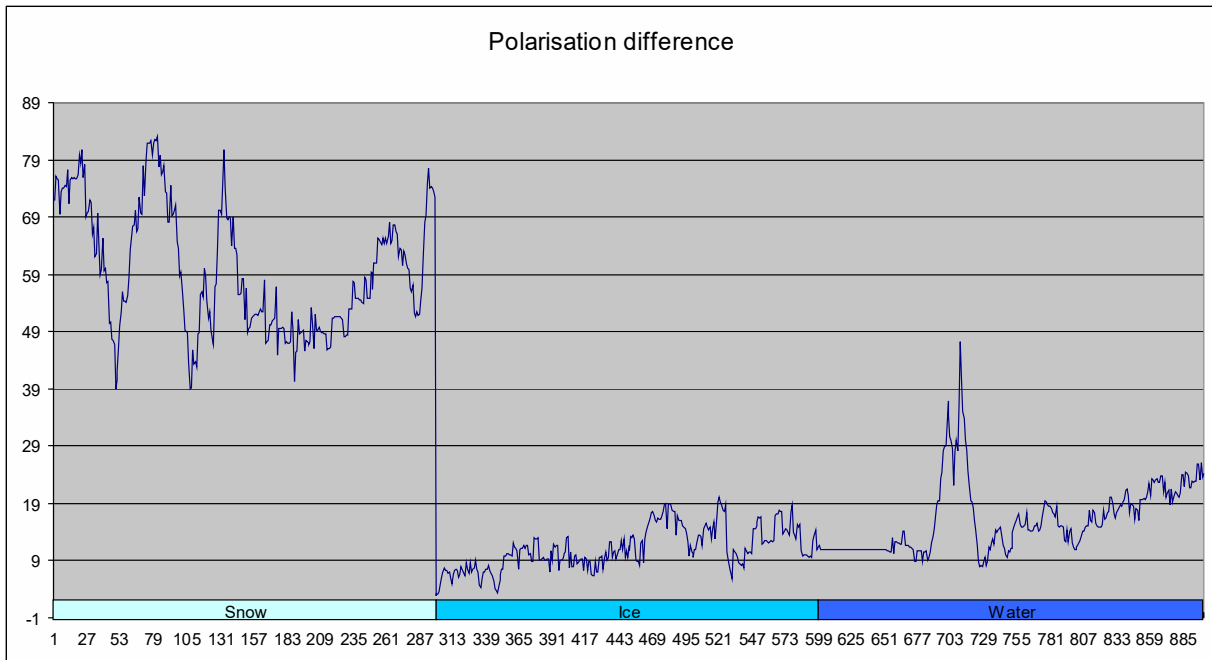
Figure 1.9 Polarization (polarisation) difference = difference between vertically filtered and horizontal filtered images. (from Jokela et al., 2009).
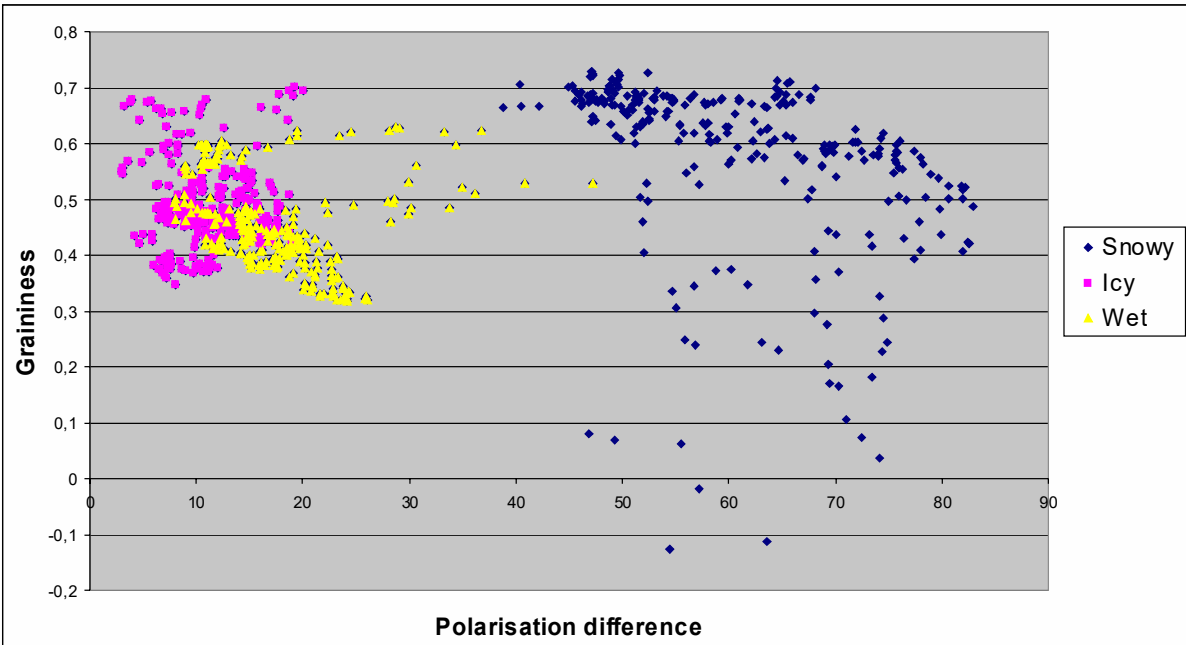
Figure 1.10 Comparison of snowy, icy and wet road. (from Jokela et al., 2009).

Omer and Fu (2010) evaluated a vehicle mounted camera system that could be installed in public vehicles such as buses and police cars, with GPS tagged images. This system would collect images as the vehicles travel their normal routes, and images would be uploaded to a central server for analysis when network connections are available. An example of the type of image captured, and how the image was cropped to only show relevant data, is shown in Figure 1.11.

Figure 1.11 Actual image (top) and cropped image with horizon and vehicle cropped (bottom). (from Omer and Fu, 2010)

Omer and Fu (2010) found that this system was accurate for snow covered vs. bare pavement when using color as the classifying image feature. For bare tracks with covered center conditions, they used grey-scale images and calculated horizontal and vertical gradients to determine the presence of straight lines. The authors describe some challenges with the initial training of the image processing system, but overall achieved 80%+ success for bare, snow-covered, and snow with bare track conditions, as shown in Table 1.2. They expect performance would improve with better quality cameras, more data for training, and better camera positioning specifically for this task.

Table 1.2 SVM classification results using validation data. (from Omer and Fu, 2010)

Source	Road Condition		
	Bare	*Covered*	*Tracks*
Drive Recorder	85%	89%	85%
Web Cam	84%	86%	85%
Analogue Video	85%	81%	85%

Horita et al. (2012) evaluated road surfaces using a surveillance camera (SONY HDR-FX7) at night and relying on vehicle headlights for illumination of the roadway surface. Replicating the process in five separate locations they determined the area of wet and dry pavement with 20 - 100% accuracy (based on number of pixels). The authors identified streetlight illumination as a primary interference, though distortion due to perspective also affected the results because individual pixels represented different areas whether in the foreground or background of the image (see Figure 1.12). Overall for five sites and three separates dates for data collection, this method achieved approximately 74% accuracy for dry conditions and 73% accuracy for wet conditions. Though the model of camera used in the study is no longer available, similar models currently cost approximately $200 - $1500 (in 2012).

(a) Dry in P_1.   (b) Wet in P_1.

(c) Dry in P_5.   (d) Wet in P_5.
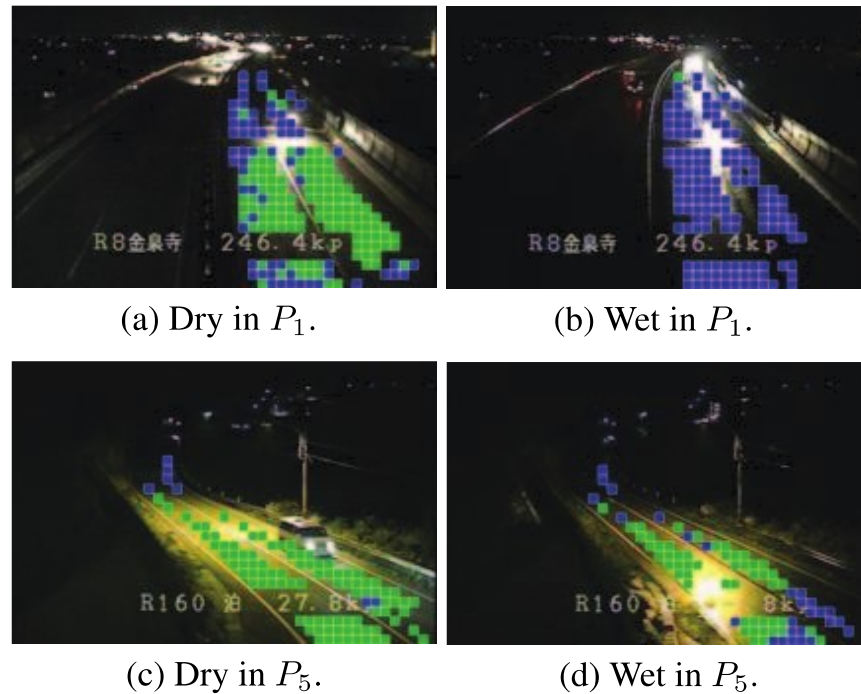
Figure 1.12 Distinction result of consolidation in 1 hour. Note: P1 & P5 are different locations. (from Horita et al., 2012)

Takeuchi et al (2012) analyzed surveillance camera images to distinguish wet and snowy conditions, both during the day and at night. The method required creating a boundary in the images around the roadway, and then dividing the roadway area into 20 x 20 pixel blocks. Each block was then classified as wet or snow. In general, the method accurately identified wet and snow conditions during the day (70 - 90% accurate) and night (60 - 90% accurate), but is limited by location (requires surveillance camera and training data at that location) and adequate nighttime illumination. The authors states that the white traffic line in the center of the roadway was consistently misclassified, as shown in Figure 1.13.

| (a) Input. | (b) Correct answer. | (a) Input. | (b) Correct answer. |

| (c) Result used Method1. | (d) Result used Method2. | (c) Result used Method1. | (d) Result used Method2. |

| (e) Result used Method3. | (e) Result used Method3. |
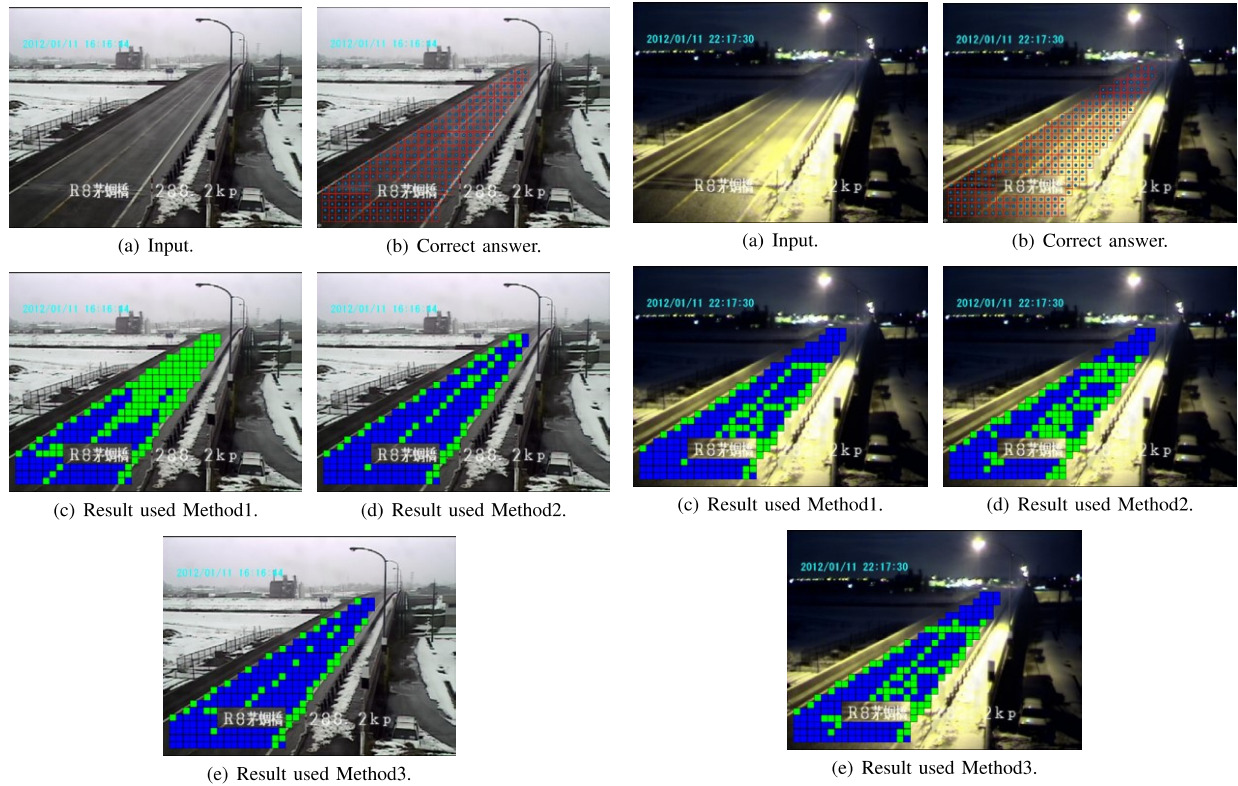
Figure 1.13 Road surveillance camera images and classification at daytime (left) and nighttime (right) at place B. (from Takeuchi et al., 2012)

Jonsson (2011) tested an array of three infrared detectors with a standard halogen lamp to determine if the detection at three wavelengths could distinguish between dry, wet, black ice, thick ice, wet snow, and cold snow. Jonsson (2011) used detectors from Hamamatsu, the first of which was a S1223 detector to operate at a peak wavelength of 960 nm, which is outside the water absorption peaks. The other two sensors, a G8370 and G5852, were chosen to operate at the water absorption peaks of 1550 nm and 1950 nm, respectively. All detectors were connected to amplifiers from Hamamatsu. The G5852 required cooling, thus it was also connected to a C1103- 04 temperature controller from Hamamatsu and set to -20 °C. The signals from the amplifiers were then connected to a PC using an Advantech PCI-1710 data acquisition card. Though this required substantial setup and testing, Jonsson (2011) shows that the different pavement conditions could be distinguished when using all three wavelengths (see Figure 1.14). Though it appears that wet conditions and black ice conditions are similar and potentially difficult to distinguish in Figure 1.14, a 3D plot of the voltage measured by each detector reveals that this distinction can be made (see Figure 1.15).
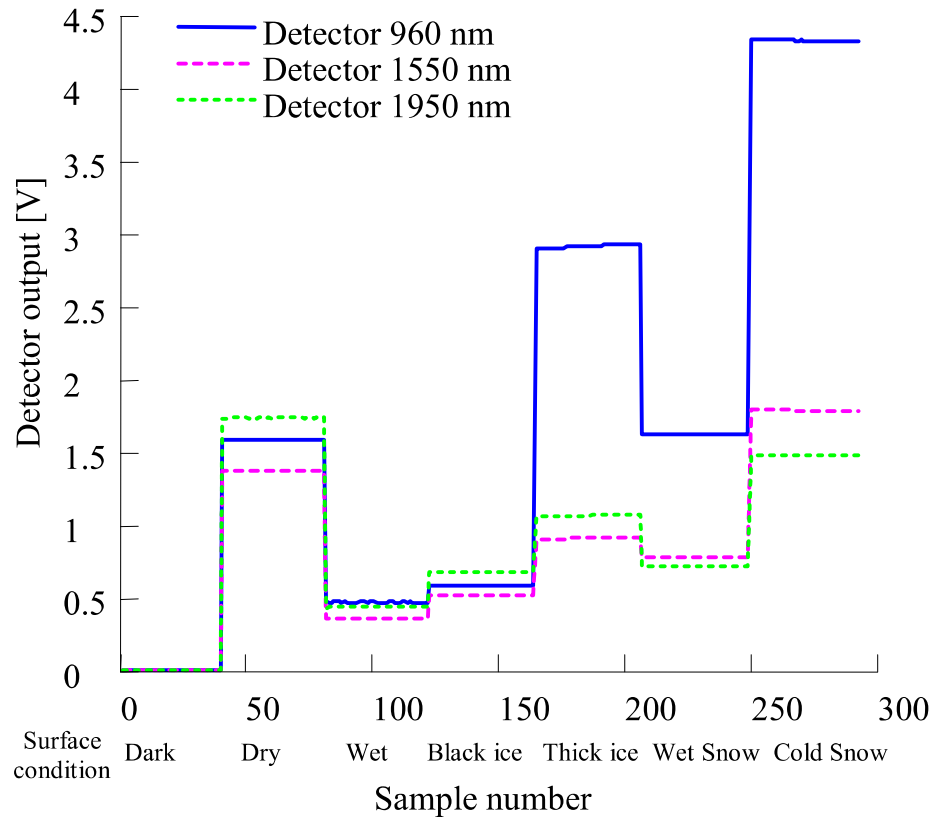
Figure 1.14 Responses from the three detectors when exposed to different surface conditions. The surface was illuminated with a halogen lamp and the reflection was measured. The first samples are measured without illumination (Dark), and the others were measured when surface was illuminated. (from Jonsson 2011)

Bubble size (data labels) = Detector 1950 nm (V)

x-axis: Detector 960 nm (V)
y-axis: Detector 1550 nm (V)

Legend:
- dry
- wet
- black ice
- thick ice
- wet snow
- cold snow

Data labels: 1.5, 1.75, 1.1, 0.7, 0.7, 0.45
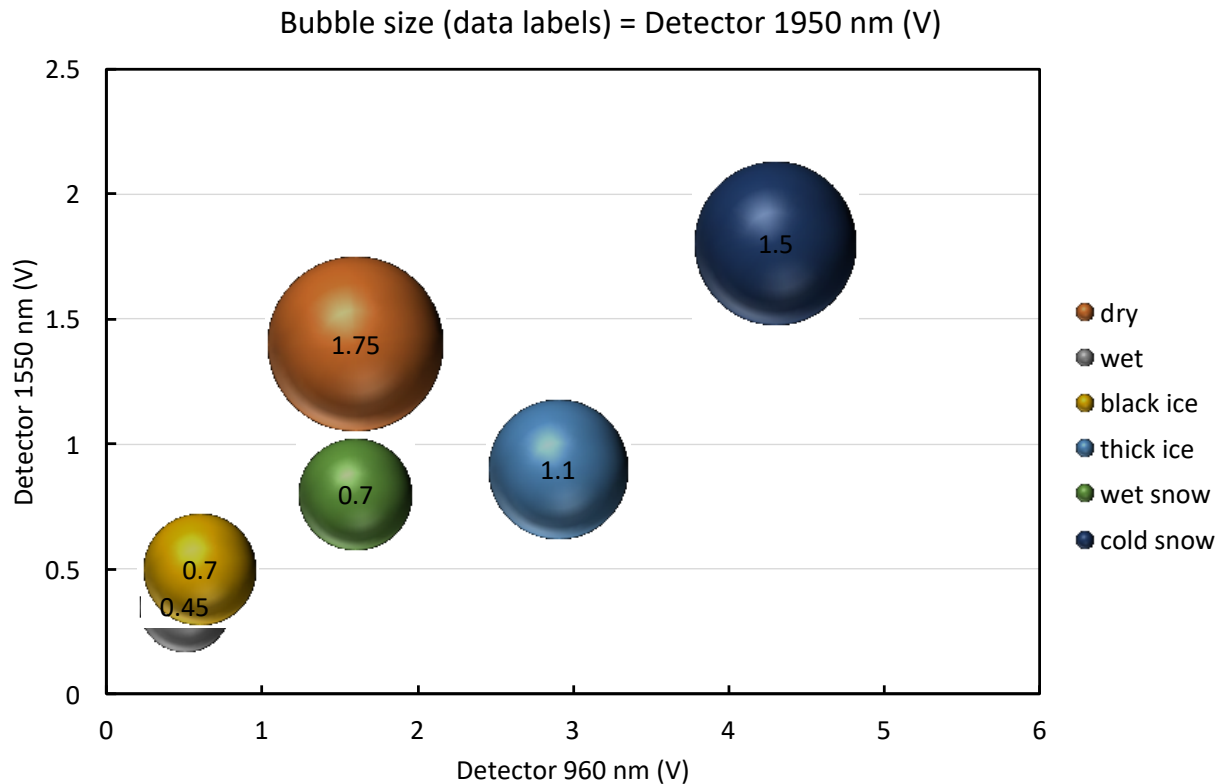
Figure 1.15 A 3D plot of the detector readings. (adapted from Jonsson 2011)

Jonsson 2011 states that a limitation of this system is that it is point-based and not image based, and that more research is required to develop an image-based system to get information for a larger portion of the roadway. In addition, the cost of the infrared image detectors was described as "high" at the time of publication.

Riehm et al. (2012) showed that the freezing of water on a pavement surface was accompanied by a dramatic increase in temperature (2.7 °C in laboratory experiments, 1.8 °C in field experiments). During the freezing process, the liquid cools to a supercooled state (below 0 °C) shortly before freezing begins, then quickly increases in temperature as the liquid freezes. This phenomenon is illustrated in Figure 1.16.
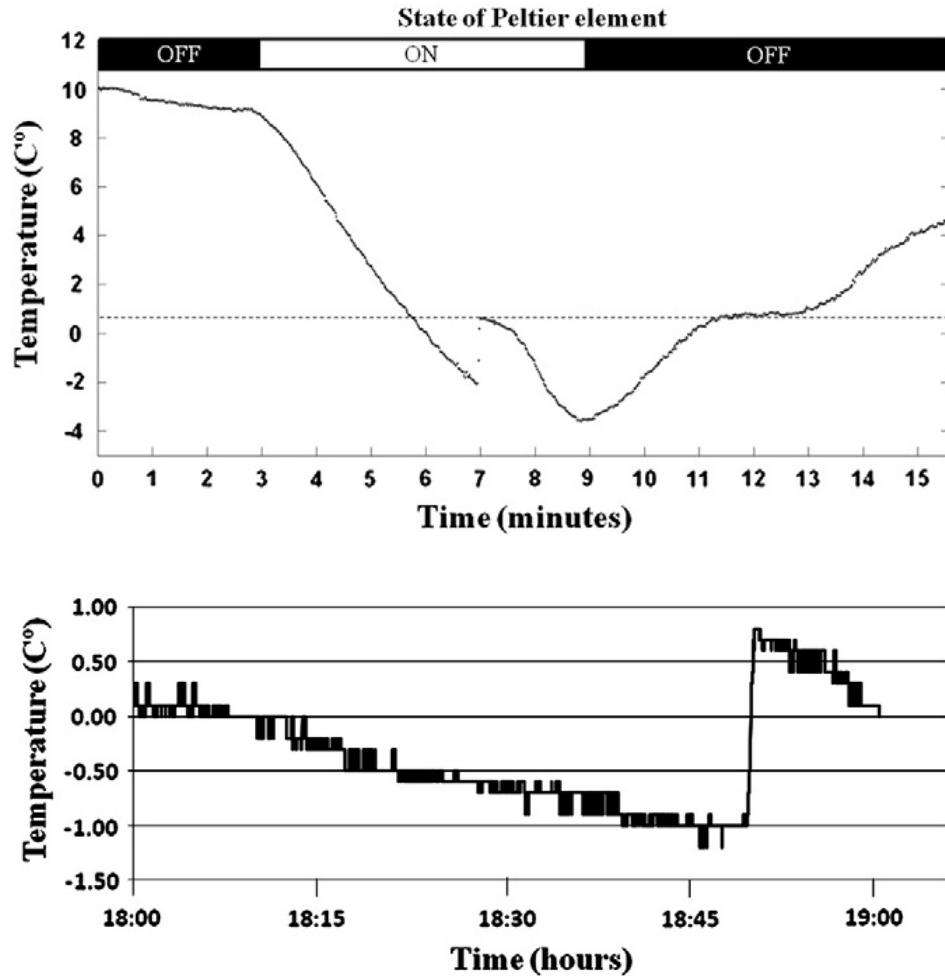
Figure 1.16 (Top) Temperature signal as ice formed on the asphalt in the laboratory climate chamber. Freezing occurred at 7 minutes and melting occurred between 11 and 13 minutes. (Bottom) The temperature signal as ice formed on the asphalt at the field site on 26 February. (from Riehm et al., 2012)

Jonsson and Riehm (2012) coupled air temperature, pavement temperature (2 mm below surface) and ground temperature (300 mm below surface) with infrared (IR) surface temperature in the wheel track and between the wheel tracks. They report several findings; first, that pavement temperature 2 mm below the surface only correlates with air temperature during dry, stable conditions. Snow and ice conditions "insulated" the pavement such that during these conditions, the pavement temperature 2 mm below the surface correlated with the ground temperature 300 mm below the surface. Second, the difference between the IR surface temperature and the pavement temperature (2 mm) is a "good metric for rapidly changing road conditions." These findings are demonstrated in Figures 1.17 and 1.18.
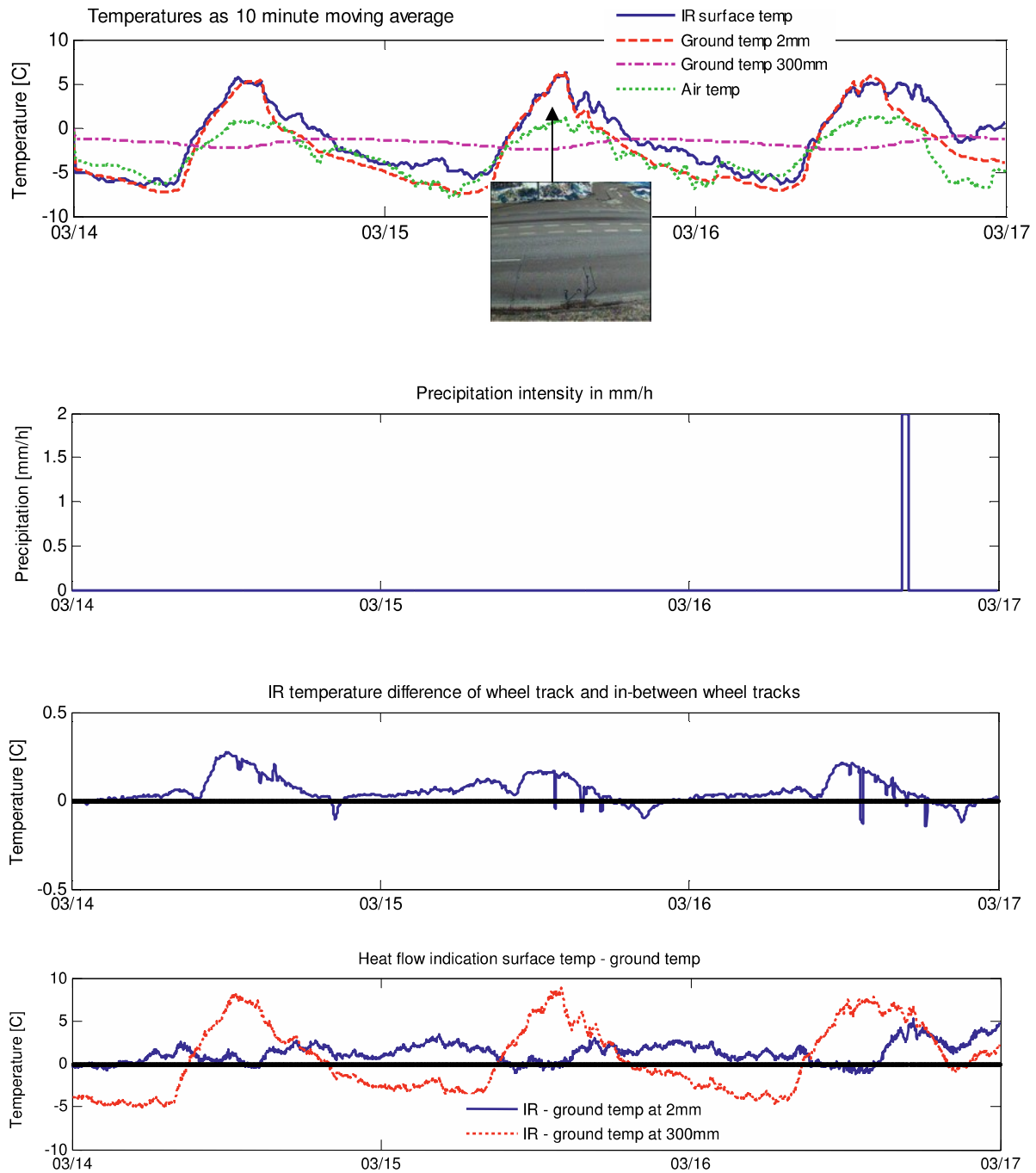
Figure 1.17 Data from a dry period with stable, dry weather conditions. This period is used as reference. The small precipitation amount detected on 16 Mar can be neglected as it could not be observed on the road surface. (from Jonsson and Riehm 2012)
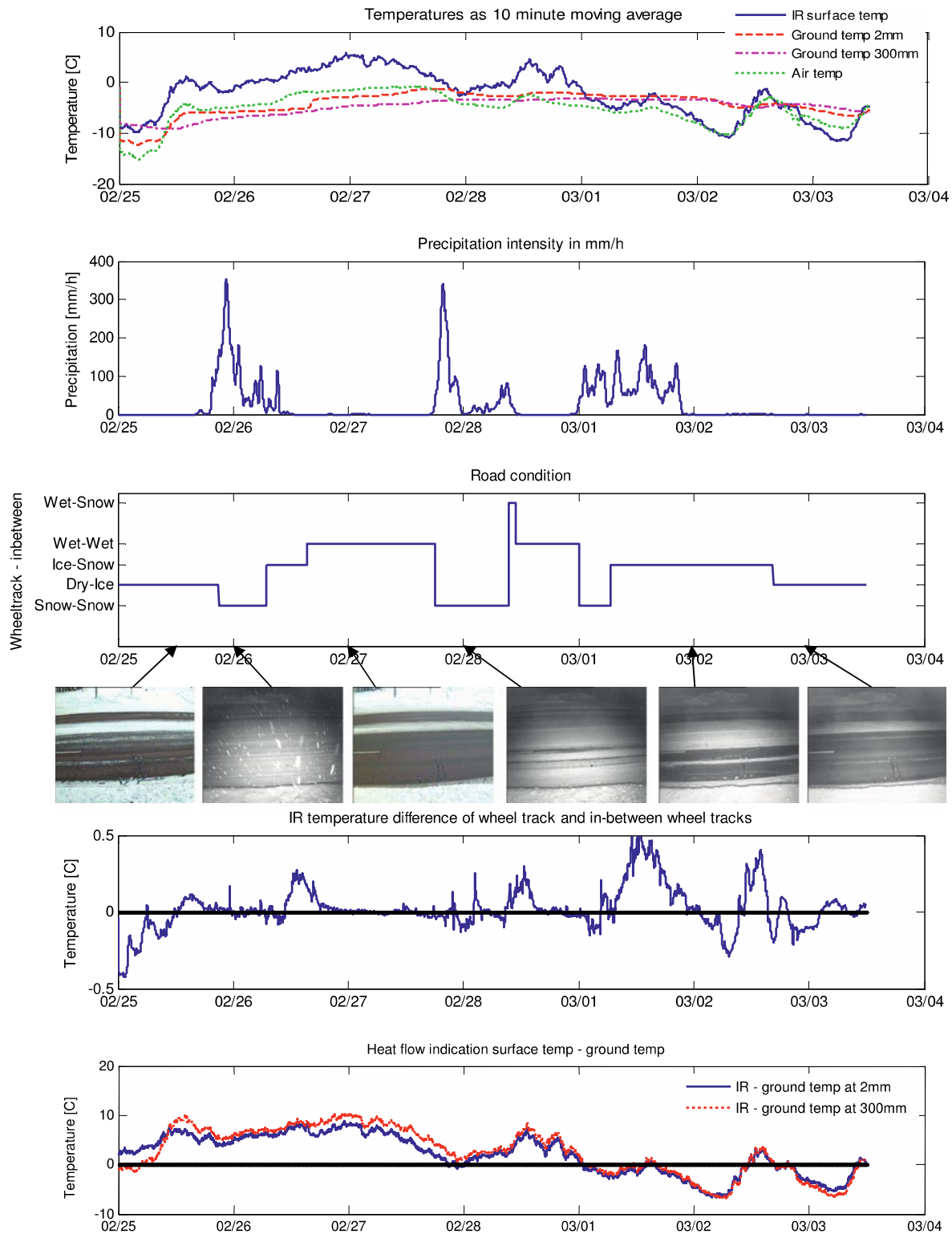
Figure 1.18 Data from a period with snow precipitation when the road surface was covered with snow or wet fluid. (from Jonsson and Riehm 2012)

Jonsson et al. (2015) expanded previous work by evaluating near infrared (NIR) camera images to distinguish road surface conditions (dry, wet, icy, snowy) for an area, both in the laboratory and in the field. For the laboratory experiments, the authors used a standard range spectrometer (NIR256-1.7T1-USB2/3.125/50m) operating within the range 900-1700 nm, and an extended range spectrometer (NIR-256-2.2T2-USB2/5/50m/1092-2238nm). These spectrometers were connected to a measurement probe (CASCONIR ELE2007-20), which contains an integrated 20W halogen lamp and capable of internal reference measurements. The results from the laboratory experiments showed that different road surface conditions (dry, wet, ice, and snow) could be distinguished using NIR spectrometers (see Figure 1.19 and 1.20). The absorption for each condition is different at certain wavelengths, and changes as wavelength increases.
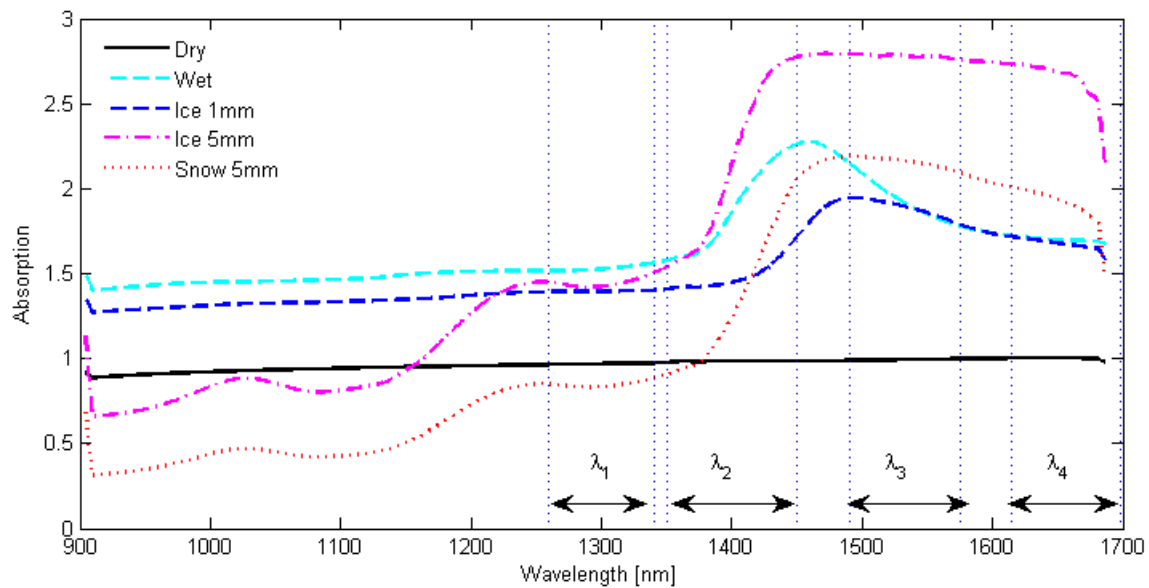
Figure 1.19 Spectral curves obtained in the laboratory for a dry, wet, icy and snowy surface retrieved from a standard range spectrometer. (from Jonsson et al. 2015)
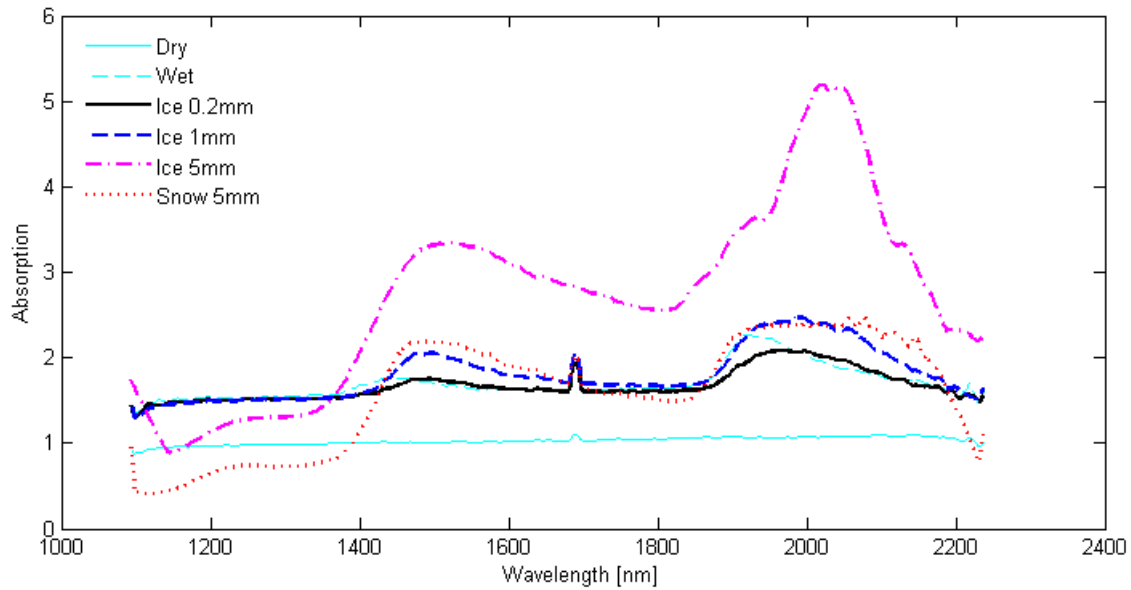
Figure 1.20 Spectral curves obtained in the laboratory for a dry, wet, icy and snowy surface retrieved from an extended range spectrometer. (from Jonsson et al. 2015)

For the laboratory and field experiments, Jonsson et al. (2015) used a FLIR SC7100 InGaAs camera (spectral range of 900 to 1700 nm) with a KOWA CCTV lens (focal length = 25 mm, minimum f-number 8) was installed on the camera. Two 55W Halogen lamps were used in the field tests to illuminate the 2 x 2 m test road section, and a web camera was used to collect visual documentation. Images were captured during winter in the "very far north," which resulted in natural darkness (minimal ambient light) for most images. Thus, no polarizing filters were used. The authors recommend, however, that polarizing filters be used in other applications to improve image quality and condition detection. Two results of field experiments are shown in Figures 1.21 and 1.22; both with a standard color (appears black and white) image and condition classification using the NIR camera images. The authors report good agreement between the detected (using camera images) and observed (verification) road surface conditions. Jonsson et al. (2015) state that this NIR camera system is "very costly." Though the specific camera used in this study is unavailable in the USA, a roughly equivalent and less expensive model (FLIR SC6200) costs approximately $64,500 (in 2015).
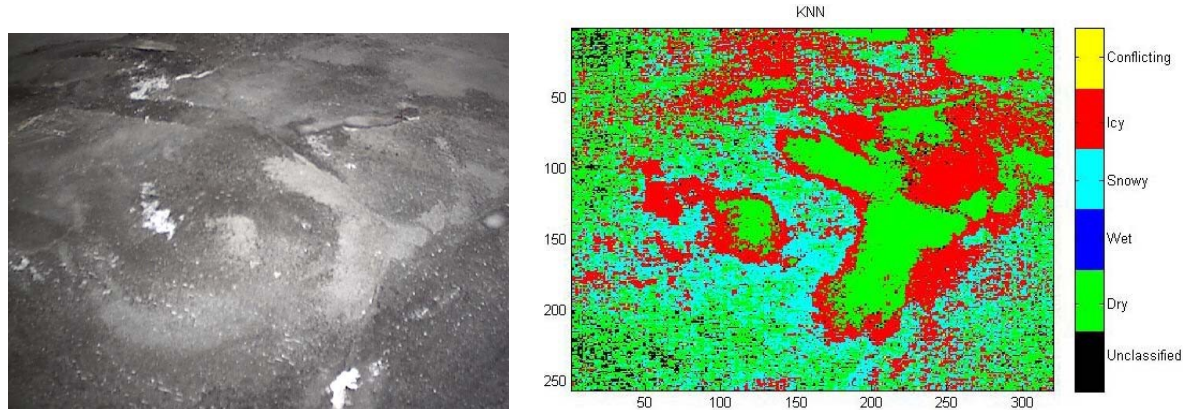
Figure 1.21 A standard color image (left) and classification of the road condition (right). The road was dry and covered with icy patches and some snow spots. The surface and air temperature were approximately −10 °C. (from Jonsson et al. 2015)
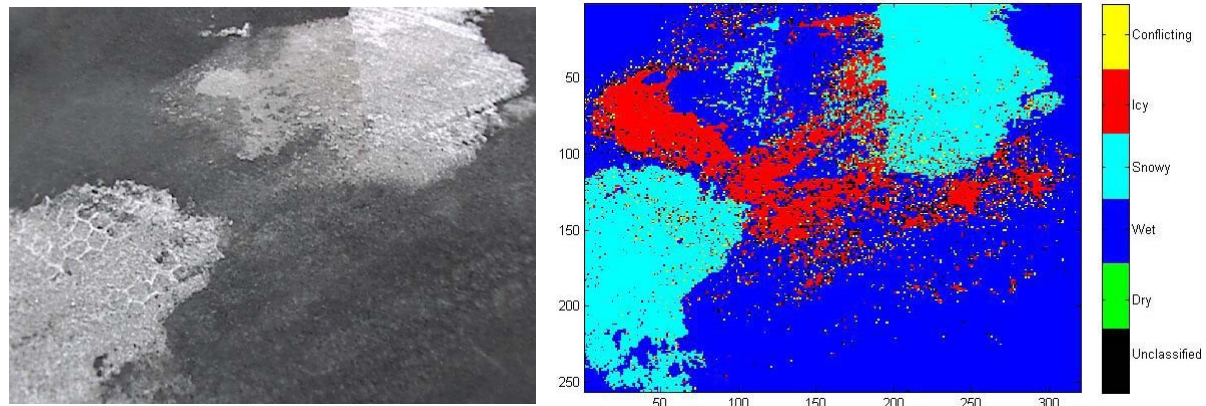
Figure 1.22 A standard color image (left) and classification of the road condition (right). The road was wet with snow covered regions. The surface temperature was approximately 0 °C and the air temperature was +2 °C. (from Jonsson et al. 2015)

Casselgren et al. (2016) evaluated smooth and rough asphalt surfaces to distinguish between dry, moist, wet, frost, icy and snowy conditions with the use of a Near Infrared (NIR) camera system. The system comprised an NIR camera (FLIR SC7100 InGaAs camera with a KOWA CCTV lens), a halogen lamp to provide ambient lighting, and an illumination module that combined three wavelengths (λ_1 = 980 nm, λ_2 = 1310 nm and λ_3 = 1550 nm) from three laser diodes and focused them onto a point on the road surface of roughly 1 cm^2. The system adequately distinguished between the different surface conditions as shown in Figure 1.23. The FLIR SC7100 camera used in this study is unavailable in the USA, but a roughly equivalent and less expensive model (FLIR SC6200) costs approximately $64,500 (in 2016).
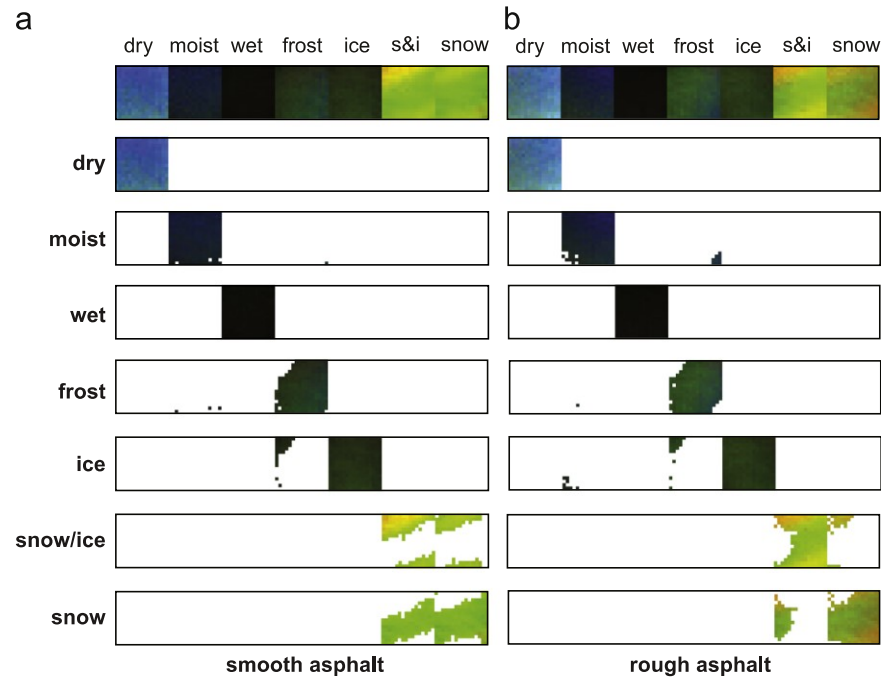
Figure 1.23 The result from the surface classification on (a) smooth and (b) rough asphalt together with an illustration of the possibility to separate the colors for the different road conditions. Note: s&i = snow on ice. (from Casselgren et al. 2016)

1.5 OTHER METHODS

Ogura et al. (2002) measured albedo using two solar cells facing opposite directions (one up for solar radiation, one down for reflected radiation), with the intent of distinguishing dry, wet, water film, snow, and ice surfaces. By using solar cells instead of pyranometers, the system can be used in the day or at night. This system was vehicle mounted and albedo changed as a function of road condition, as shown in Figure 1.24. It is important to note that the albedo values for snow and ice are approximately an order of magnitude larger than the albedo values for dry and wet pavement. Though the authors illustrate how albedo varies with road surface condition, they did not apply the system to real road conditions to verify the system and thus the accuracy and robustness is unknown.
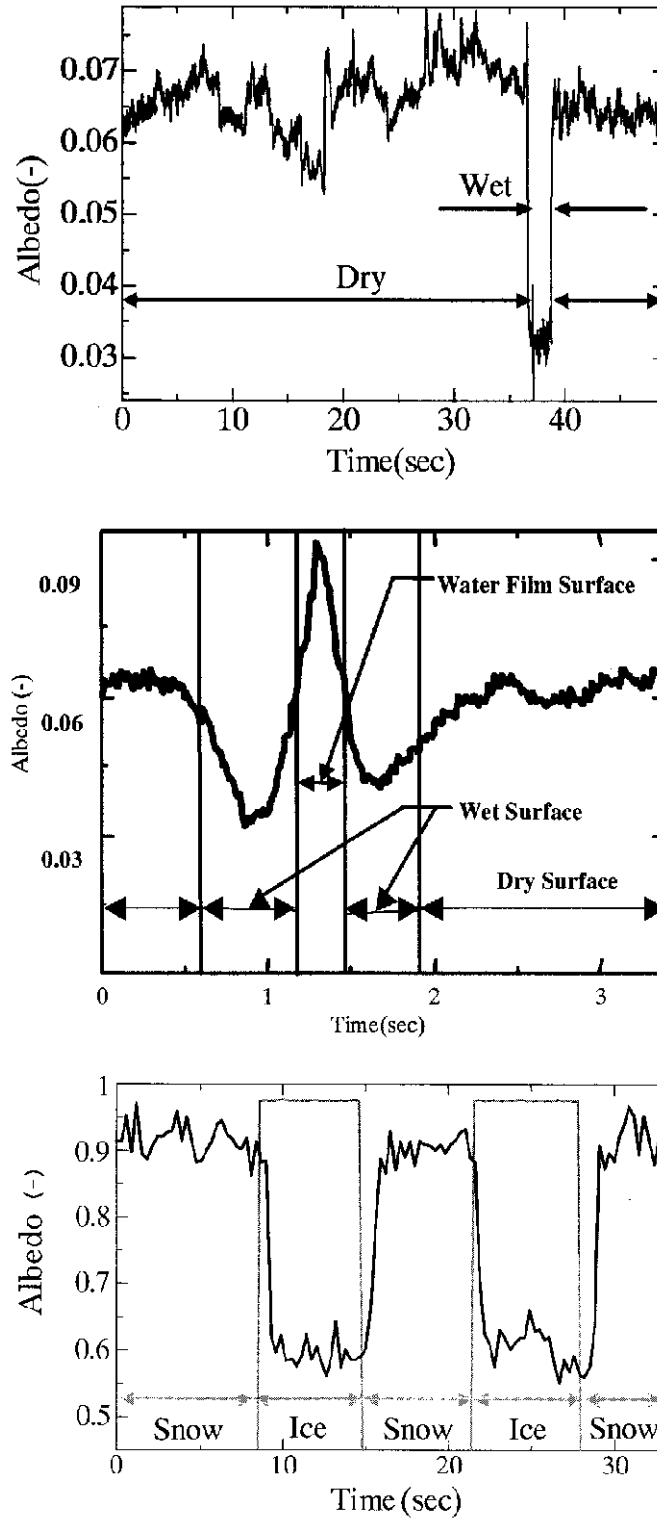
Figure 1.24 Albedo measurements on dry and wet conditions (top); dry, wet, and water film conditions (middle); and snow and ice conditions (bottom). (from Ogura et al., 2002)

Feng et al. (2010) considered surface friction measurements to distinguish between bare dry, bare wet, thin snow cover, slushy snow cover, partially snow cover, and mostly snow cover. As discussed in their review of the literature, mean surface friction is adequate for separating bare pavement from ice or snow cover, but often cannot distinguish dry from wet pavements or between different types of snow cover (see Figure 1.25). Feng et al. (2010) collected friction data using fixed-slip-ratio continuous friction measurement equipment, called Traction Watcher One (TWO). Expanding analysis of friction data to examine probability density parameters and spectral density parameters resulted in better prediction of road surface conditions. The cost of continuous friction measurement equipment like the TWO system is roughly $100,000 or more (in 2010).
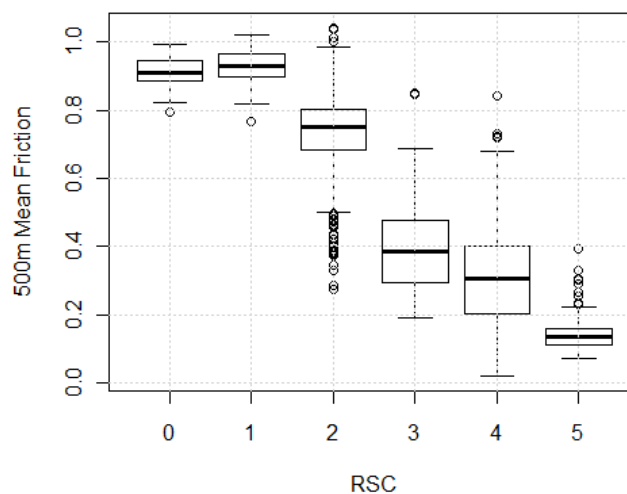
Figure 1.25 Distribution of Mean Friction. Note: RSC = Road Surface Condition; 0 = bare dry, 1 = bare wet, 2 = thin snow cover, 3 = slushy snow cover, 4 = partially snow cover, and 5 = mostly snow cover. (from Feng et al., 2010)

1.6 COMPARISON OF PERMEABLE AND IMPERMEABLE PAVEMENTS

A study in Robbinsdale, MN (Wenck 2014) evaluated permeable and impermeable pavements on sand and clay substrate. The purpose of the study was to investigate whether permeable asphalt can be used as a physical substitute for road salt as an ice prevention method. Two low-volume residential intersections in Robbinsdale were selected as test sites. One portion of each was reconstructed using permeable asphalt pavement. An adjacent impermeable intersection at each served as control. During the two-year monitoring period, the impermeable intersections were plowed and salted as usual. The permeable sections were plowed, but no salt or sand was applied.

Though images were collected by a closed-circuit camera and processed to estimate bare pavement at each intersection at 9 am, noon, and 3 pm each day, results were not quantified or reported. Wenck (2014) state that observational results suggest that unsalted porous asphalt pavement can have net bare pavement comparable to a salted traditional pavement section. In addition, salted impermeable

pavement starts melting a few to several hours before unsalted permeable pavement. Meltwater from snow and ice infiltrates into permeable pavement and is not susceptible to refreezing as was observed on impermeable pavement.

In addition to photo data, thermocouple arrays were installed in the permeable and impermeable pavement sections in Robbinsdale. These arrays measured temperature in the pavement and below the pavement to a max depth of 17 – 22 inches. These temperature data will be used in the current research project for evaluation and modeling of heat flux through the pavement and subbase. Several conclusions can be made from the data collected in the Wenck (2014) study, as follows:

- During mid-winter (e.g., January or February) when the pavement surface temperature is warmer than the subbase temperature (e.g., at 18"), the permeable pavement surface is warmer than the impermeable pavement surface. Conversely, when the pavement surface temperature is colder than the subbase temperature (e.g., at 18"), the permeable pavement surface is colder than the impermeable pavement surface. This is demonstrated in Figure 1.27 below:
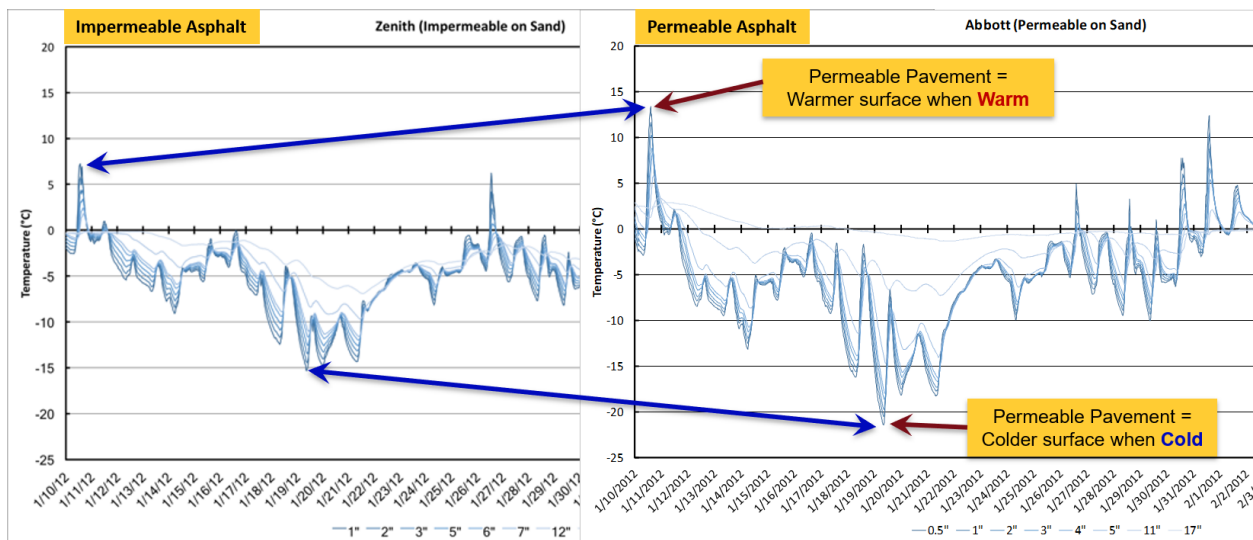
Figure 1.26 Temperature profiles for impermeable asphalt pavement and permeable asphalt pavement on sand substrate. Data series are depths below surface (e.g., 1" below surface, etc.) in which darker color indicates closer to the pavement surface. (adapted from Wenck 2014)

- During mid-winter (e.g., January or February), the difference in temperature between the surface and approximately 18" below the surface is greater in the permeable pavement compared to the impermeable pavement, regardless of the pavement surface temperature. In addition, the subbase temperature at 18" below the surface is warmer in the permeable pavement compared to the impermeable pavement. This suggests that permeable pavements and the porous subbase beneath them function as thermal insulators, preventing heat transfer from the surface to below or vice versa. This is demonstrated in Figure 1.28 below:
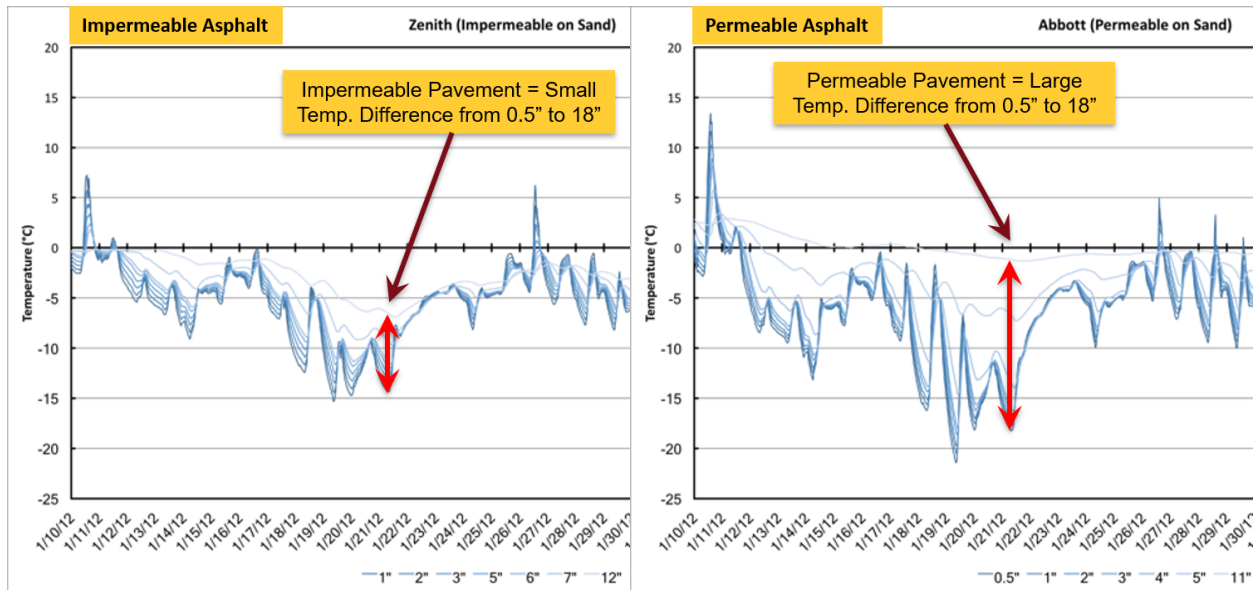
Figure 1.27 Near surface temperature measurements for all sites. (adapted from Wenck 2014)

1.7 SUMMARY AND CONCLUSIONS

Several studies have shown that acoustic, imagery, and other data can be used to distinguish different winter road surface conditions, including dry, wet, icy, slushy, and snowy. There is a tradeoff, however, between accuracy, automation, and cost. In addition, a study in Robbinsdale, MN compared permeable and impermeable pavements and showed that permeable pavements and their porous subbase function as thermal insulators, though quantification of winter road surface conditions was minimal. The techniques used in these studies were considered when developing a low-cost, reliable, and quantifiable system for comparing winter road surface conditions on permeable and impermeable pavements in Minnesota.

CHAPTER 2: FIELD EQUIPMENT, INSTALLATION, METHODS, AND MEASUREMENTS

2.1 PROJECT YEAR 1 - MNROAD

During the first year of the project (2016), it was determined that extensive data could be collected for this project at the MNRoad Research Facility, near Albertville, MN (see Figures 2.1 and 2.2) because it contains sections of permeable pavement, both asphalt and concrete, in controlled environmental conditions (limited access to the public) with in-pavement temperature sensors previously installed. Thus, it was decided that data for Year 1 should be collected at MNRoad. The following sections describe the data that was collected at this site during the first winter season of the project.
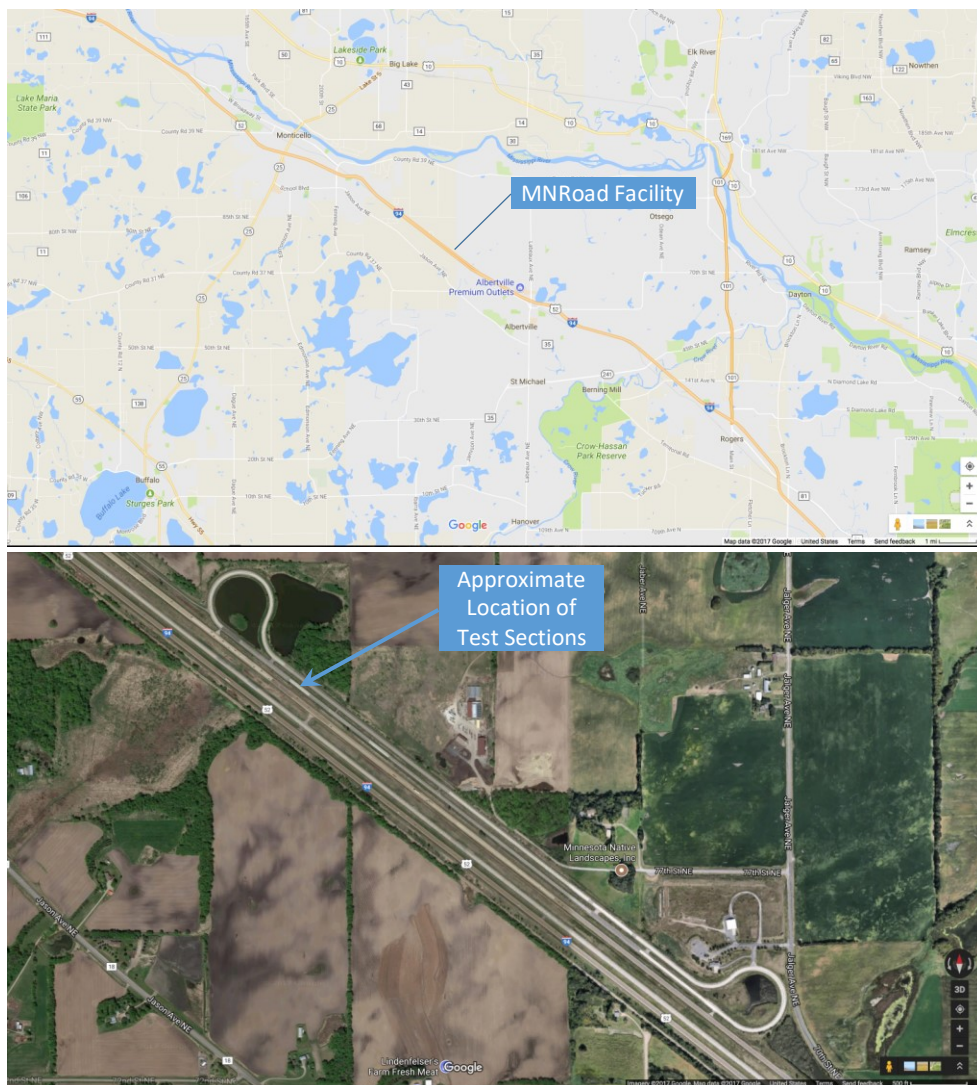
Figure 2.1 Location of MNRoad Research Facility, near Albertville, MN.
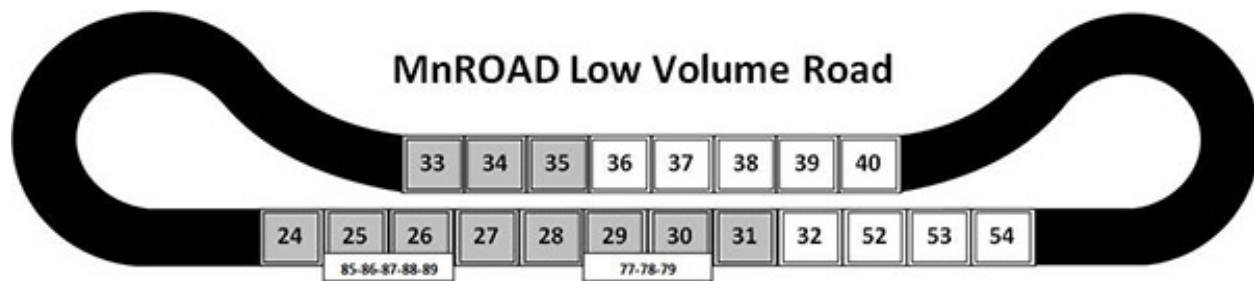
Figure 2.2 MNRoad Research Facility Test Sections. Data was collected on section 32 (impermeable concrete, Mn/DOT Special Mix - GGBFS, Specification 3102) and sub-sections 85 (porous concrete, Mn/DOT Specification 2301), 86 (porous asphalt, Mn/DOT Specification 2360), 87 (impermeable asphalt, Mn/DOT Specification SPWEB340B). Note that sub-sections 85-87 are located within sections 25 and 26. Sunlight conditions are similar for all sections.

2.1.1 Photographic Data Collection

Photographic Data (photos) were collected at the MNRoad Research Facility on four different pavement sections (permeable concrete, permeable asphalt, impermeable concrete, impermeable asphalt) from December 6, 2016 through April 20, 2017. These cameras were Distianert Low Glow Black Infrared Trail & Game Scouting Camera 12MP 1080P Detection Range 80ft purchased from Amazon.com. In addition, AA batteries were purchased to power the cameras and 8GB memory cards were purchased to store time lapse images captured by the cameras. One camera each was installed at the permeable concrete and impermeable concrete sections. Three cameras each were installed at the permeable asphalt and impermeable asphalt sections. At each asphalt section, a camera with a vertical polarizing lens (vertical polarization), a camera with a horizontal polarizing lens (horizontal polarization), and a camera without any polarizing lens (Nonpolarization) was installed on January 19th, 2017. The advantages of polarizing lens are described in the literature review completed in Task 1 of this project. All cameras were set to capture one photo per hour continuously.

The number of photos captured at each site on each camera between December 6, 2016 and April 20, 2017 is listed in Table 2.1. In general, the camera did not capture photos when the air temperature was near or below $-20°C$ ($-4°F$), especially during nighttime conditions due to the use of the infrared flash because of the additional power required to operate the flash. In addition, two memory cards became faulty during March and April 2017, and thus photos were not captured on two cameras at different times. Overall, 13,628 photos were captured.

Table 2.1 Distribution of photos collected at the MNRoad Research Facility from December 6, 2016 through April 20, 2017.

	Photos Collected
Impermeable Concrete	2,397
Permeable Concrete	1,974
Permeable Asphalt	
--Nonpolarization	2,547
--Vertical Polarization[1]	921
--Horizontal Polarization[1]	168
Impermeable Asphalt	
--Nonpolarization	1,325
--Vertical Polarization[1]	2,141
--Horizontal Polarization[1]	2,155
TOTAL =	13,628

[1]Polarized cameras were only deployed from 01/19/2017 - 04/20/2017

2.1.2 Surface Temperature Data Collection

Three thermal sensors (infrared thermistors, Micro-Epsilon Model CS) were installed in an enclosure at MNRoad to continuously measure pavement surface temperatures at three locations in one cross section (permeable asphalt, section 86). Temperature measurements represent approximately a circular portion of the roadway with approximately 30-cm diameter. Temperatures were taken at 10-second intervals and stored in 5-minute averages by a Campbell Scientific CR-1000 data logger, with roughly 25,000 sets of measurements recorded from Jan 19 – April 20, 2017. Two enclosures were used for the IR thermistors: the first enclosure ("Box 1") was installed on Jan 19, 2017, with an RM Young shielded air temperature sensor was added to the site on Feb 10. Box 1 was uninstalled March 16 and replaced with a second set of three IR sensors in another enclosure ("Box 2"). All equipment, including Box 2, was removed on April 20. During the data collection period (Jan 19 – Apr 20), only a few snowfall events were observed, the largest of which occurred on Jan 25, Feb 7, and Mar 12. The setup for one cross section is shown with 3 trail cameras in Figure 2.3.

Figure 2.3 Monitoring setup at the permeable asphalt test section: gray box at top is the enclosure and mount for the 3 infrared sensors; 3 trail cameras (two with polarized lenses) are mounted below the enclosure.

2.1.3 In-pavement Temperature Sensors

Temperature sensors (thermocouples) were constructed and installed by MNRoad staff directly into the pavement at depths of ½ inch, 1½, 2½, 3½, 5, 7, 9, 11, 13, 15, 24, 28, 36, 43, 48, 60, and 72 inches below the surface (where applicable) prior to this project. The data from these sensors can be accessed from the MNRoad website (historical) or Mn/DOT staff (current). An example of this in-pavement temperature data is shown in 2.4.
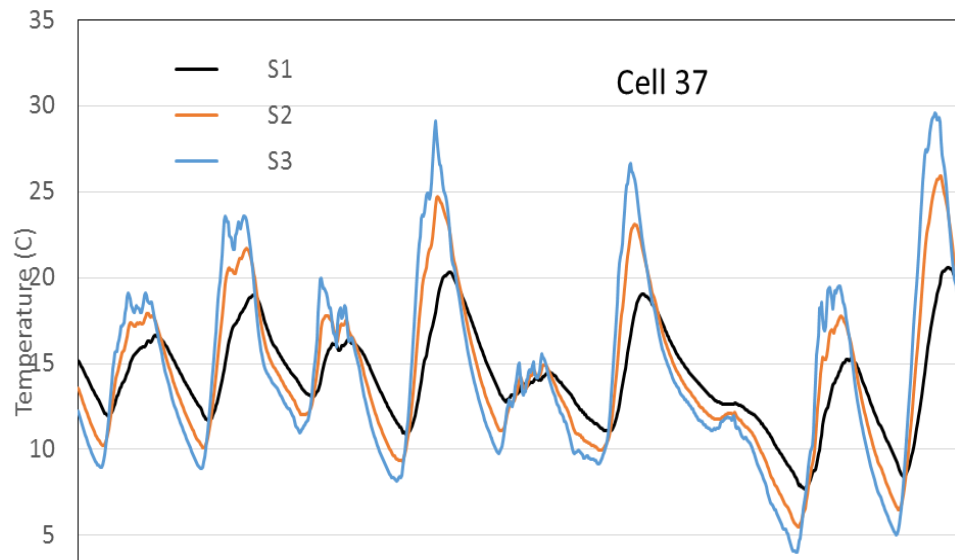
Figure 2.4 Temperature time series from cell 37 in 2010 for three thermocouples (S1, S2, S3). Note that sensor S3 appears to be the closest to the pavement surface.

2.1.4 Air Temperature Sensors

An air temperature sensor with radiation shield was also installed for comparison to surface and in-pavement temperature measurements.

2.1.5 Data recording

The surface temperature and air temperature sensors are connected to a Campbell Scientific CR1000 data logger to record and store the temperature data. A laptop computer was regularly connected to the CR1000 to download and save the data for future analysis.

2.2 PROJECT YEAR 2 - CITY OF ROBBINSDALE AND MAPLEWOOD PUBLIC WORKS

The MNRoad Research Facility, near Albertville, MN was not available for data collection during the second year of the project because all sections of permeable pavement, both asphalt and concrete, were removed during summer 2017. Thus, alternative sites and measurement methods were needed for data collection during year 2. Sites were identified within the City of Robbinsdale, MN and at the Maplewood (MN) Public Works Facility, which are described below. In addition, data were also collected at St. Peter's Catholic Church in North St. Paul, MN (02/15/2018).

2.2.1 Sarsys-ASFT T2Go Portable Friction Tester

A Sarsys-ASFT T2Go portable friction tester (https://www.sarsys-asft.com/t2go) was purchased with private funds and was used to collected friction data as part of this project. The cost of the T2Go was

approximately $20,000 (in 2017). The T2Go is designed as a portable, pedestrian push-behind friction tester than can measure friction is small spaces without the need for high speed or a vehicle. Though the T2Go is design for measuring friction of wet pavement, the T2Go was used without water during winter measurements so as to not damage the instrument or skew the results when attempting to measure the presence of snow or ice on a pavement surface. This device measures friction of the surface as well as surface temperature along the path over which the device is pushed. Surface friction and temperature data are collected at 3 cm intervals in the pathwise direction. The output from the device is the friction coefficient (μ) on a scale from 0 (no friction) to 1 and is calibrated such that $\mu = 1$ is equivalent to 7 kg of force between the two fixed-slip tires. As a result of this calibration method, some friction measurements exceed a friction coefficient of 1 for some surfaces, but provide the same amount of traction. Thus, values of $\mu \geq 1$ are considered to have the same friction for the analysis within this report. For the purpose of pedestrian safety, Sarsys-ASFT T2Go suggests that values of $\mu < 0.35$ require pedestrian caution and values of $\mu < 0.25$ are unsafe for pedestrian travel. A picture of the T2Go is shown in Figure 2.5.

Figure 2.5 Sarsys-ASFT T2Go portable friction tester (https://www.sarsys-asft.com/t2go).

2.2.2 Robbinsdale Field Site

The first site is located in Robbinsdale, MN at the intersections of 41st Ave N & Abbott Ave N (permeable asphalt), and at 41st Ave N & Zenith Ave N (impermeable asphalt, as shown in Figure 2.6. In-pavement temperature sensors are deployed at Robbinsdale in both pavement sections, and surface temperature sensors were deployed on the permeable section (41st Ave N & Abbott Ave N). Surface temperature sensors were not deployed on the impermeable section (41st Ave N & Zenith Ave N) due to frost in the ground, which limited access to the underground connections to the in-pavement sensors. In addition, pavement friction and surface temperature measurements were collected with an ASFT T2Go portable pavement friction measurement device on both pavement sections in Robbinsdale during 2018. The dates friction and surface temperature data were collected at Robbinsdale include January 26, February 7, February 16, February 23, and February 27.

Figure 2.6 Location of Robbinsdale Field Site (41st Ave N & Abbott Ave N; 41st Ave N & Zenith Ave N)

2.2.2.1 Surface Temperature Data Collection

Surface temperature measurements were recorded during winter 2017-2018 (Year 2) at the permeable asphalt site at Abbott Ave and 41st Ave in Robbinsdale. The same equipment as in Year 1 was used: three thermal sensors (infrared thermistors, Micro-Epsilon Model CS), installed in an enclosure at the side of the road and mounted at a height of roughly 6 feet. The sensors continuously recorded surface temperatures at three, roughly evenly-spaced locations in a cross section of the roadway. Sensors record infrared radiation from circular portions of the roadway with approximately 30-cm, 80-cm, and 100-cm diameters at the near, middle, and far positions, respectively, and convert these radiation values into temperature. Temperatures were logged at 10-second intervals and stored in 15-minute averages by a Campbell Scientific CR-1000 data logger. A shielded air temperature sensor (RM Young) was also

installed at the site and set to record to the data logger at 15-minute intervals. The city of Robbinsdale installed thermocouples in a vertical profile within the permeable asphalt at the time of its construction in 2010; these were located and connected to the data logger and set to record temperatures at 15-minute intervals. All equipment was installed and setup on December 18-19, 2017 and collected data through winter 2017-2018. While no trail cameras were installed at the site to validate extent of snow or ice coverage, several large snow events occurred during the field season that would have caused complete coverage of the road.

2.2.3 Maplewood Public Works

Data was collected at other sites during year 2, including the Maplewood Public Works Facility (Figure 2.7). In-pavement and surface temperature sensors were not installed or deployed at this site, but surface friction and temperature measurements were collected using an ASFT T2Go portable pavement friction measurement device. In addition to collecting measurements during natural winter conditions (February 15, 2018), field experiments were conducted that induced liquid water which was allowed to freeze on the permeable and impermeable pavement sections and then subsequently melt during warmer daytime conditions (March 10, 16-17, 2018). Friction and surface temperature measurements were collected throughout the experimental process.
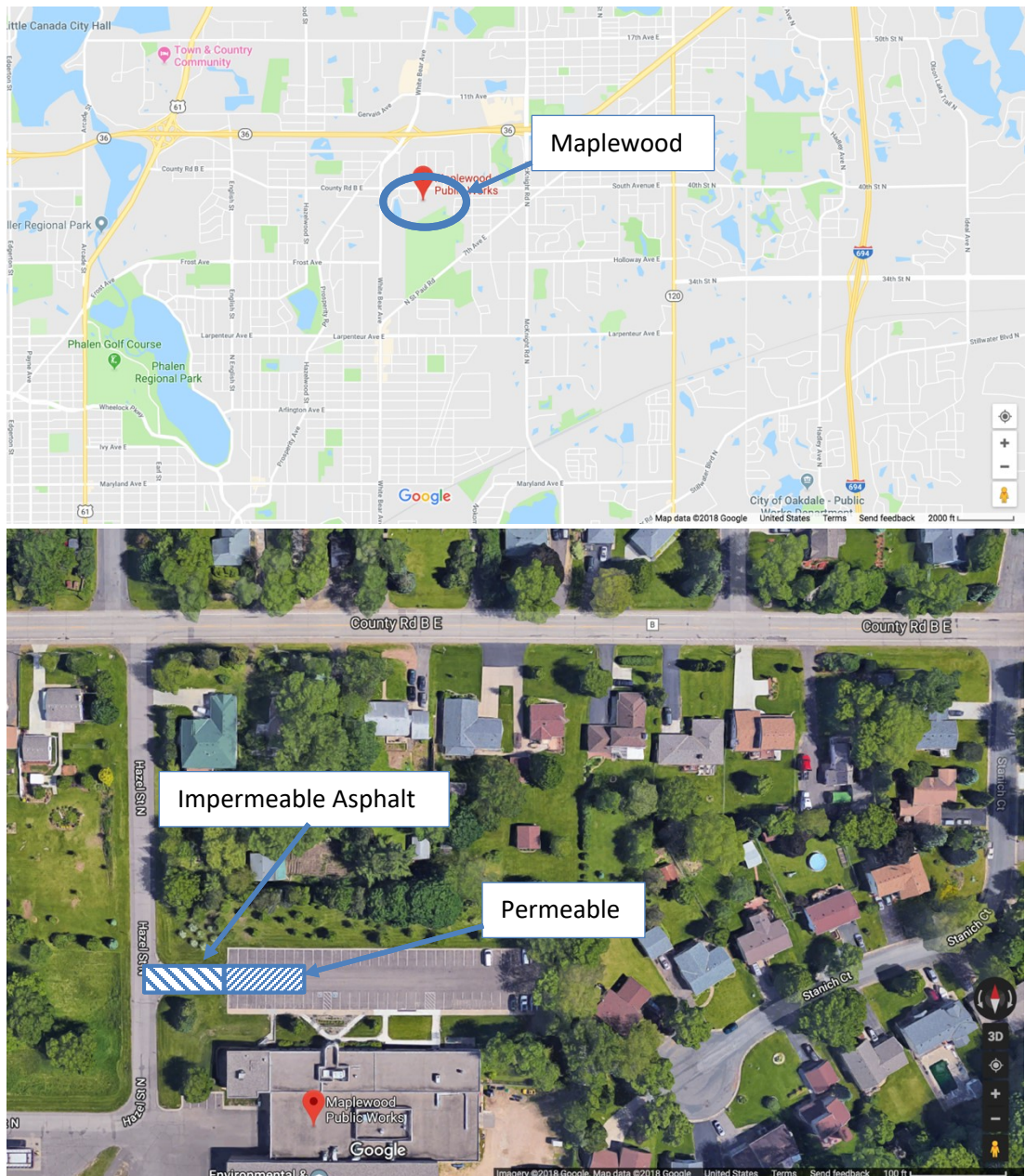
Figure 2.7 Location of Maplewood Public Works Field Site (1902 County Rd B E, Maplewood, MN 55109)

2.3 PERMEABLE PAVEMENT SITE SURVEY

A survey was conducted in January 2018 of local municipalities and at least 44 locations around the Twin Cities Metro Area were identified as possible permeable pavement measurement sites, including locations of permeable asphalt, permeable concrete, and permeable block pavers. These sites were evaluated and 22 were found to be suitable for data collection during winter 2019-2020 (Year 4).

CHAPTER 3: FIELD DATA

3.1 SUMMARY OF RESULTS - YEAR 1 MNROAD

Pictures were captured at MNRoad using the cameras described in Chapter 2 above. The cameras were operated in daytime, nighttime, clear weather, cloudy, snowy, and rainy conditions. The cameras did not always capture images when the air temperature dropped near or below − 20°C (− 4°F), especially during nighttime conditions (due to the use of the infrared flash). Several examples of these photos are shown in Figures 3.1 – 3.5.
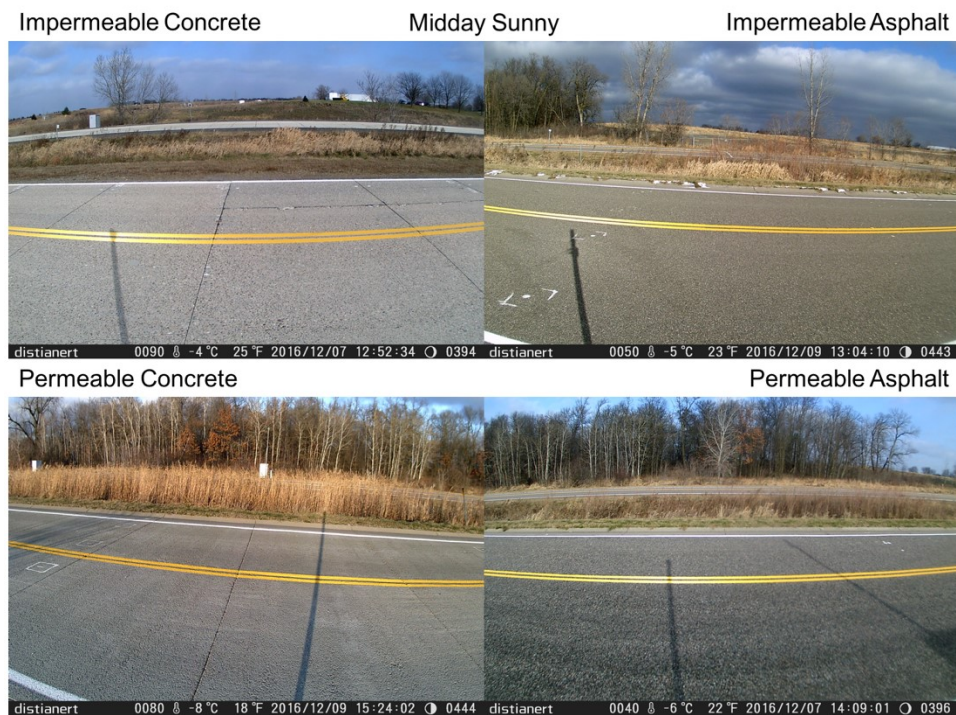
Figure 3.1 Permeable and Impermeable pavements at MNRoad during sunny conditions.
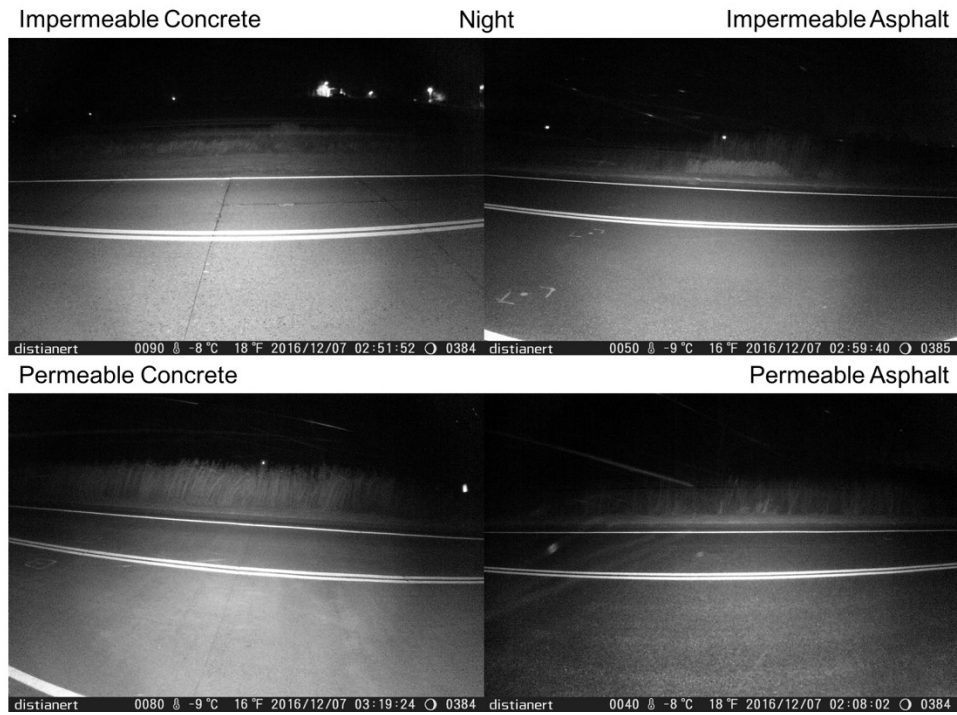
Figure 3.2 Permeable and Impermeable pavements at MNRoad during nighttime conditions.

Figure 3.3 Permeable and Impermeable pavements at MNRoad during light snow conditions.
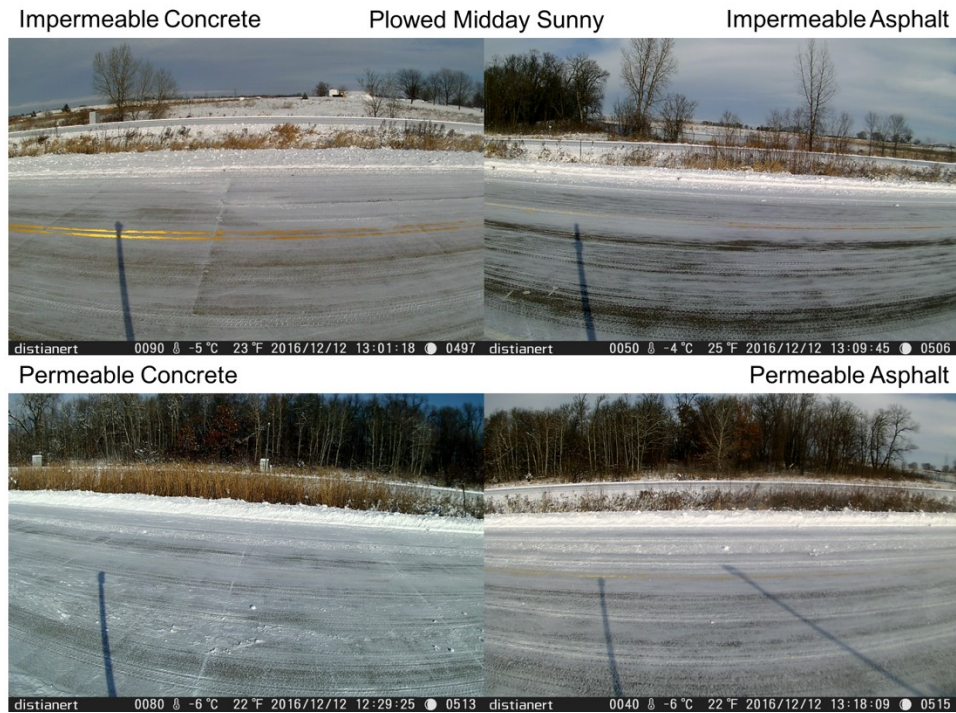
Figure 3.4 Permeable and Impermeable pavements at MNRoad after a snow storm and subsequent plowing.
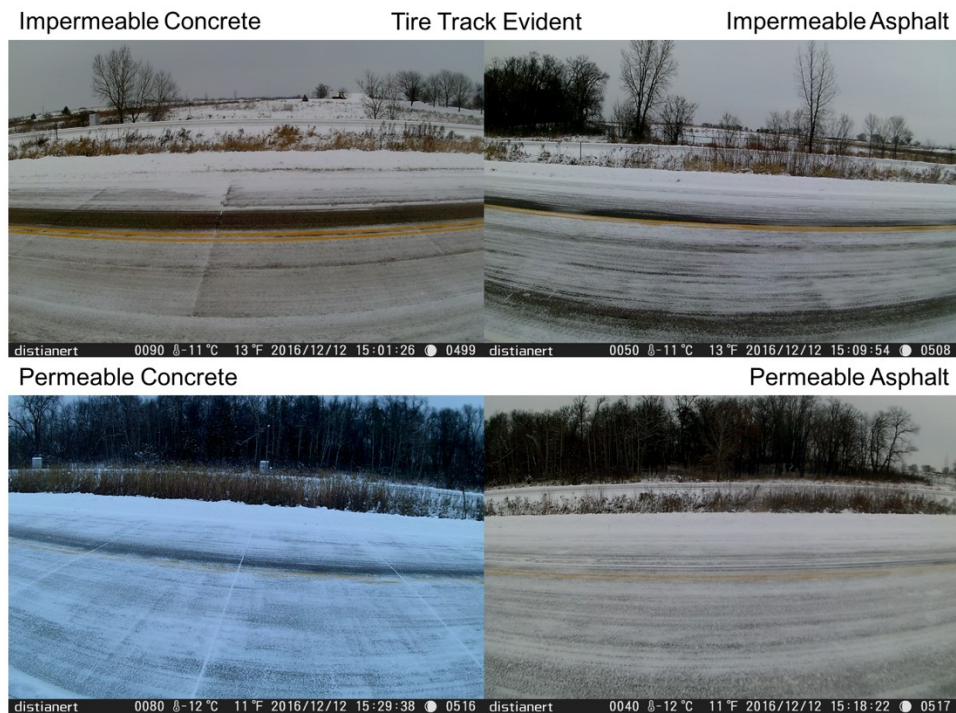
Figure 3.5 Permeable and Impermeable pavements at MNRoad after snow plowing with evidence of a wheel track causing bare pavement (background lane).

Figure 3.6 shows a sample of temperature measurements with the infrared sensors before and during a small snow event in late January. Note the sharp difference in surface temperatures associated with snow cover and removal in one lane (see Figure 3.7 for photos). Note also that Sensor #3 appears to have an offset that was later corrected.
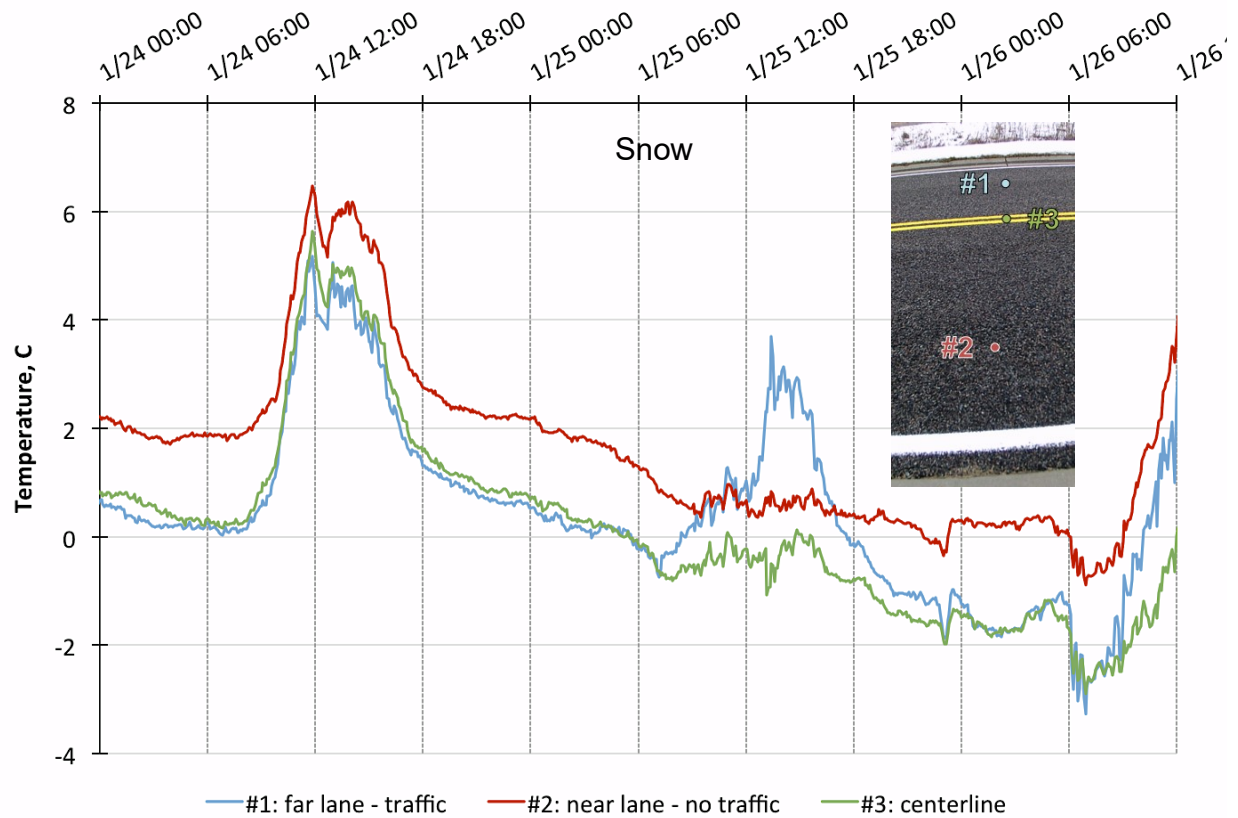
Figure 3.6 Sample infrared temperature data collected at the permeable asphalt site. Snowfall occurred very early during the morning of 1/25, causing a divergence in temperatures (see Figure 3.7 for photos and details).
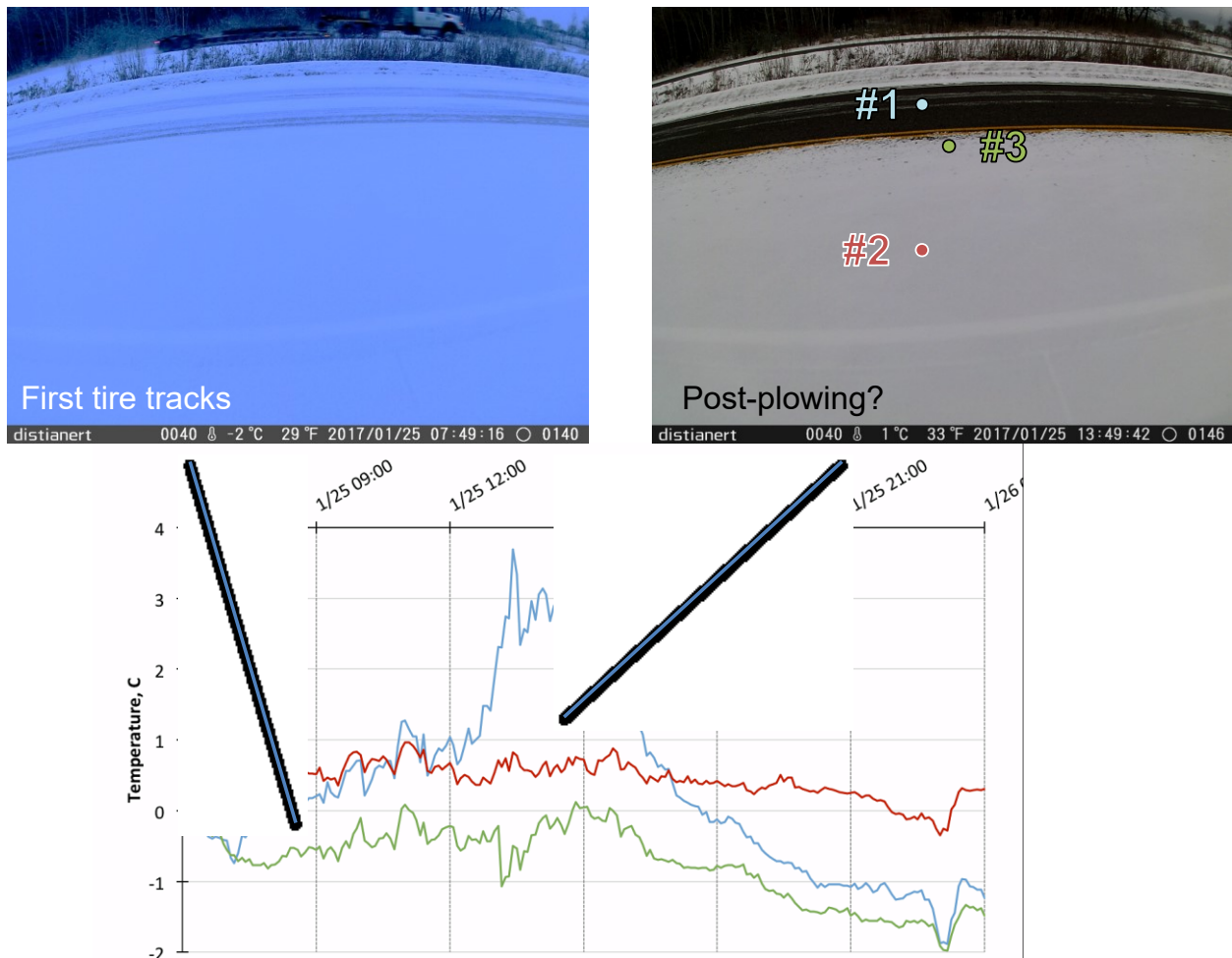
Figure 3.7 Temperature time series on the permeable asphalt test section during a light snow and plow event, measured by infrared temperature sensor aimed at 3 different positions on the pavement. Note the divergence of temperatures at location on bare road (blue, #1) and that near the road centerline covered in snow (green, #3).

3.1.1 Event #1: Jan 25, 2017 (Light Snow)

Very light snowfall occurred during the early morning of Jan 25. See Figure 3.8 for selected photos and infrared temperature time series. Two of the infrared temperature probes (#1 and #3) converge while snow falls, consistent with uniform surface temperature expected when covered with snow -- offset error appears present for Probe #2 (red line in plot), as it does not converge with the other probes. The two good probes (#1 and #3) drop below the 0.5-inch-depth pavement temperature around 7:00 am, at peak snow cover, which may be a pattern consistent with a rapid cooling of the pavement surface from snowfall. The two probes rapidly diverge once snow disappears from the far lane (#1) as the truck makes passes beginning around 8:00 am, with Probe #2 (centerline) tracking the near-surface pavement temperature (0.5-inch depth).
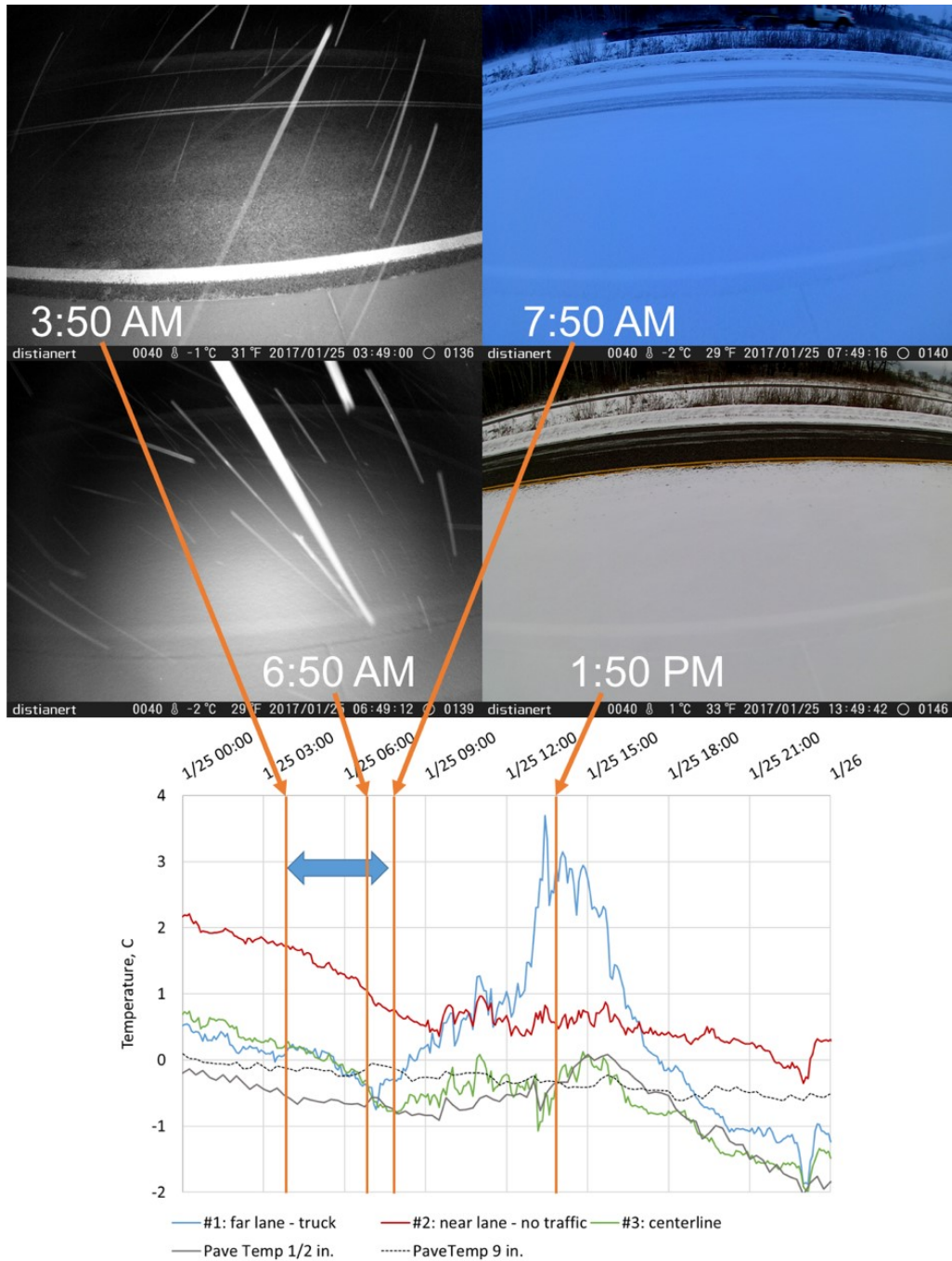
Figure 3.8 Sample infrared temperature data, and selected photos to illustrate surface conditions, collected at the permeable asphalt site. Snowfall occurred very early during the morning of 1/25 (approximate duration indicated by blue arrow). Pave Temp indicates temperature probes below the pavement surface. Photo descriptions: 3:50 AM shows snow falling (white streaks) but no apparent accumulation on the roadway surface; 6:50 AM shows snow falling and snow accumulation on the roadway surface (white coating); 7:50 AM shows snow has ceased (lack of white streaks), snow accumulation on the roadway surface, and tire tracks in the far lane (dark parallel lines).

3.1.2 Event #2: Feb 7, 2017 (Dusting of snow)

Light snowfall occurred around 13:00 on Feb 7, 2017. See Figure 3.9 for selected photos and temperature time series. Offset error again appears present for Probe #2 (red line in plot), as it does not converge with the other probes. Note that the near-surface pavement temperature (0.5-inch depth) is below the IR probe temperatures until snowfall occurs, after which it becomes very similar to IR temperatures measured by Probe #1 and #3. After snow has been blown away and/or melted (around 15:00), the temperature measured by the IR probes decreases rapidly, and becomes less than the temperature measured within the pavement at the 0.5-inch depth.
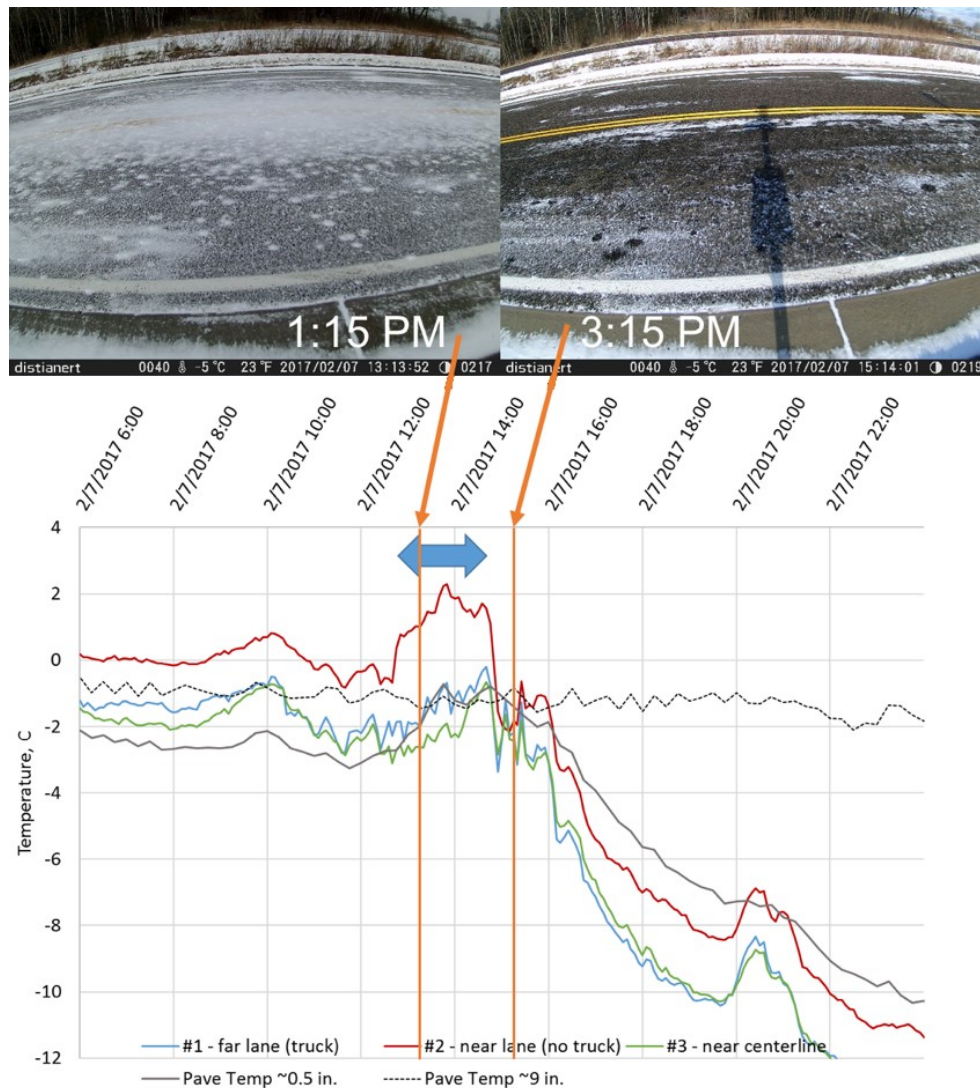
Figure 3.9 Sample infrared temperature data collected at the permeable asphalt site for a dusting of snow around 13:00 on Feb 7, 2017 (approximate duration of cover indicated by blue arrow). Time stamps for photos are 13:13 (left) when snow is visible on the surface and 15:14 (right) when snow is mostly vacant from the surface. Pave Temp indicates temperature probes below the pavement surface.

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3.1.3 Event #3: Mar 12, 2017 (Wet snow)

Relatively heavy, wet snowfall began in late afternoon around 14:00 on Sunday, Mar 12, 2017. Figure 3.10 shows the temperature time series, including air temperature; photos were not available at the time of this writing to illustrate snow coverage. Snow cover can be inferred to exist until early morning of 3/13 (when the truck would have commenced driving on the far lane), from the difference between near-surface pavement temperature (0.5-inch depth) and the surface temperatures measured by the IR sensors, which show sub-zero diurnal fluctuations while the 0.5-inch depth was relatively constant over the interval. More specifically, prior to the snow event, the 0.5-inch depth temperature was similar to that measured by the IR probes, with a slightly lower amplitude (higher than the IR surface temperature at night, lower during the day). This pattern changes with the onset of snowfall and a rapid drop in surface temperature as shown by the IR probes, which does not propagate to the 0.5-inch depth, potentially due to the insulating effect of the snow. Roughly 18 hours later, when snow presumably has melted due to the truck and/or increasing air temperature and sunlight, the temperature time series resume expected dynamics for snow-free pavement.
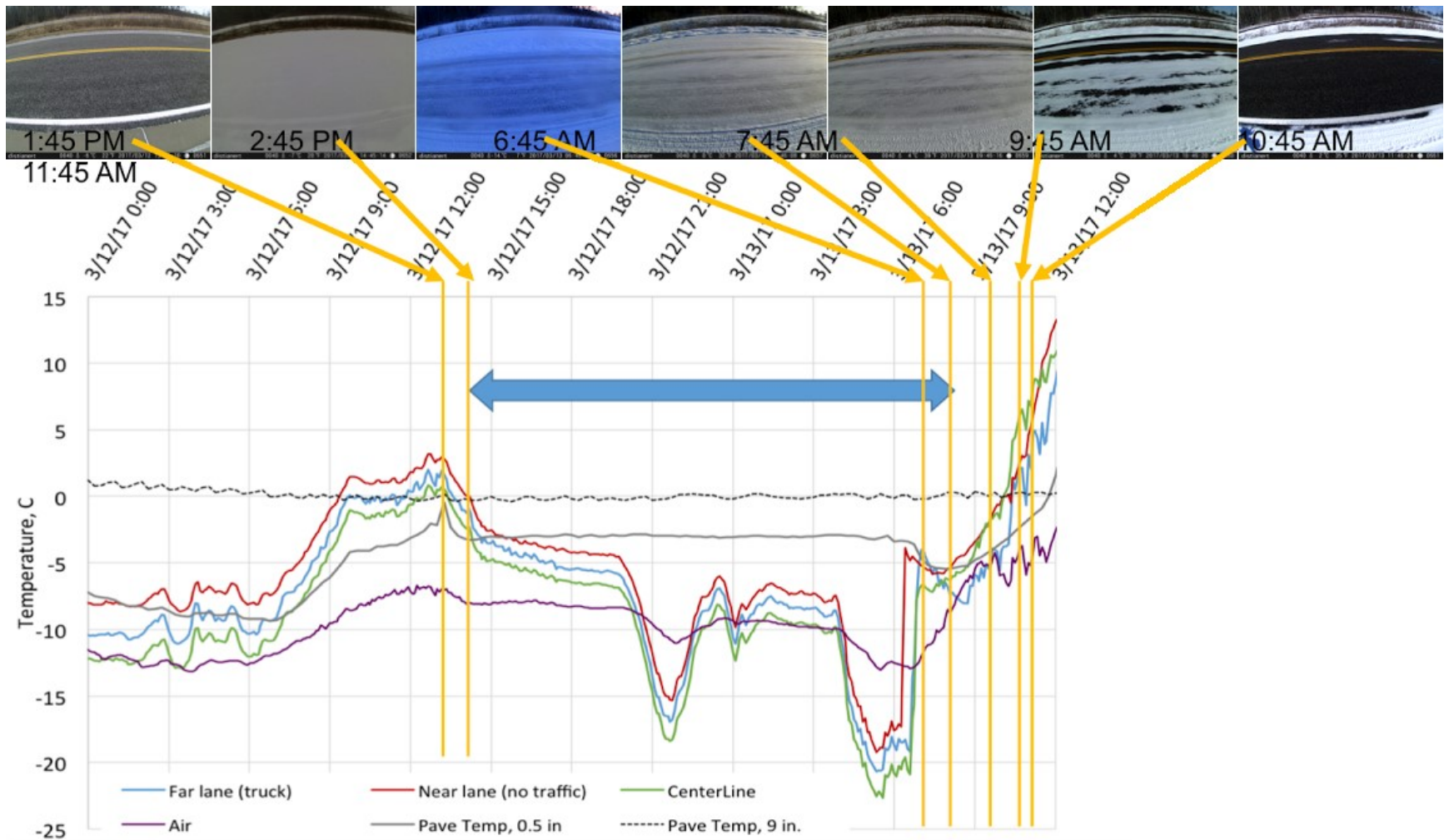
Figure 3.10 Sample infrared temperature data collected at the permeable asphalt site for a wet snow event around 14:00 on Mar 12, 2017 (approximate duration of snow cover, originally inferred from TEMPERATURE data, is indicated by blue arrow). Pave Temp indicates temperature probes below the pavement surface. Photos illustrate clear roadway surface (1:45 PM), snow covering (2:45 PM), snow covering after plowing near lane (6:45 AM), snow covering after plowing both lanes (7:45 am), snow covering in near lane and tire tracks in far lane (9:45 AM), wind-blown snow covering near lane and well-developed tire tracks far lane (10:45 AM), and clear roadway surface (11:45 AM).

3.1.4 Conclusions from Year 1

Photographic, surface temperature, and in-pavement temperature data were collected from December 2016 - March 2017. We learned that photographic data is illustrative and capable of demonstrating when snow is present on the pavement surface but could not adequately distinguish ice from wet pavement. In addition, photographic data must be evaluated manually, which is labor intensive and subjective to the user. The combination of air temperature, surface temperature, and in-pavement temperature were adequate in distinguishing bare pavement from snow and/or ice cover, but often required verification by photographic data. Due to the challenge of predicting the surface conditions based on these parameters, individual sites would likely need to collect this level of detailed data to calibrate a predictive model. Most sites would not be appropriate for installation of photographic data collection equipment or in-pavement surface temperature measurement equipment. Thus, this data collection system is likely only applicable to research projects such as this.

3.2 SUMMARY OF RESULTS - YEAR 2

3.2.1 Robbinsdale Field Site

Temperature dynamics (time series) are shown below for several storm events at the Robbinsdale Field Site.

3.2.1.1 Large Snowfall Event: January 22 – 23, 2018

Roughly one foot of snow fell on the evening of January 22, 2018. Temperature data recorded at the Abbott/41st permeable asphalt site are shown in Figure 3.11 below. Infrared temperature is plotted as the mean of the three probes for simplification of the presentation of the data. The difference between the mean infrared temperature and sub-surface temperature (TC#1, located nearest the surface at a depth of roughly 0.5 in.) appears to give an indication of when snow covered the roadway. The infrared sensors would be recording surface temperature of the snow when it covered the road, which could be much lower than that of the pavement due to radiation and convective heat losses (note the rapid decrease of IR temperature at the onset of snowfall, Jan 22). Snow may also provide temporary insulation for the pavement, preventing it from reaching the much lower temperature of the snowpack (note the nearly constant sub-surface temperature during snowfall). The abrupt change in IR – pavement temperature difference at around 6 am on January 23, which is driven by the sudden change in pavement temperature, likely reflects plowing of snow, which would have exposed the pavement near the thermocouples and allowed the pavement to lose heat to the air. Fluctuation of the temperature difference above and below 0°C is likely evidence of repeated plowing, accumulating snowmelt, and/or blowing snow. Some infiltration of snowmelt could also have caused this pattern, although infiltration performance of this section of permeable pavement was known to be limited.
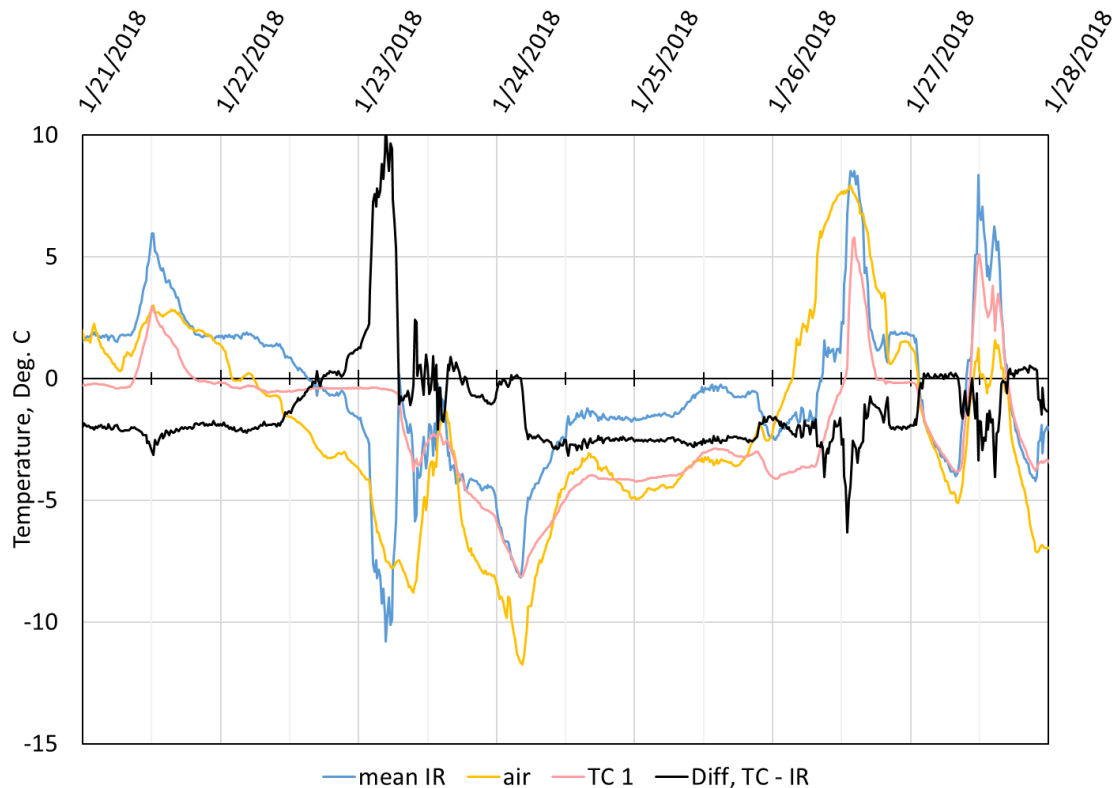
Figure 3.11 Infrared ("Mean IR"), air, and sub-surface thermocouple temperature ("TC 1") data recorded at the Abbott/41st permeable asphalt site during a ~12-inch snowstorm from late evening on Jan 22 through early morning Jan 23, 2018. Data from the three infrared temperature sensors are shown averaged together into a single time series (blue line) to simplify presentation. The sub-surface temperature ("TC 1") is located at a depth of roughly one-half inch below the pavement surface. The black line is the difference between the sub-surface temperature and mean surface IR temperature.

3.2.1.2 Spring snowfall: April 2018

While substantial temperature differences between surface and sub-surface (pavement) might be expected during January, a very snowy April provided an opportunity to investigate surface/pavement temperature dynamics during a warmer period. Figure 3.12 shows the infrared, and pavement (sub-surface thermocouple TC 1) temperature time series for April 1 – April 20, 2018 at the Abbott/41st site. Snowfall recorded at the Minneapolis-St. Paul Airport is shown for reference. Positive differences between the sub-surface (pavement) and infrared surface temperatures ("T Diff" in the plot; black line) again showed the likely presence of snow on the pavement, in particular for a snowstorm on April 3 and during the blizzard on April 14 and 15. Following both storms, pavement temperature (blue line) remained relatively constant (insulated by overlying snow), while the IR surface temperature (orange line) decreased rapidly, although perhaps not as severely as in the January 22 storm (Figure 3.11). Plowing on April 4 may be indicated by the rapid drop in IR-pavement temperature difference; this is less apparent on April 16, but much more snow would have been present at the time. The decrease in

IR-pavement temperature difference on April 16 and April 17, combined with the positive oscillation of the IR temperature likely indicates bare pavement from rapid melting.
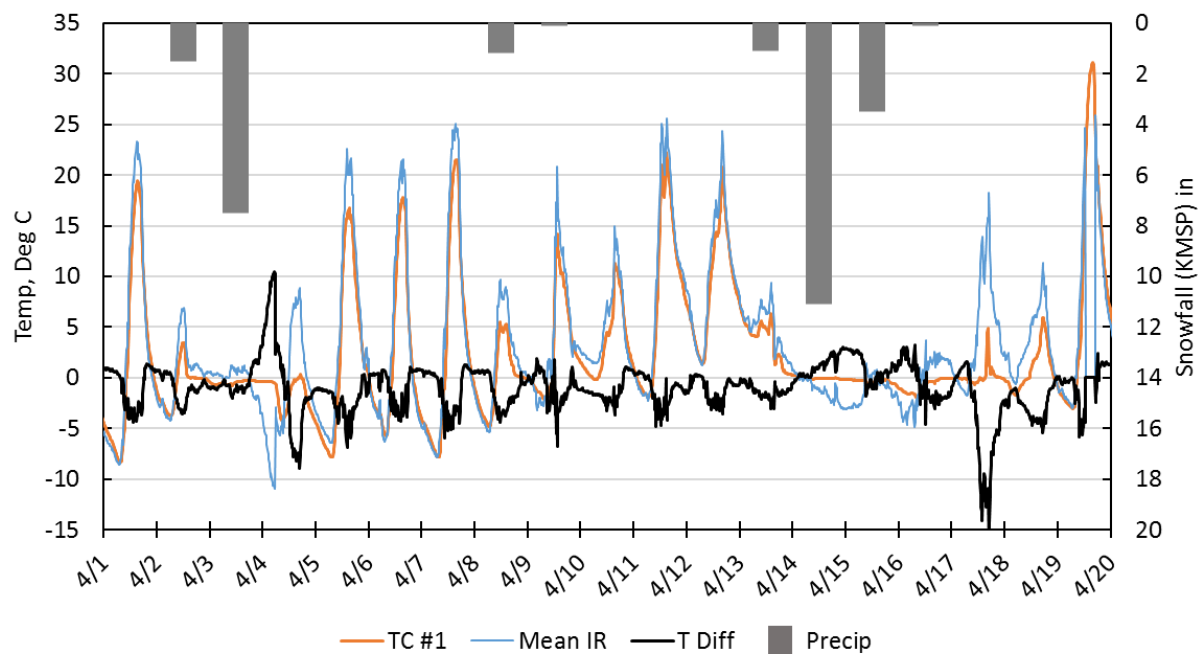
Figure 3.12 Infrared ("Mean IR") and sub-surface thermocouple temperature ("TC #1") data recorded at the Abbott/41st permeable asphalt site from April 4 through April 20, 2018. Data from the three infrared temperature sensors are shown averaged together into a single time series (blue line) to simplify presentation. The sub-surface temperature ("TC 1") is located at a depth of roughly one-half inch below the pavement surface. The black line is the difference between the sub-surface temperature and mean surface IR temperature.

3.2.1.3 Pavement (Thermocouple) - Surface (Infrared) Temperature Difference vs. Snowfall at KMSP

Positive differences between pavement temperature (sub-surface thermocouple at 0.5-inch depth) and infrared (surface) temperature appear to indicate periods when snow or ice cover was present on the roadway at the Abbott/41st site. Figure 3.13 shows a summary of temperature-difference data at the site along with snowfall recorded at the Minneapolis-St. Paul airport (KMSP). Temperature difference is plotted as the number of 15-minute intervals per day in which the pavement – infrared temperature difference exceeded 2.0 °C (likely indicating that the pavement was covered in snow or ice). These temperature "exceedances" tended to occur following snowfall events, as expected. In late February and early March, when very little snowfall occurred, the temperature exceedances may be caused by snowmelt freezing temporarily on the pavement.
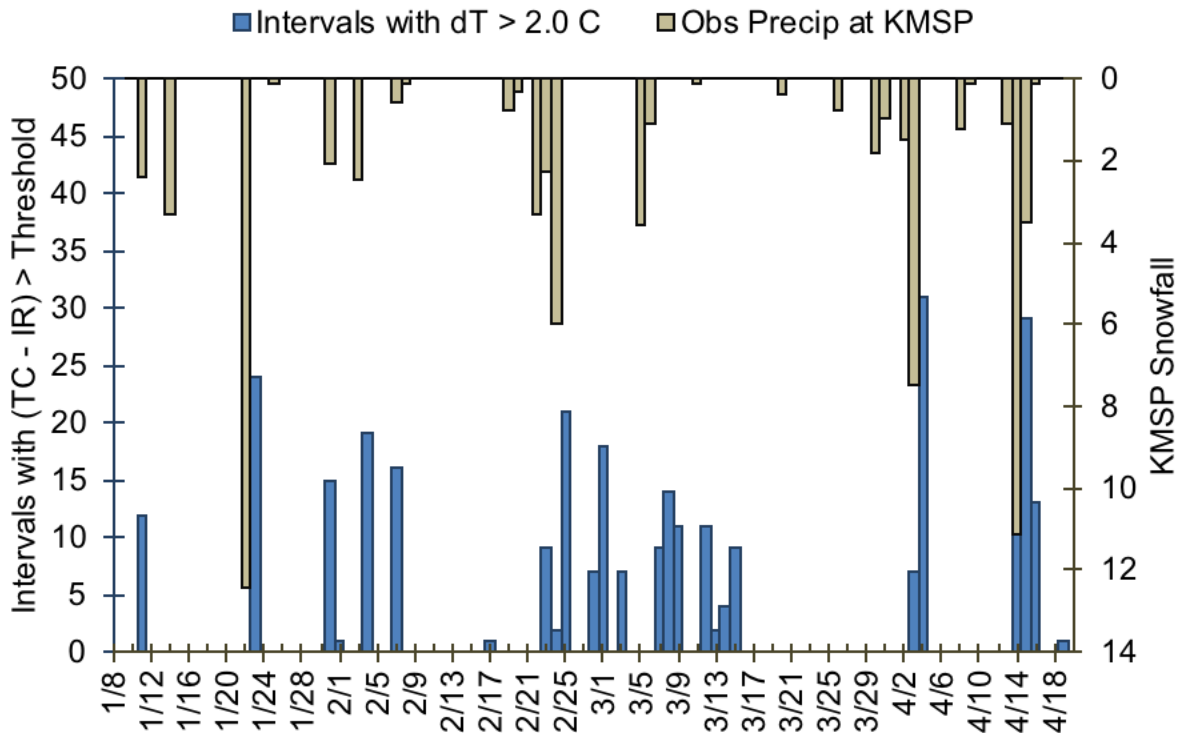
Figure 3.13 Number of measurement intervals per day with a pavement – infrared temperature difference of 2.0 °C or greater during January – April, 2018 at the Abbott/41st site, potentially indicating snow or ice on the road surface. Snowfall observed at the Minneapolis-St. Paul Airport shown for reference.

3.2.2 Maplewood Public Works

A sample of the friction measurement data from an experiment at Maplewood Public Works is shown in Figure 3.14 below. The experiment consisted of visiting the site during freezing conditions (air and pavement surface temp < 0 °C), adding liquid water to the pavement and allowing it to freeze. Once frozen, surface pavement and temperature data were collected for a given area on both the permeable and impermeable (asphalt) pavement sections. Surface temperature data was also collected by the ASFT T2Go and data is visually similar to friction data shown in Figure 3.14.
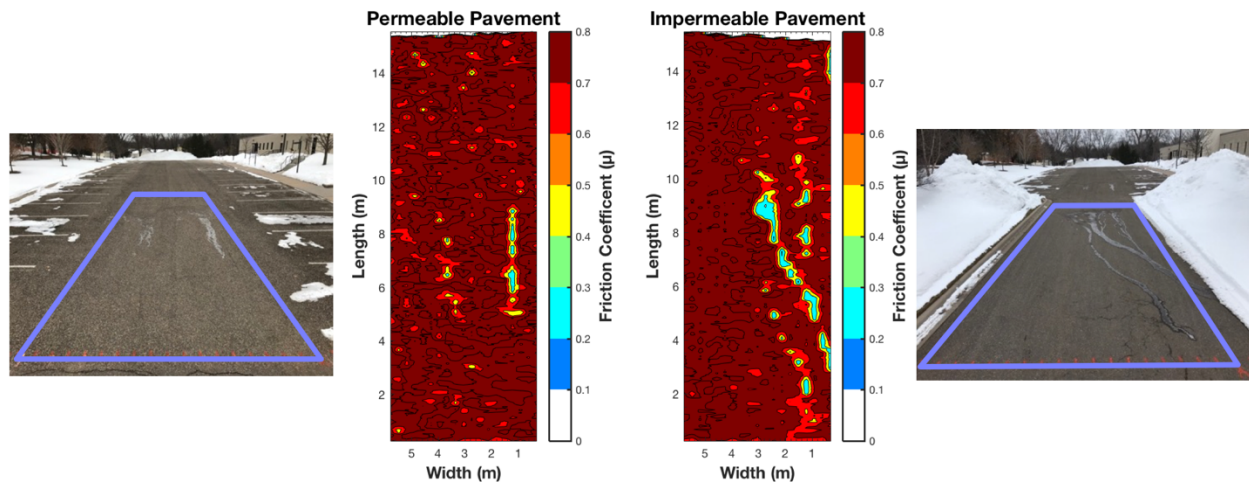
Figure 3.14 Surface friction data collected at Maplewood Public Works Facility on March 10th, 2018. Left picture and graph are for permeable pavement; right picture and graph are for impermeable data.

3.2.3 Conclusions from Year 2

Surface and in-pavement temperature data were collected from December 18-19, 2017 through summer 2018, and pavement surface friction and temperature data were collected at three sites from January 2018 through March 2018. We learned from the surface temperature measurements in conjunction with the in-pavement temperature measurements that the surface conditions of bare pavement can be distinguished from snow or ice cover on the road surface, but the type of covering (snow, ice, frost, etc.) is challenging to discern. Surface and in-pavement temperature measurements alone may not be sufficient to predict surface conditions. The surface friction measurements were found to be a direct measurement of the surface conditions as they related to vehicle and pedestrian traction. Regardless of the type of pavement covering (snow, ice, frost, etc.), the friction measurements characterized whether the surface was slippery or not. From this, we've concluded that surface friction measurements are the best method for comparing the performance of permeable pavement to impermeable pavement for this project.

3.3 YEAR 4 - MULTIPLE SITES EXISTING CONDITIONS

Of the sites identified in the permeable pavement site survey (section 2.3 above), 22 sites were evaluated using the ASFT T2Go portable friction tester for the existing conditions at the site on the day of measurement. Those sites are presented below in alphabetical order. Friction data is presented as 11 transects in the pathwise direction spread evenly across the sections of pavement measured at each site. Transects were numbered from 1 to 11, increasing from left to right in every photo except for the site in Inver Grove Heights (Figure 3.23 and 3.24), Mahtomedi Public Works (Figure 3.29). The T2Go was pushed from bottom to top in every picture (right to left for Inver Grove Heights, Figures 3.23 and 3.24; background for foreground for Mahtomedi Public Works, Figure 3.29) and thus distance in the pathwise direction is measured from zero to the length of the transect. Pavement surface temperature was measured, when possible, by the T2Go. When possible, the air temperature is provided by the National

Weather Service mobile app and the T2Go onboard air temperature sensor. The T2Go onboard did not always report air temperature, however. In general, friction and surface temperature were measured at on a 10ft x 10ft (3m x 3m) portion of the impermeable and permeable pavement.

3.3.1 Blaine Fire Department

The Blaine Fire department building in Blaine, MN has a permeable asphalt section located in a turnaround portion of their parking lot. Friction and surface temperature were measured on a 10ft x 10ft (3m x 3m) portion of permeable section and a 10ft x 10ft (3m x 3m) portion of the impermeable asphalt immediately adjacent to the permeable section, as shown in Figures 3.15 and 3.16.

Impermeable Pavement

Figure 3.15 Surface friction, surface temperature, air temperature, and photo of testing space for Impermeable Pavement at Blaine Fire Department.

Permeable Pavement

Figure 3.16 Surface friction, surface temperature, air temperature, and photo of testing space for Permeable Pavement at Blaine Fire Department.

When comparing the friction, the impermeable section has more friction (average μ = 1.18) and warmer surface temperature (average T = 7.43°C) compared to the permeable pavement (average μ = 0.39, average T = -0.29°C). The photos illustrate that the permeable section has snow and ice cover while the impermeable section does not. This accounts for the temperature difference because the snow and ice on the pavement surface are typically at or below the air temperature (-1 < T air < 1°C) while bare pavement during sunny days are typically warmer than air temperature due to absorption of solar radiation. The presence of snow and ice on the surface also explains the difference in surface friction. The amount and roughness of the snow and ice on the permeable pavement surface was such that the friction (average μ = 0.39) exceed the manufacturer recommendations for caution (μ < 0.35).

3.3.2 Blaine Lakeside Commons Park

The Blaine Lakeside Commons Park in Blaine, MN has several parking stalls that are permeable interlocking paver blocks. Friction and surface temperature were measured on a 10ft x 10ft section covering approximately 2/3rds of one stall and a 10ft x 10ft section of a nearby impermeable asphalt parking stall, as shown in Figures 3.17 and 3.18.

Impermeable Pavement

Figure 3.17 Surface friction, surface temperature, air temperature, and photo of testing space for Impermeable Pavement at Blaine Lakeside Commons Park.

Permeable Pavement

Figure 3.18 Surface friction, surface temperature, air temperature, and photo of testing space for Permeable Pavement at Blaine Lakeside Commons Park.

When comparing the friction, the impermeable section has similar friction (average μ = 1.17) and surface temperature (average T = -1.12°C) compared to the permeable pavement (average μ = 1.18, average T = -1.54°C). The photos illustrate that the permeable and impermeable sections have bare pavement throughout, except for a small portion in the top right section of the impermeable asphalt section. The ice in this section is evident from the friction data in Figure 3.17, as shown by transects 9, 10, and 11 which all decrease in friction at distances of 2 - 3 meters. Transects 9 and 10 decrease to nearly μ = 0.2), which is below the manufacturer recommendation for unsafe pedestrian travel (μ < 0.25).

3.3.3 Blaine Public Works Facility

The Blaine Public Works Facility in Blaine, MN has several parking stalls that are permeable concrete. Friction and surface temperature were measured on a 10ft x 10ft section covering approximately 2/3[rds] of one stall and a 10ft x 10ft section of immediately adjacent impermeable asphalt parking stall, as shown in Figures 3.19 and 3.20.

Impermeable Pavement

Figure 3.19 Surface friction, surface temperature, air temperature, and photo of testing space for Impermeable Pavement at Blaine Public Works Facility.

Permeable Pavement

Figure 3.20 Surface friction, surface temperature, air temperature, and photo of testing space for Permeable Pavement at Blaine Public Works Facility.

When comparing the friction, the impermeable section (Figure 3.19) has more friction (average μ = 1.36) and warmer surface temperature (average T = 5.93°C) compared to the permeable pavement (average μ = 1.01, average T = 3.98°C). For the purposes of this report, friction values of $\mu \geq 1$ are considered to have the same level of friction. The photos illustrate that the permeable and impermeable sections have bare pavement throughout, and friction values exceed manufacturer recommendations for safe pedestrian travel ($\mu < 0.35$). The difference in temperature (impermeable average T = 5.93°C vs. permeable average T = 3.98°C) can be explained by the difference in pavement color. The permeable concrete is lighter in color compared to impermeable asphalt, and thus likely absorbs less solar radiation.

3.3.4 Falcon Heights City Hall

The Falcon Heights City Hall in Falcon Heights, MN has several a section of permeable asphalt in one entrance. Friction and surface temperature were measured on a 10ft x 10ft section of the permeable asphalt and a 10ft x 10ft section of immediately adjacent impermeable asphalt drive lane, as shown in Figures 3.21 and 3.22.

Impermeable Pavement

Figure 3.21 Surface friction, surface temperature, air temperature, and photo of testing space for Impermeable Pavement at Falcon Heights City Hall.

Permeable Pavement

Figure 3.22 Surface friction, surface temperature, air temperature, and photo of testing space for Permeable Pavement at Falcon Heights City Hall.

When comparing the friction, the impermeable section has more friction (average $\mu = 0.70$) and cooler surface temperature (average T = -0.12°C) compared to the permeable pavement (average $\mu = 0.55$, average T = 0.44°C). The photos illustrate that both the permeable and impermeable sections have some snow and ice on the surface, though the permeable has visibly more snow and ice. The ice in both sections is evident from the friction data in Figures 3.21 and 3.22, as shown by several transects that decrease in friction to values of approximately $\mu = 0.2$. Friction values below ($\mu < 0.25$) are categorized as unsafe for pedestrian travel according to the manufacturer recommendations. Surface temperatures in both the permeable and impermeable are approximately equal to each other and the ambient air temperature during testing. This suggests that solar radiation was not important for this site at this time. As shown in the photos, pavements are both asphalt of approximately the same color and the measurements were collected on an overcast, cloudy day and thus solar radiation was likely minimal.

3.3.5 Inver Grove Heights, Target Parking Lot

A Target store in Inver Grove Heights, MN has several sections of their parking lot as permeable asphalt, surrounded by impermeable asphalt. Friction and surface temperature were measured on a 10ft wide x 18ft long section covering approximately one stall in both the permeable and impermeable asphalt sections, as shown in Figures 3.23 and 3.24.

Impermeable Pavement

Figure 3.23 Surface friction, surface temperature, air temperature, and photo of testing space for Impermeable Pavement at Inver Grove Heights, Target parking lot. Impermeable section in the foreground, permeable section in the background. T2Go path from distance = 0m on the right to distance = 5.5m on the left.

Permeable Pavement

Figure 3.24 Surface friction, surface temperature, air temperature, and photo of testing space for Permeable Pavement at Inver Grove Heights, Target parking lot. T2Go path from distance = 0m on the right to distance = 5.5m on the left.

When comparing the friction, the impermeable section has more friction (average μ = 0.92) and warmer surface temperature (average T = 1.72°C) compared to the permeable pavement (average μ = 0.72, average T = 0.05°C). The photos illustrate that both the permeable and impermeable sections have some snow and ice on the surface, though the permeable has visibly more snow and ice. The ice in both sections is evident from the friction data in Figures 3.23 and 3.24, as shown by several transects that decrease in friction to values of approximately μ = 0.2. Friction values below (μ < 0.25) are categorized as unsafe for pedestrian travel according to the manufacturer recommendations. Surface temperatures in both the permeable and impermeable are approximately equal to each other and the ambient air temperature during testing. This suggests that solar radiation was not important for this site at this time. As shown in the photos, pavements are both asphalt of approximately the same color and the measurements were collected on an overcast, cloudy day and thus solar radiation was likely minimal.

3.3.6 Mahtomedi Century College

Century College in Mahtomedi, MN has several sections of their parking lot as permeable asphalt, surrounded by impermeable asphalt. Friction and surface temperature were measured on a 10ft x 10ft section covering approximately 2/3^{rds} of one stall in both the permeable and impermeable asphalt sections, as shown in Figures 3.25 and 3.26.
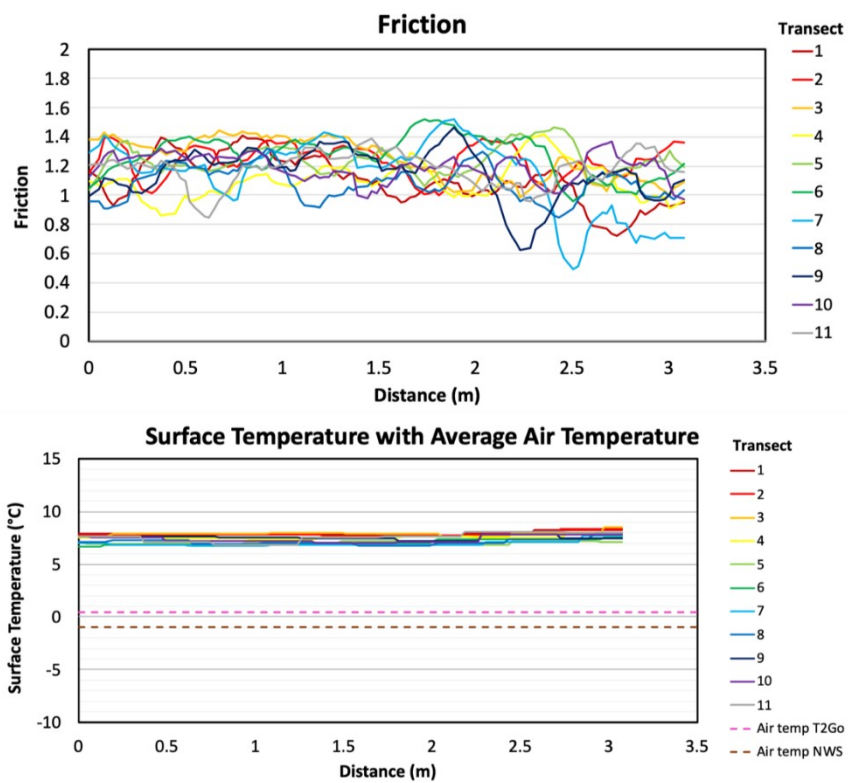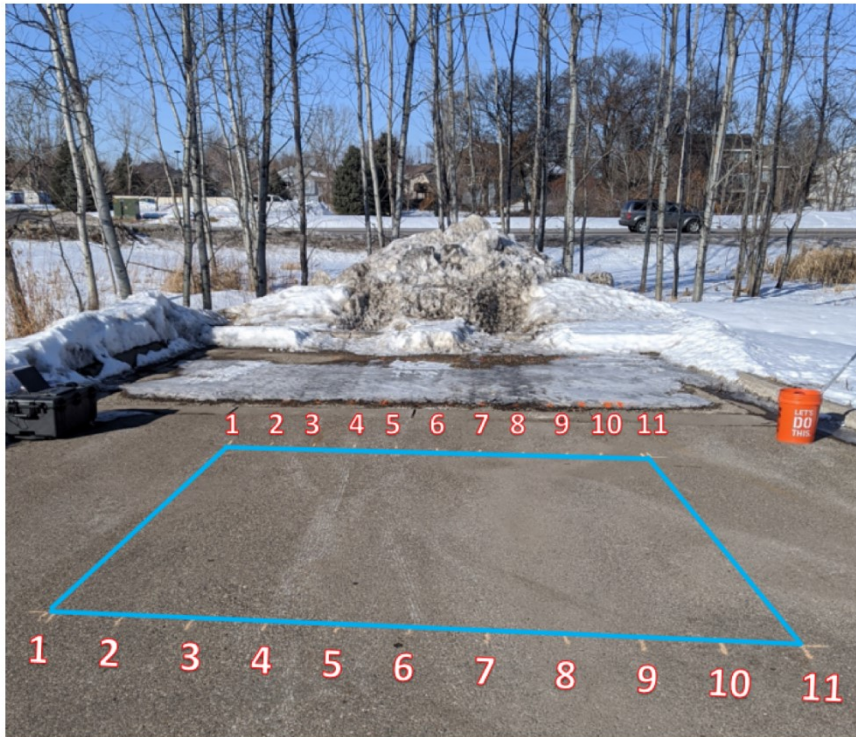
Impermeable Pavement

Figure 3.25 Surface friction, surface temperature, air temperature, and photo of testing space for Impermeable Pavement at Mahtomedi Century College.

Permeable Pavement

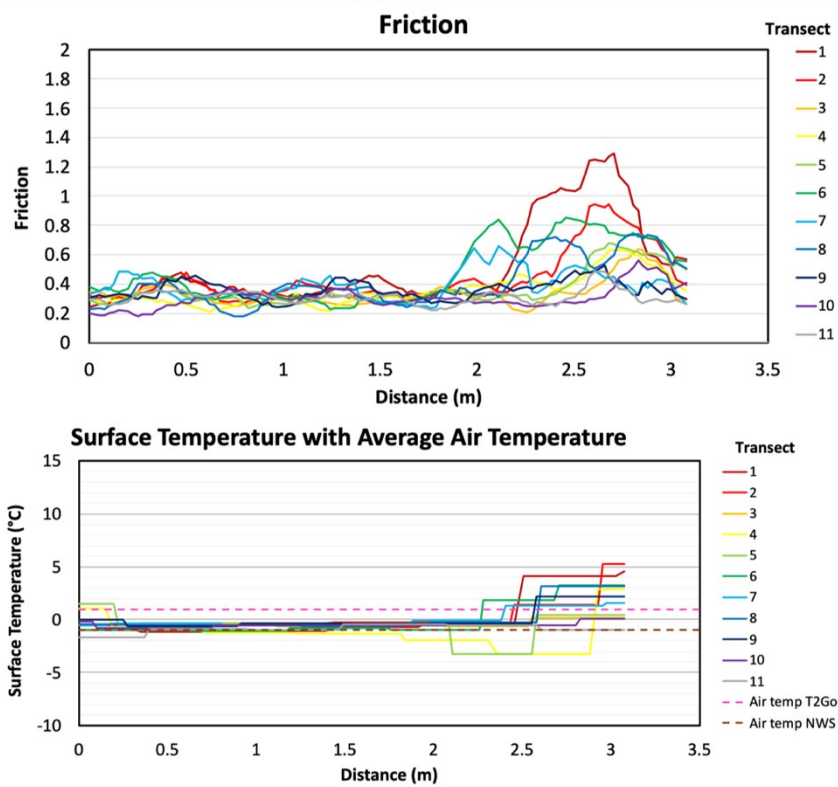**Figure 3.26 Surface friction, surface temperature, air temperature, and photo of testing space for Permeable Pavement at Mahtomedi Century College.**

When comparing the friction, the impermeable section has more friction (average μ = 1.23) and cooler surface temperature (average T = 3.82°C) compared to the permeable pavement (average μ = 1.02, average T = 4.74°C). For the purposes of this report, friction values of $\mu \geq 1$ are considered to have the same level of friction. The photos illustrate that the permeable and impermeable sections have bare pavement throughout, and friction values exceed manufacturer recommendations for safe pedestrian travel ($\mu < 0.35$). The difference in temperature (impermeable average T = 3.82°C vs. permeable average T = 4.74°C) can be explained by the difference in pavement color. The permeable concrete is darker in color compared to impermeable asphalt, and thus likely absorbs more solar radiation.

3.3.7 Mahtomedi District Education Center

The District Education Center in Mahtomedi, MN has several parking stalls constructed of interlocking concrete block pavers with the rest of the parking lot constructed of impermeable asphalt. Friction and surface temperature were measured on a 10ft x 10ft section covering approximately 2/3^{rds} of one stall in both the permeable and impermeable asphalt sections, as shown in Figures 3.27 and 3.28.

Impermeable Pavement

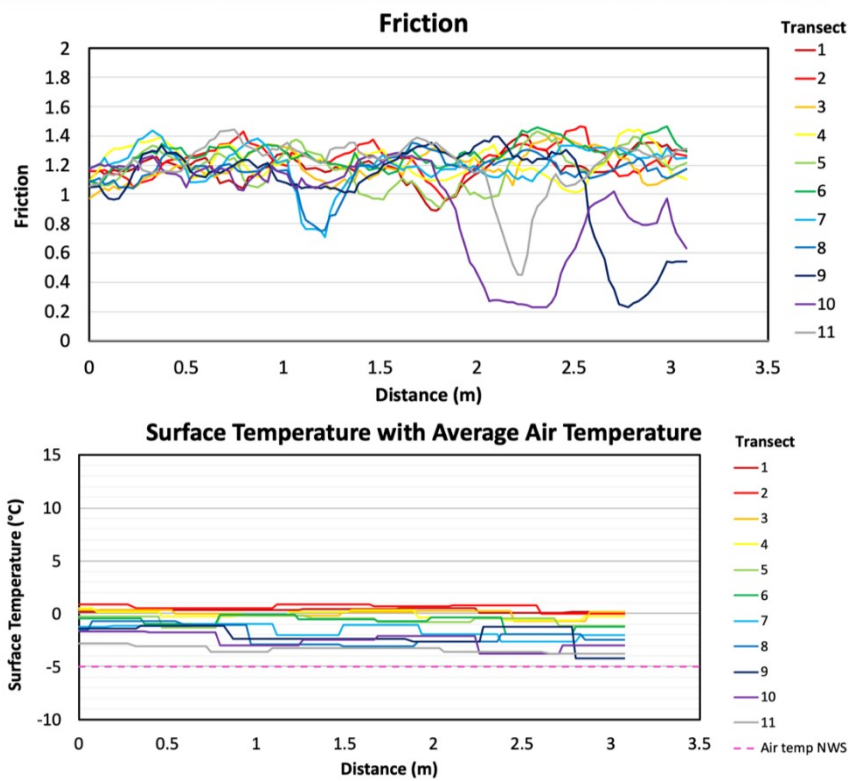**Figure 3.27 Surface friction, surface temperature, air temperature, and photo of testing space for Impermeable Pavement at Mahtomedi District Education Center.**
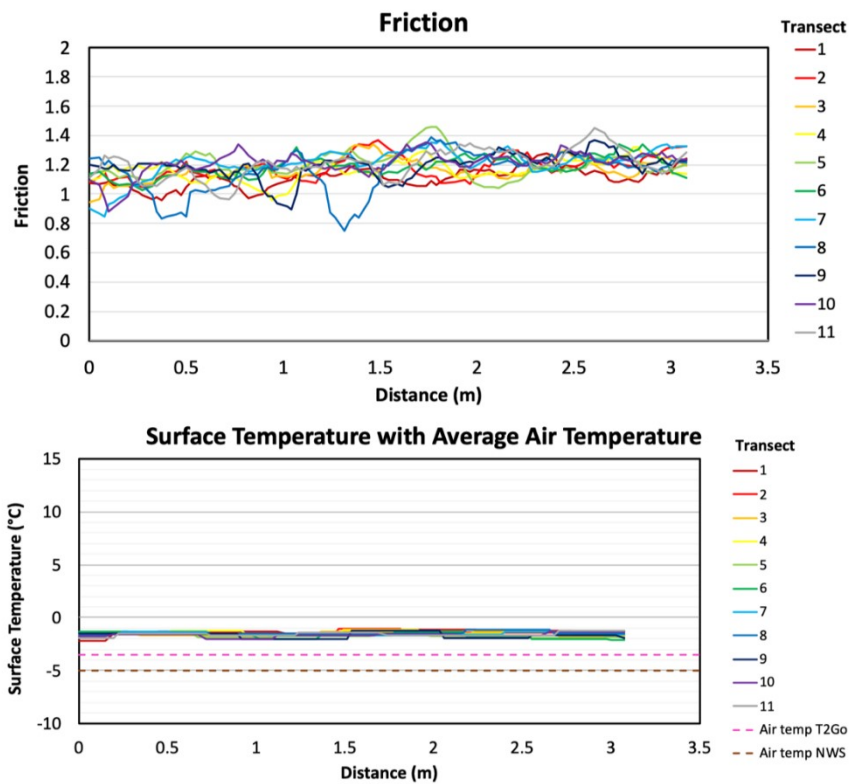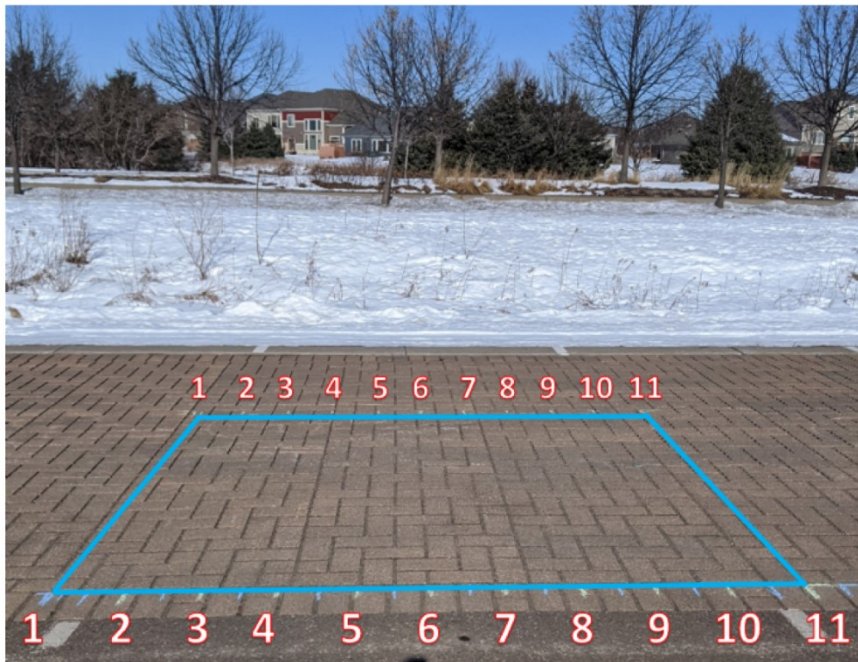
Permeable Pavement

Figure 3.28 Surface friction, surface temperature, air temperature, and photo of testing space for Permeable Pavement at Mahtomedi District Education Center.

When comparing the friction, the impermeable section has more friction (average μ = 0.61) and warmer surface temperature (average T = -0.34°C) compared to the permeable pavement (average μ = 0.39, average T = -2.50°C). The photos illustrate that both the permeable and impermeable sections have some snow and ice on the surface, though the permeable has visibly more snow and ice. The ice in both sections is evident from the friction data in Figures 3.27 and 3.28, as shown by several transects that decrease in friction to values of approximately μ = 0.2. Friction values below (μ < 0.25) are categorized as unsafe for pedestrian travel according to the manufacturer recommendations. The difference in temperature (impermeable average T = -0.34°C vs. permeable average T = -2.5°C) can be explained by the difference in pavement color. The permeable interlocking concrete paver blocks are lighter in color compared to impermeable asphalt, and thus likely absorbs less solar radiation. This is supported by the observation that the permeable block pavers are similar in temperature as the ambient air temperature whereas the impermeable asphalt is warmer than the ambient air temperature.

3.3.8 Mahtomedi Public Works

The Mahtomedi Public Works Facility in Mahtomedi, MN has several permeable asphalt parking stalls, surrounded by impermeable asphalt. Friction and surface temperature were measured on a 10ft x 10ft section covering approximately 2/3^{rds} of one stall in the permeable asphalt and a 10ft x 10ft portion of the impermeable asphalt unused surface, because all of the parking stalls in the impermeable asphalt were occupied, as shown in Figures 3.29 and 3.30.
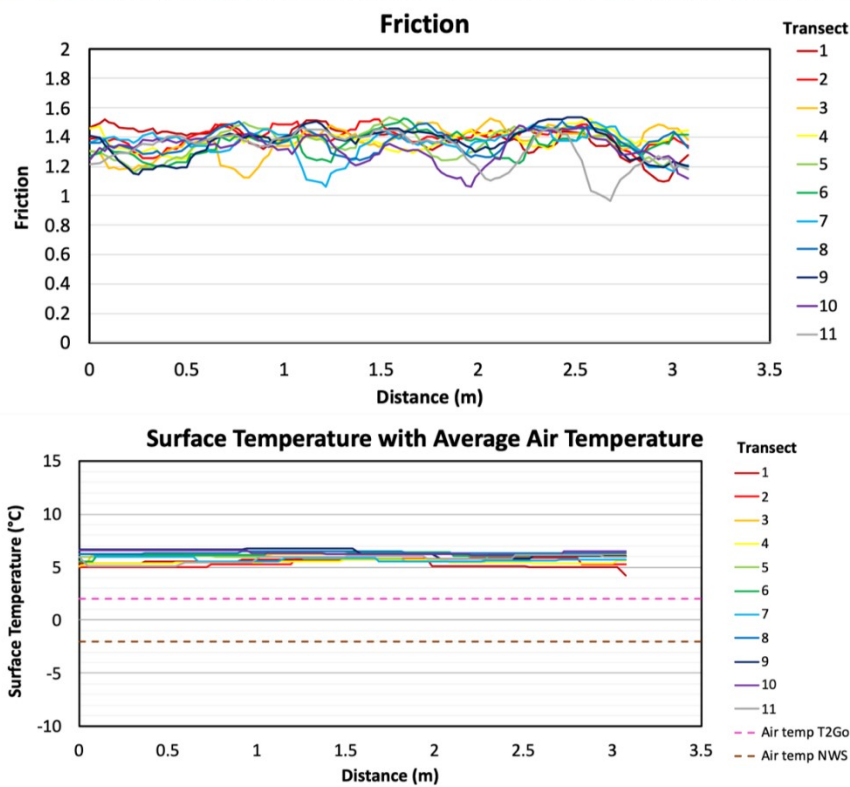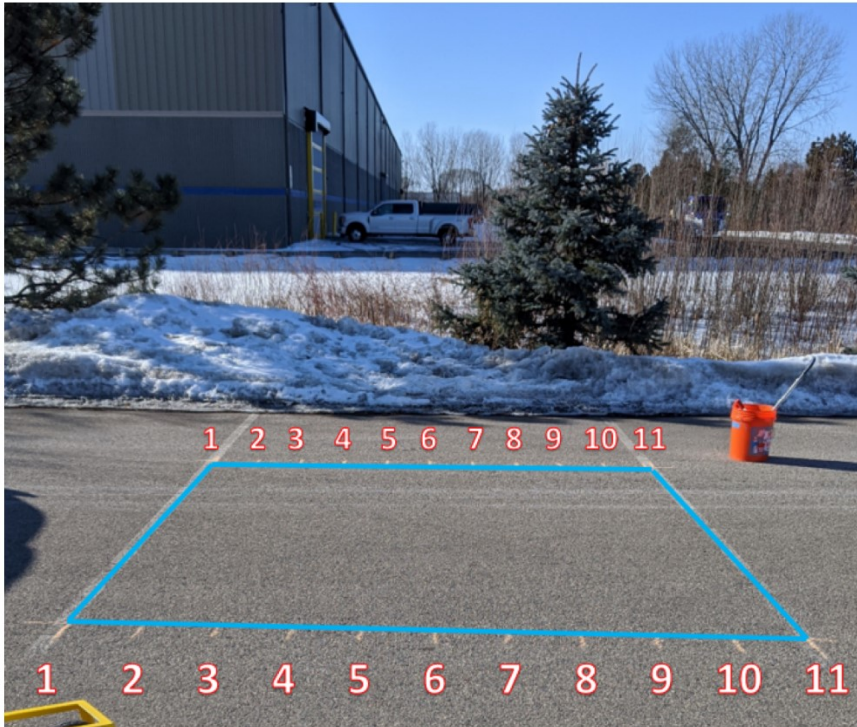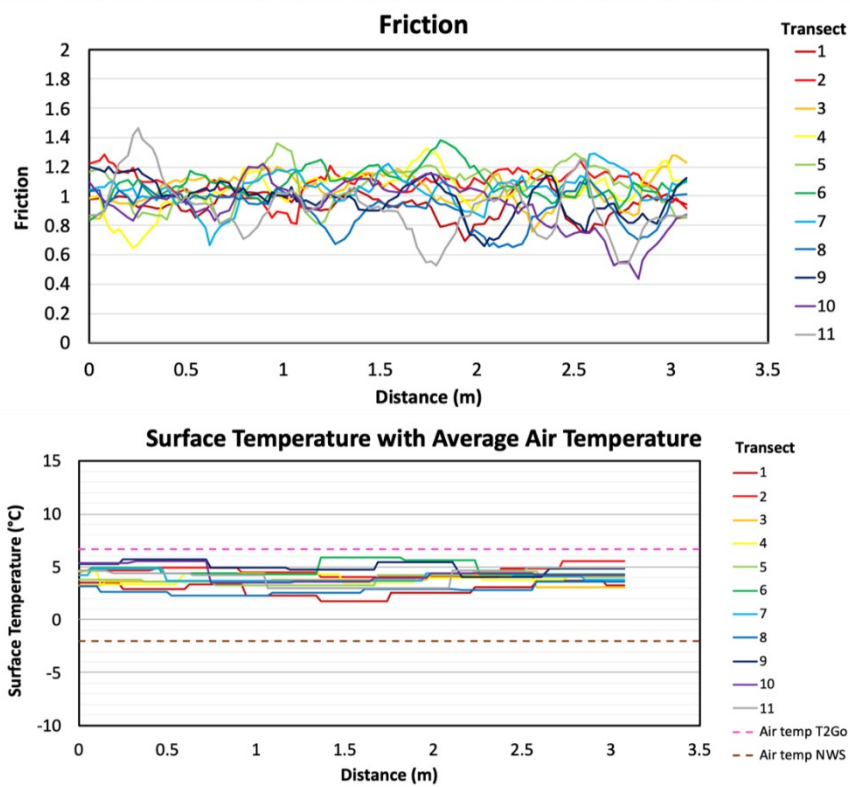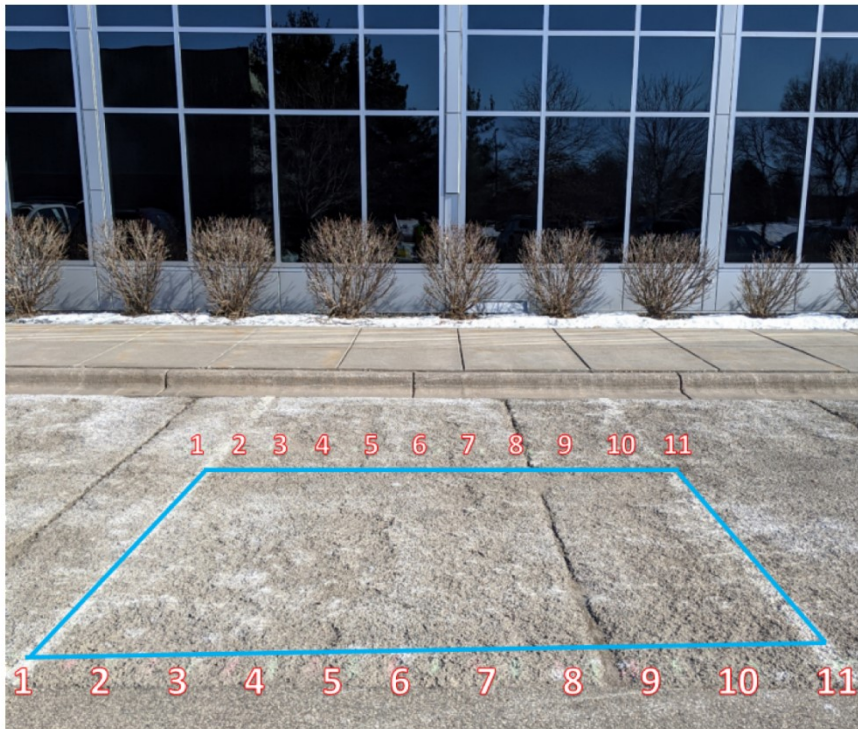
Impermeable Pavement

Figure 3.29 Surface friction, surface temperature, air temperature, and photo of testing space for Impermeable Pavement at Mahtomedi Public Works Facility. T2Go path from distance = 0m in the background of the photo to distance = 3m in the foreground of the photo.

Permeable Pavement
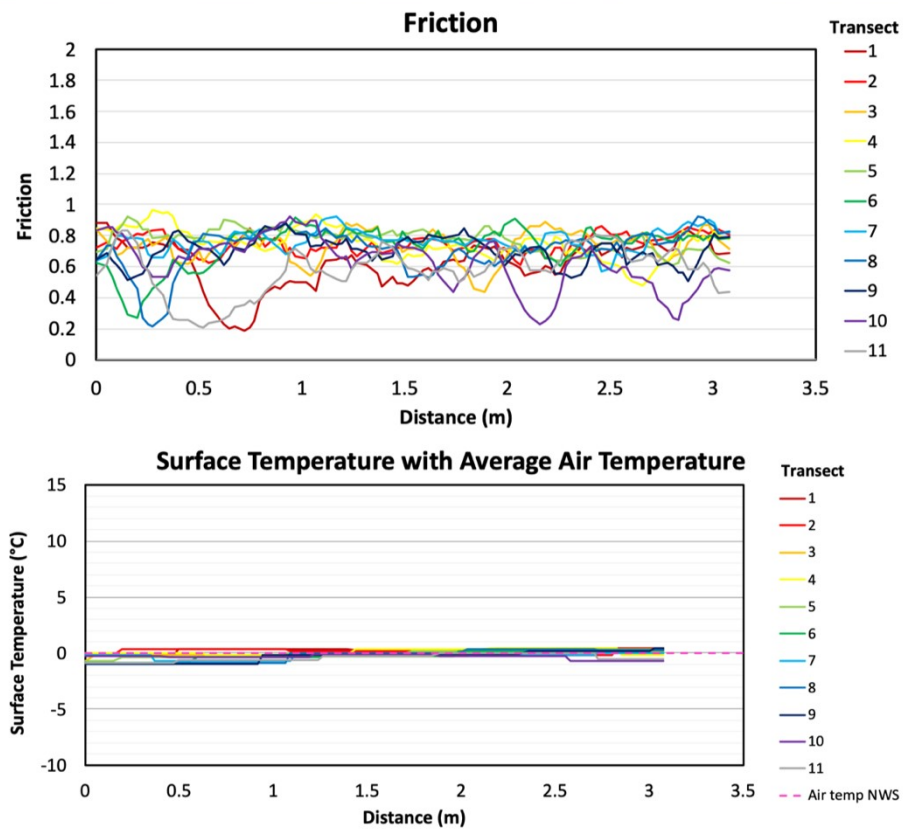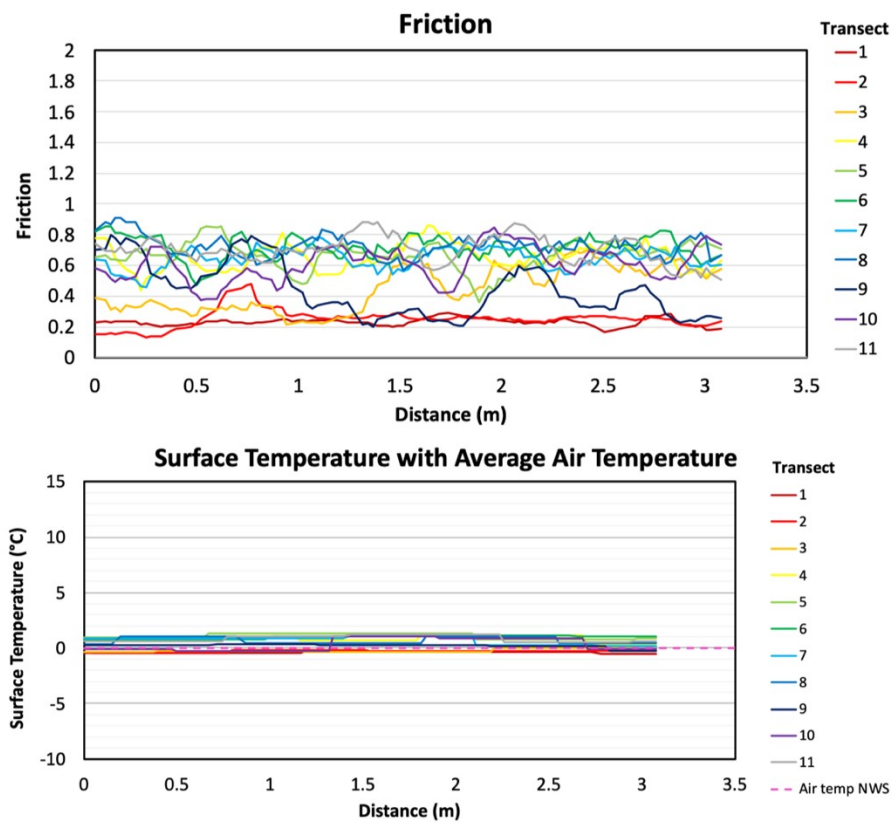

Figure 3.30 Surface friction, surface temperature, air temperature, and photo of testing space for Permeable Pavement at Mahtomedi Public Works Facility.

When comparing the friction, the impermeable section has more friction (average μ = 0.94) and cooler surface temperature (average T = 1.46°C) compared to the permeable pavement (average μ = 0.75, average T = 3.23°C). The photos illustrate that both the permeable and impermeable sections have some snow and ice on the surface, though the permeable has visibly more snow and ice. The ice in both sections is evident from the friction data in Figures 3.29 and 3.30, as shown by several transects that decrease in friction to values of approximately μ = 0.2. Friction values below (μ < 0.25) are categorized as unsafe for pedestrian travel according to the manufacturer recommendations. The difference in temperature (impermeable average T = 1.46°C vs. permeable average T = 3.23°C) can be explained by the difference in shading. The permeable asphalt is in full sunlight compared to impermeable asphalt which has partial shade from trees. Thus, the impermeable likely absorbs less solar radiation due to shading. This is supported by the observation that the permeable asphalt is warmer than the ambient air temperature whereas the impermeable asphalt is roughly equivalent to the ambient air temperature.

3.3.9 Mahtomedi Universalist Church

The Mahtomedi White Bear Universalist Church in Mahtomedi, MN has several permeable asphalt parking stalls, surrounded by impermeable asphalt. Friction and surface temperature were measured on a 10ft x 10ft section covering approximately 2/3^{rds} of one stall in each of the permeable and asphalt impermeable asphalt areas, as shown in Figures 3.31 and 3.32.

Impermeable Pavement

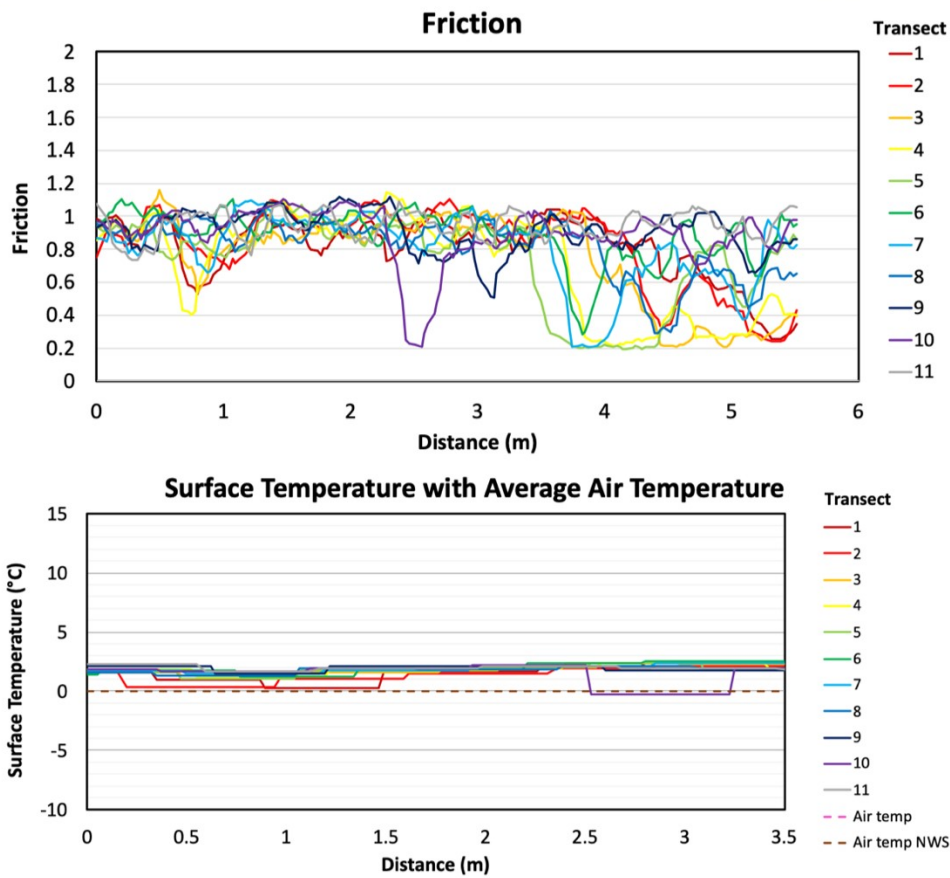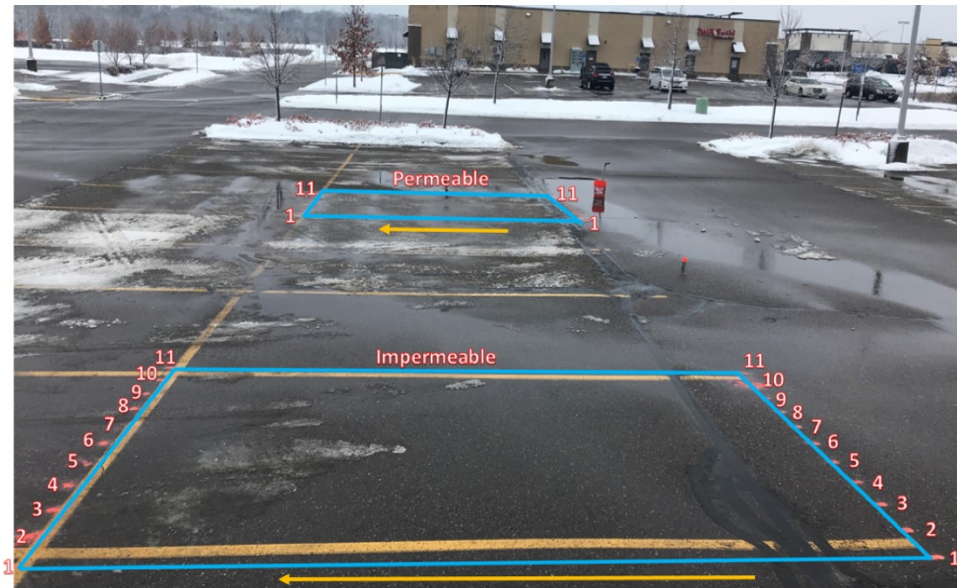**Figure 3.31 Surface friction, surface temperature, air temperature, and photo of testing space for Impermeable Pavement at Mahtomedi Universalist Church.**

Permeable Pavement

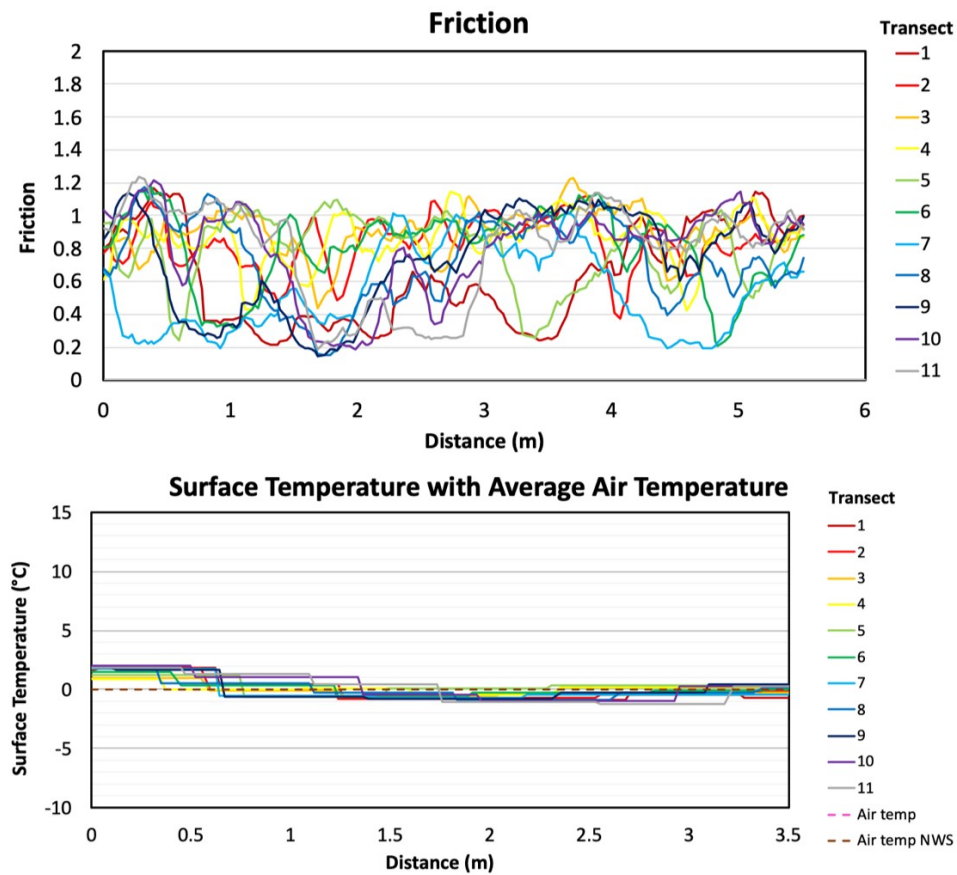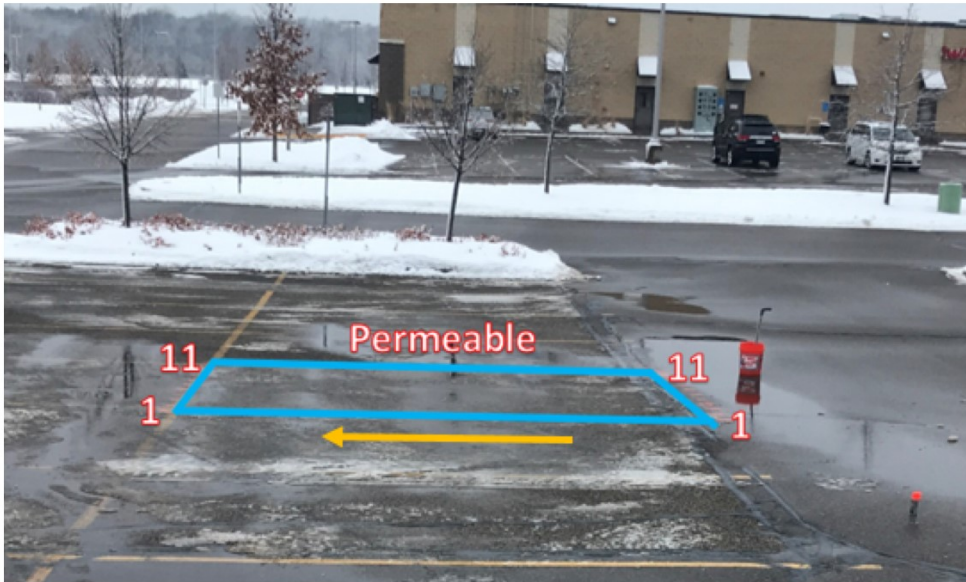**Figure 3.32 Surface friction, surface temperature, air temperature, and photo of testing space for Permeable Pavement at Mahtomedi Universalist Church.**

When comparing the friction, the impermeable section has more friction (average μ = 1.15) and cooler surface temperature (average T = 3.09°C) compared to the permeable pavement (average μ = 1.01, average T = 4.29°C). For the purposes of this report, friction values of $\mu \geq 1$ are considered to have the same level of friction. The photos illustrate that the permeable and impermeable sections have bare pavement throughout, and friction values exceed manufacturer recommendations for safe pedestrian travel ($\mu < 0.35$). The difference in temperature (impermeable average T = 3.09°C vs. permeable average T = 4.29°C) can be explained by the difference in shading. The permeable asphalt is in full sunlight compared to impermeable asphalt which has partial shade from trees. Thus, the impermeable likely absorbs less solar radiation due to shading. This is supported by the observation that the permeable asphalt is warmer than the ambient air temperature (T2Go air temp) whereas the impermeable asphalt is roughly equivalent to the ambient air temperature.

3.3.10 Maplewood Public Works

The Maplewood Public Works Facility in Maplewood, MN has a parking lot with permeable asphalt and a nearby parking lot with impermeable asphalt. Friction and surface temperature were measured on a 10ft x 10ft section covering approximately 2/3rds of one stall in each of the permeable asphalt and impermeable asphalt areas, as shown in Figures 3.33 and 3.34.

Impermeable Pavement

Figure 3.33 Surface friction, surface temperature, air temperature, and photo of testing space for Impermeable Pavement at Maplewood Public Works.

Permeable Pavement

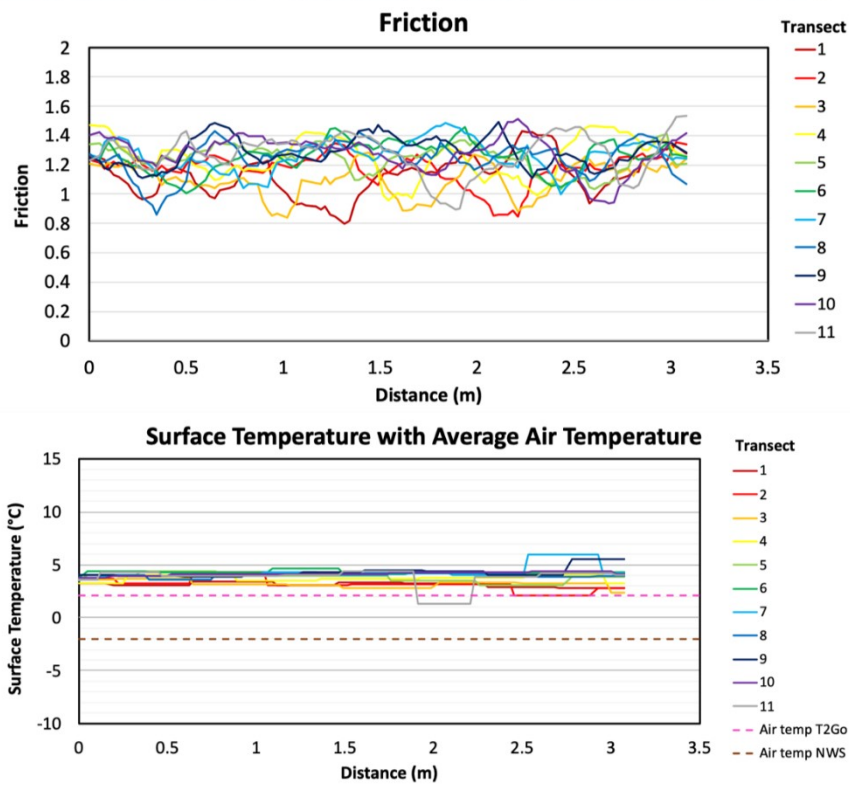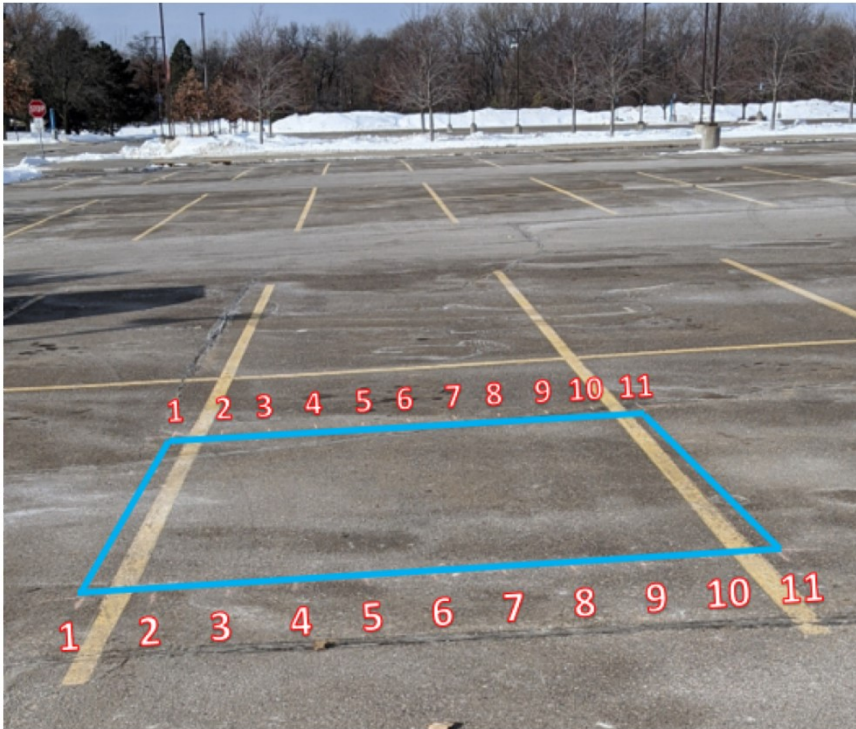**Figure 3.34 Surface friction, surface temperature, air temperature, and photo of testing space for Permeable Pavement at Maplewood Public Works.**

When comparing the friction, the impermeable section has less friction (average μ = 0.90) and cooler surface temperature (average T = 8.67°C) compared to the permeable pavement (average μ = 1.17, average T = 11.72°C). The photos illustrate that the permeable and impermeable sections have bare pavement throughout, and friction values exceed manufacturer recommendations for safe pedestrian travel (μ < 0.35). The difference in temperature (impermeable average T = 8.67°C vs. permeable average T = 11.72°C) can be explained by the air temperature and difference in pavement color. The permeable asphalt is darker in color compared to impermeable asphalt, and thus likely absorbs more solar radiation. The ambient air temperature between measurements also increased from 3.5°C on the impermeable to 6.1°C on the permeable pavement, which is nearly the same difference in surface temperature for the impermeable compared to the permeable.

3.3.11 Minneapolis Pearl Park

The Minneapolis Pearl Park in Minneapolis, MN has parking lot stalls with permeable block pavers and nearby parking stalls with impermeable asphalt. Friction and surface temperature were measured on a 10ft x 10ft section covering approximately 2/3^{rds} of one stall in each of the permeable block pavers and impermeable asphalt areas, as shown in Figures 3.35 and 3.36.

Impermeable Pavement

Figure 3.35 Surface friction, surface temperature, air temperature, and photo of testing space for Impermeable Pavement at Minneapolis Pearl Park.
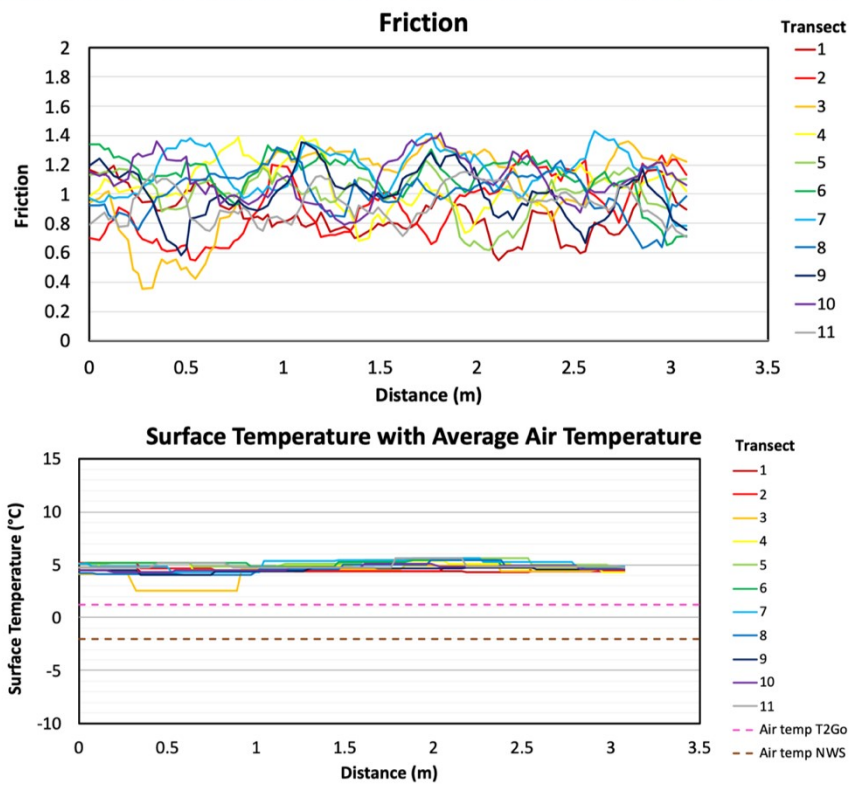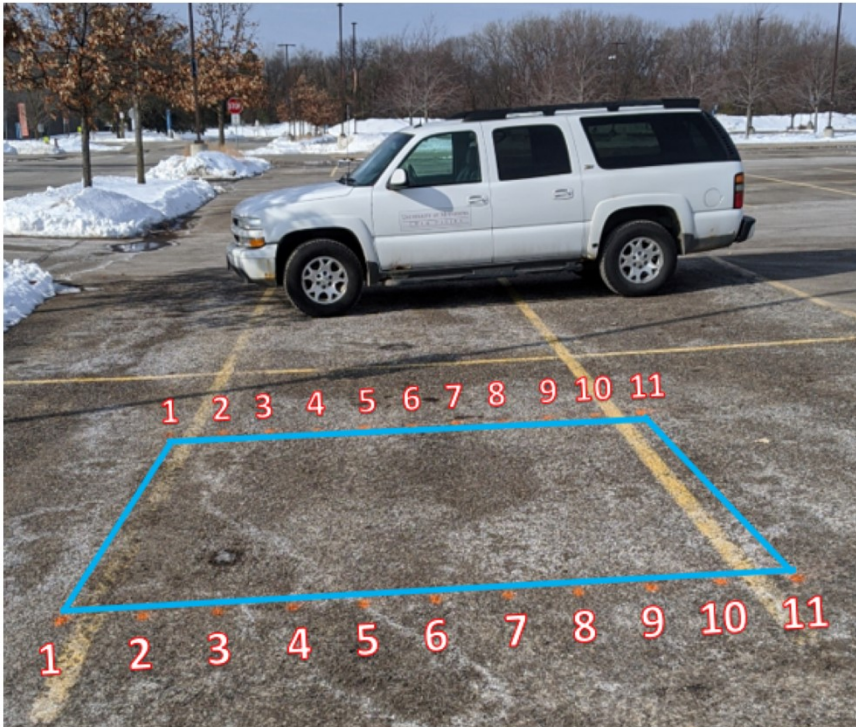
Permeable Pavement

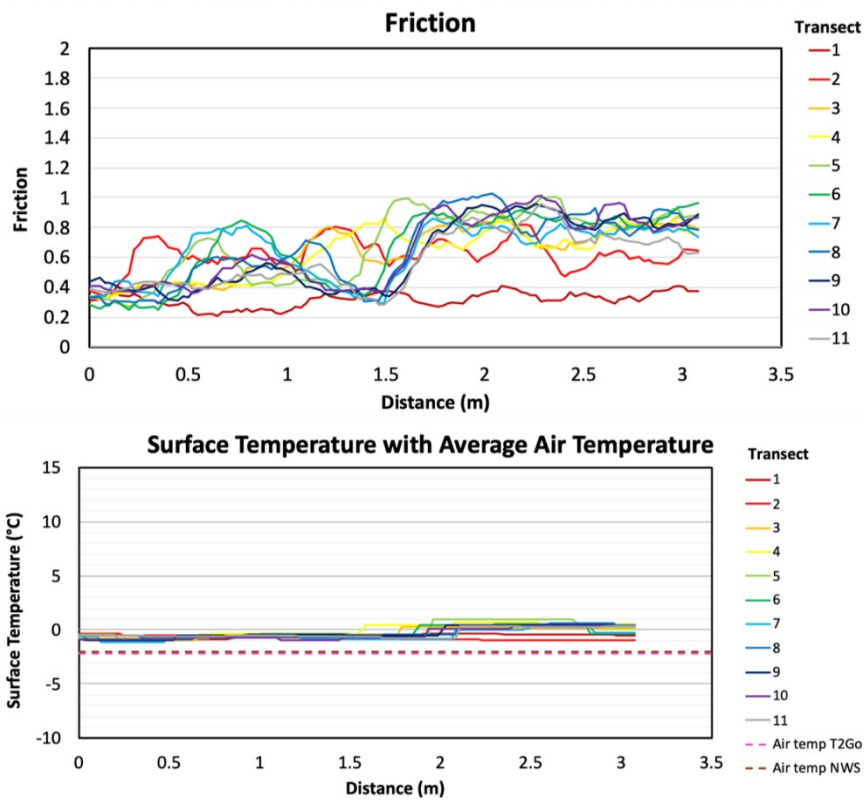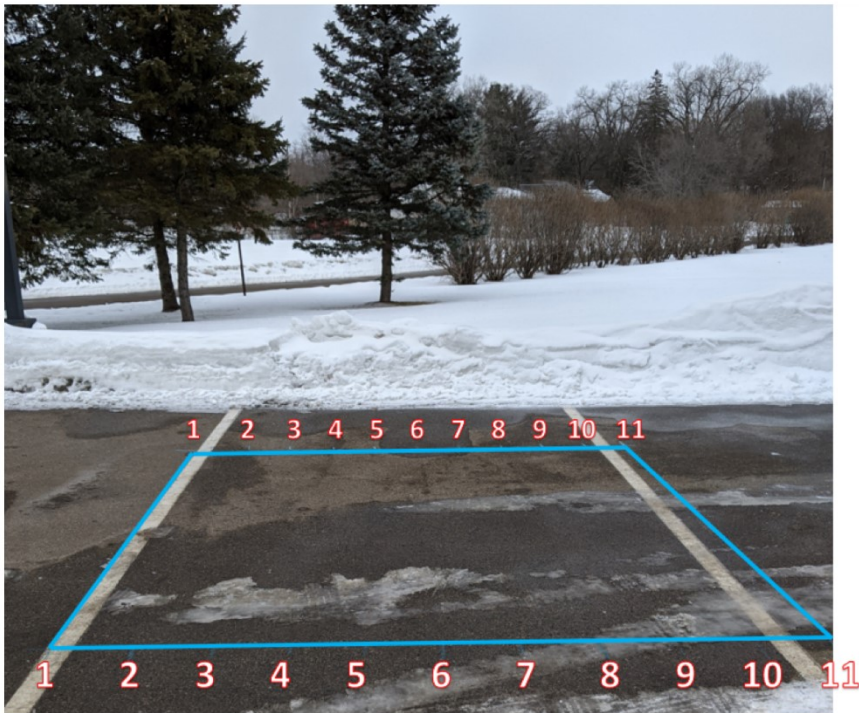**Figure 3.36 Surface friction, surface temperature, air temperature, and photo of testing space for Permeable Pavement at Minneapolis Pearl Park.**

When comparing the friction, the impermeable section has similar friction (average μ = 0.48) and warmer surface temperature (average T = 1.31°C) compared to the permeable pavement (average μ = 0.45, average T = -1.12°C). The photos illustrate that both the permeable and impermeable sections have some snow and ice on the surface, though the permeable has visibly more snow and ice. The ice in both sections is evident from the friction data in Figures 3.35 and 3.36, as shown by most of the transects exhibiting friction values between 0.2 and 0.8. Friction values below (μ < 0.25) are categorized as unsafe for pedestrian travel according to the manufacturer recommendations. The difference in temperature (impermeable average T = 1.31°C vs. permeable average T = -1.12°C) can be explained by the difference in pavement color. The permeable paver blocks are lighter in color compared to impermeable asphalt, and thus likely absorbs less solar radiation. This is supported by the observation that the permeable block pavers are similar in temperature as the ambient air temperature (NWS temp) whereas the impermeable asphalt is warmer than the ambient air temperature.

3.3.12 North St. Paul Church of St. Peter

The Church of St. Peter in North St. Paul, MN has several parking areas of permeable asphalt immediately adjacent to other parking areas of impermeable asphalt. Friction and surface temperature were measured on a 10ft x 10ft section covering approximately 2/3rds of one stall in each of the permeable asphalt and impermeable asphalt areas, as shown in Figures 3.37 and 3.38.
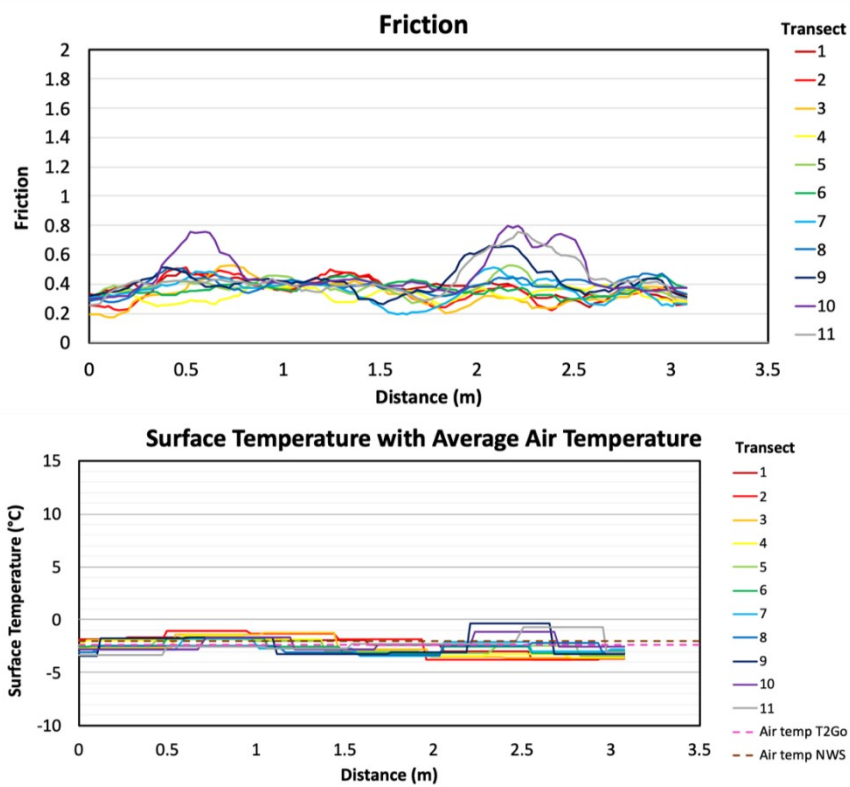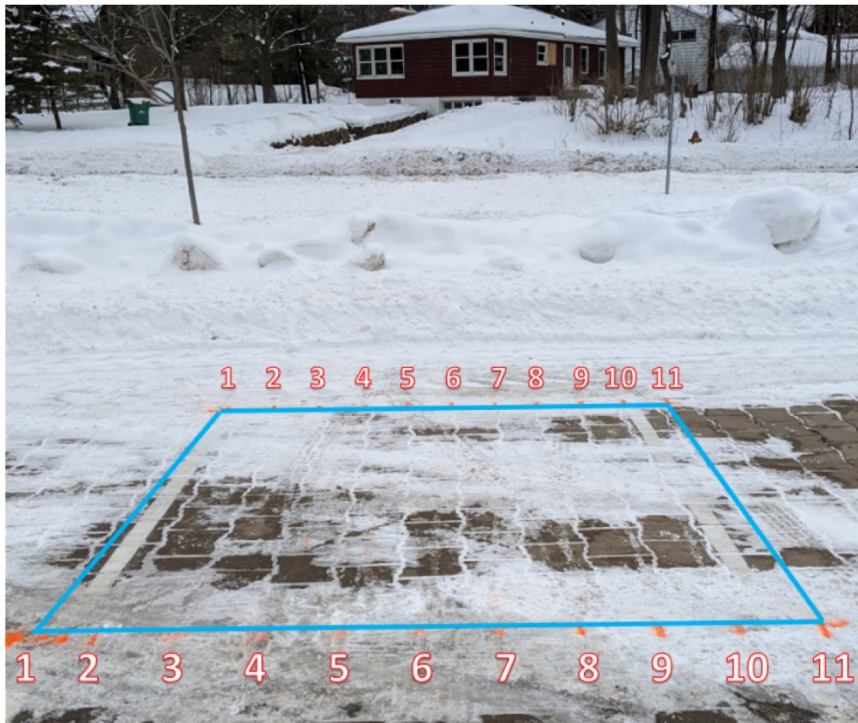
Impermeable Pavement

Figure 3.37 Surface friction, surface temperature, air temperature, and photo of testing space for Impermeable Pavement at Church of St. Peter in North St. Paul, MN. (Note: Photo was taken 6 days after friction and temperature measurements and may not accurately illustrate the pavement conditions when measured. Transect locations are accurate.)

Permeable Pavement

Figure 3.38 Surface friction, surface temperature, air temperature, and photo of testing space for Permeable Pavement Church of St. Peter in North St. Paul, MN . (Note: Photo was taken 6 days after friction and temperature measurements and may not accurately illustrate the pavement conditions when measured. Transect locations are accurate.)

When comparing the friction, the impermeable section has similar friction (average μ = 1.18) and similar surface temperature (average T = 5.67°C) compared to the permeable pavement (average μ = 1.15, average T = 5.55°C). For the purposes of this report, friction values of $\mu \geq 1$ are considered to have the same level of friction. The photos illustrate that the impermeable section has bare pavement and the permeable pavement has a small portion covered with snow. The snow on the permeable section is evident from the friction data in Figure 3.38, as shown by some transects at distances less than 0.5m with friction values of 0.4 - 0.6. Overall, though, the impermeable and permeable asphalt have similar friction and surface temperature.

3.3.13 North St. Paul Preservation Park

The North St. Paul Preservation Park in North St. Paul, MN has parking lot stalls with permeable block pavers and nearby parking stalls with impermeable asphalt. Friction and surface temperature were measured on a 10ft x 10ft section covering approximately 2/3rds of one stall in each of the permeable block pavers and impermeable asphalt areas, as shown in Figures 3.39 and 3.40.
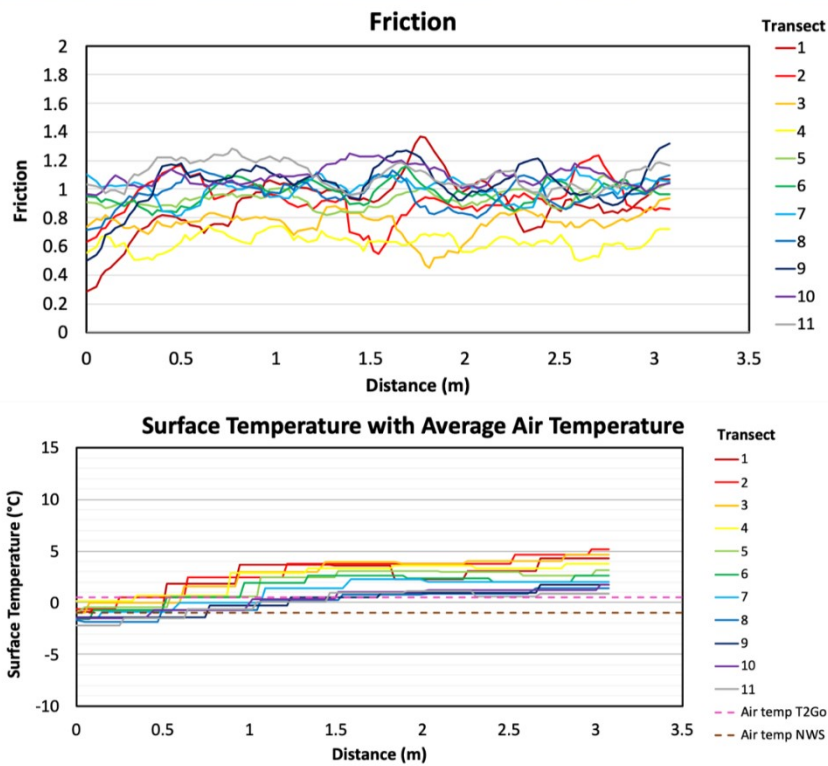
Impermeable Pavement

Figure 3.39 Surface friction, surface temperature, air temperature, and photo of testing space for Impermeable Pavement at North St. Paul Preservation Park.
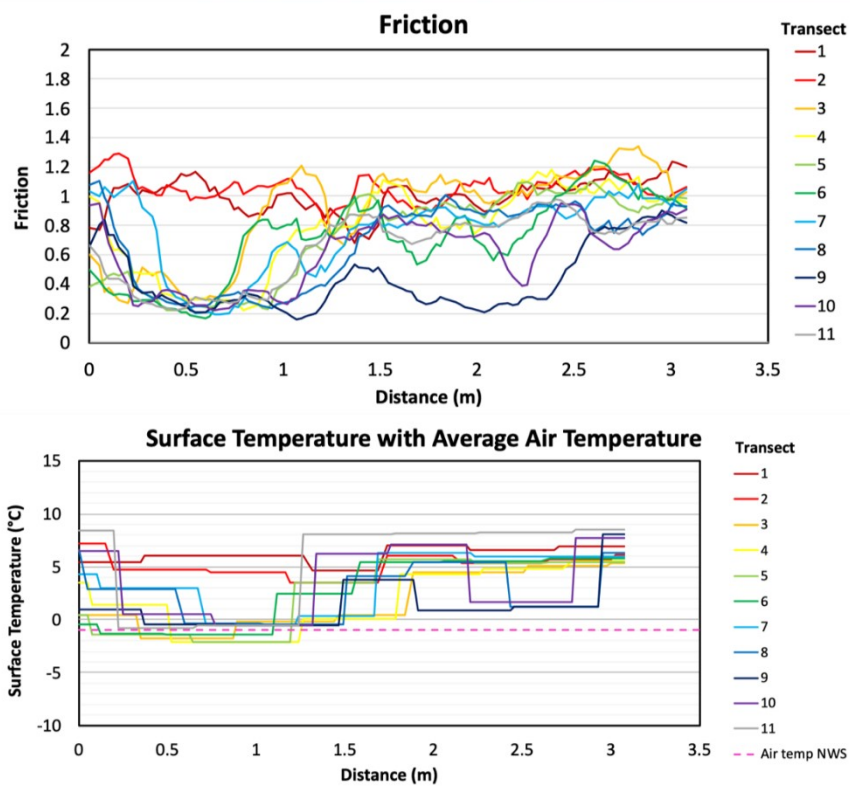
Permeable Pavement

Figure 3.40 Surface friction, surface temperature, air temperature, and photo of testing space for Permeable Pavement at North St. Paul Preservation Park.

When comparing the friction, the impermeable section has more friction (average μ = 0.84) and cooler surface temperature (average T = 8.90°C) compared to the permeable pavement (average μ = 1.24, average T = 6.27°C). The photos illustrate that both the permeable and impermeable sections have some snow and ice on the surface. The ice in both sections is evident from the friction data in Figures 3.39 and 4.40, as shown by some transects decreasing in friction to values of 0.4 (impermeable) and 0.2 (permeable) at distances of 2.5 - 3m. Friction values below (μ < 0.25) are categorized as unsafe for pedestrian travel according to the manufacturer recommendations. The difference in temperature (impermeable average T = 8.90°C vs. permeable average T = 6.27°C) can be explained by the difference in pavement color. The permeable paver blocks are lighter in color compared to impermeable asphalt, and thus likely absorbs less solar radiation. This is supported by the observation that the permeable block pavers are similar in temperature as the ambient air temperature (T2Go temp) whereas the impermeable asphalt is warmer than the ambient air temperature.

3.3.14 Roseville Fire Department

The Roseville Fire Department in Roseville, MN has parking lot stalls with permeable asphalt and nearby parking stalls with impermeable asphalt. Friction and surface temperature were measured on a 10ft x 10ft section covering approximately 2/3^{rds} of one stall in each of the permeable asphalt and impermeable asphalt areas, as shown in Figures 3.41 and 3.42.
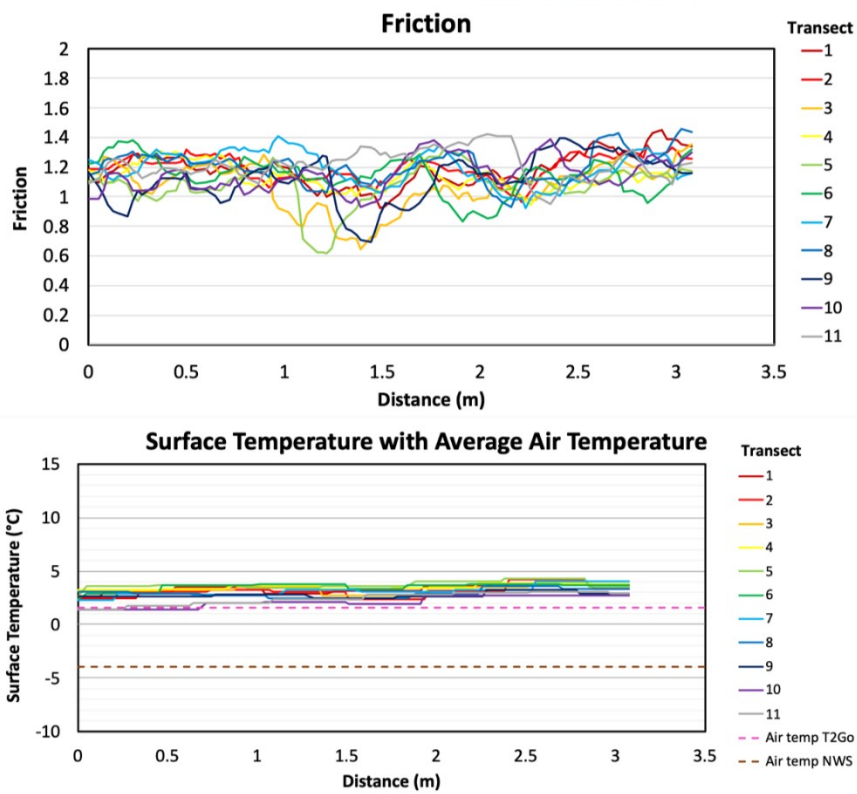
Impermeable Pavement

Figure 3.41 Surface friction, surface temperature, air temperature, and photo of testing space for Impermeable Pavement at Roseville Fire Department.
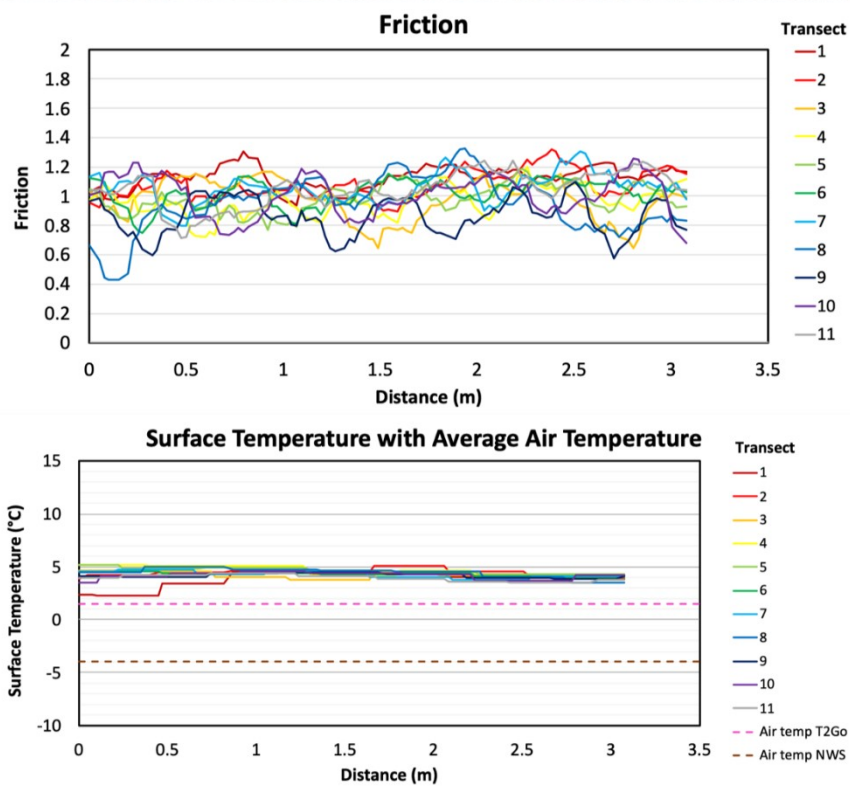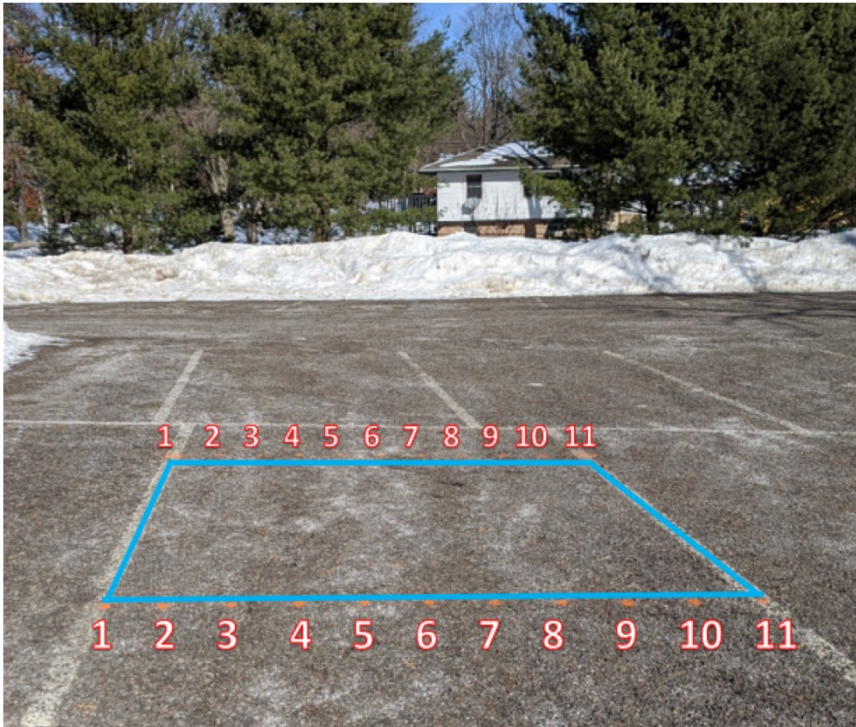
Permeable Pavement

Figure 3.42 Surface friction, surface temperature, air temperature, and photo of testing space for Permeable Pavement at Roseville Fire Department.

When comparing the friction, the impermeable section has similar friction (average μ = 1.16) and cooler surface temperature (average T = 4.17°C) compared to the permeable pavement (average μ = 1.16, average T = 4.78°C). The photos illustrate that the permeable and impermeable sections have bare pavement throughout, and friction values exceed manufacturer recommendations for safe pedestrian travel (μ < 0.35). The difference in temperature (impermeable average T = 4.17°C vs. permeable average T = 4.78°C) can be explained by the difference in pavement color. The permeable asphalt is darker in color compared to impermeable asphalt, and thus likely absorbs more solar radiation.

3.3.15 Ramsey Washington Metro Watershed District

The Ramsey Washington Metro Watershed District in Little Canada, MN has portions of its parking lot as permeable concrete, permeable interlocking block pavers, and impermeable asphalt. Friction and surface temperature were measured on 10ft x 10ft sections in each of the permeable concrete, permeable pavers, and impermeable asphalt areas, as shown in Figures 3.43, 3.44, and 3.45.

Impermeable Pavement

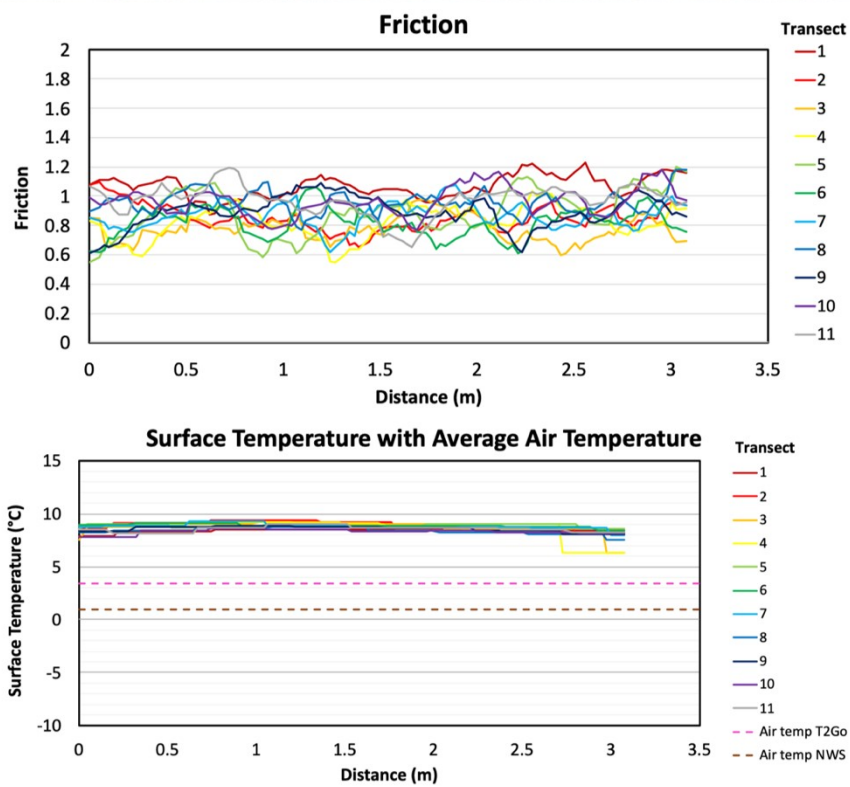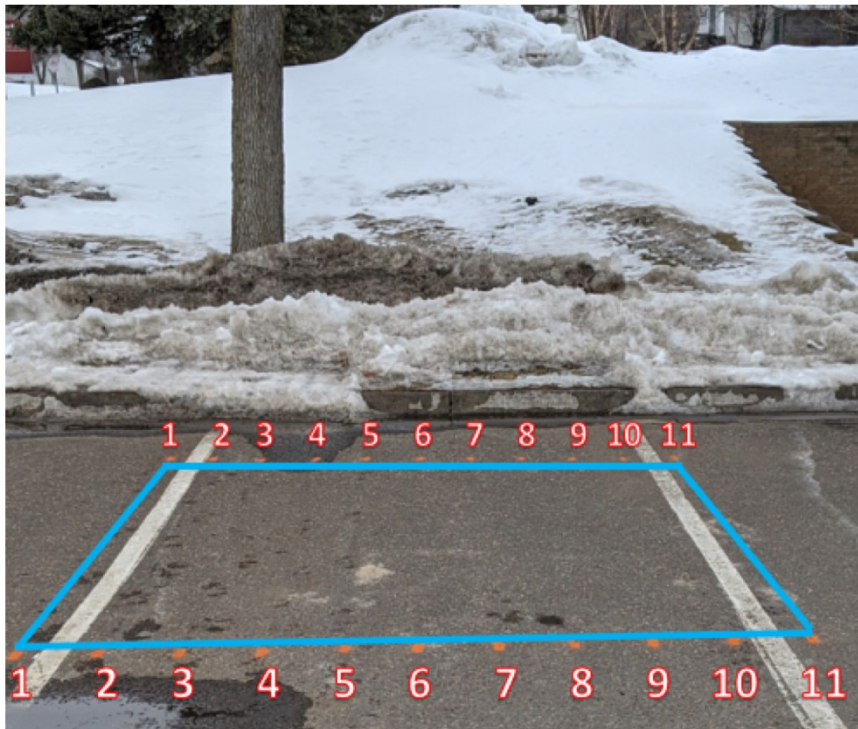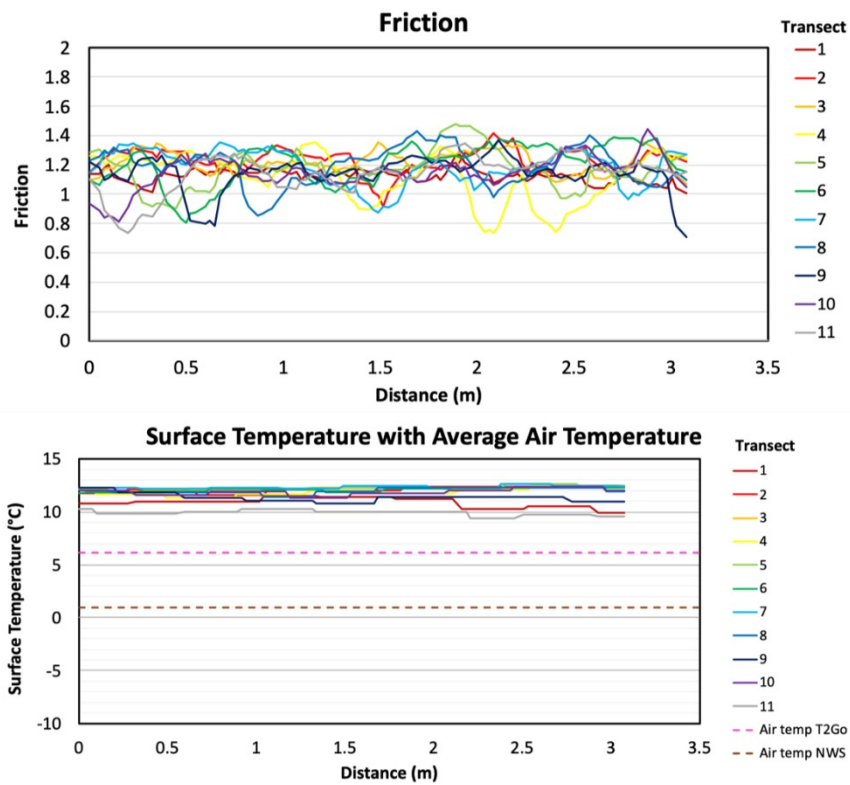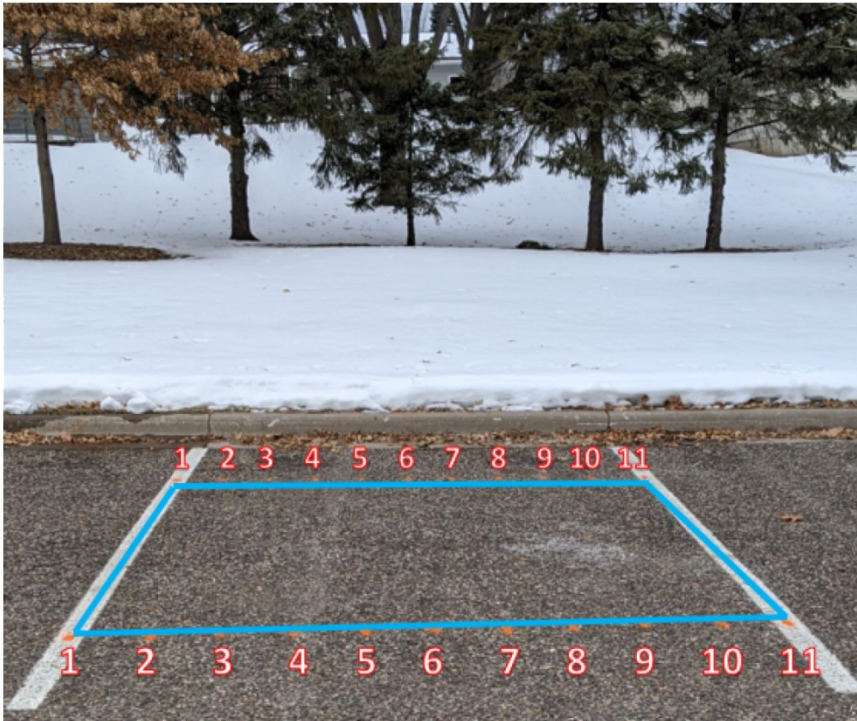**Figure 3.43 Surface friction, surface temperature, air temperature, and photo of testing space for Impermeable Pavement at Ramsey Washington Metro Washington District.**

Permeable Pavement

Figure 3.44 Surface friction, surface temperature, air temperature, and photo of testing space for Permeable Block Pavers Pavement at Ramsey Washington Metro Washington District .

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Permeable Pavement

Figure 3.45 Surface friction, surface temperature, air temperature, and photo of testing space for Permeable Pavement at Ramsey Washington Metro Washington District .

When comparing the friction, the impermeable section has similar friction (average μ = 1.23) and warmer surface temperature (average T = 10.17°C) compared to the permeable interlocking block pavers pavement (average μ = 1.08, average T = 2.01°C) and the permeable concrete (average μ = 1.23, average T = 8.40°C). For the purposes of this report, friction values of $\mu \geq 1$ are considered to have the same level of friction. The photos illustrate that the permeable and impermeable sections have bare pavement throughout, and friction values exceed manufacturer recommendations for safe pedestrian travel ($\mu < 0.35$). The difference in temperature (impermeable average T = 10.17°C vs. permeable interlocking block pavers average T = 2.01°C vs. permeable concrete average T = 8.40°C) can be explained by the difference in pavement color. The impermeable asphalt (warmest) is darker in color compared to the permeable interlocking pavers (coolest) and the permeable concrete, and thus likely absorbs more solar radiation. The permeable interlocking pavers are lighter in color than the permeable concrete, and thus likely absorbs less solar radiation.

3.3.16 Shoreview Janice Street

The City of Shoreview, MN has several residential streets of permeable interlocking block pavers, one of which is along Janice Street. Friction and surface temperature were measured on a 10ft x 10ft section of the permeable pavers and another 10ft x 10ft section on nearby impermeable asphalt, as shown in Figures 3.46 and 3.47.
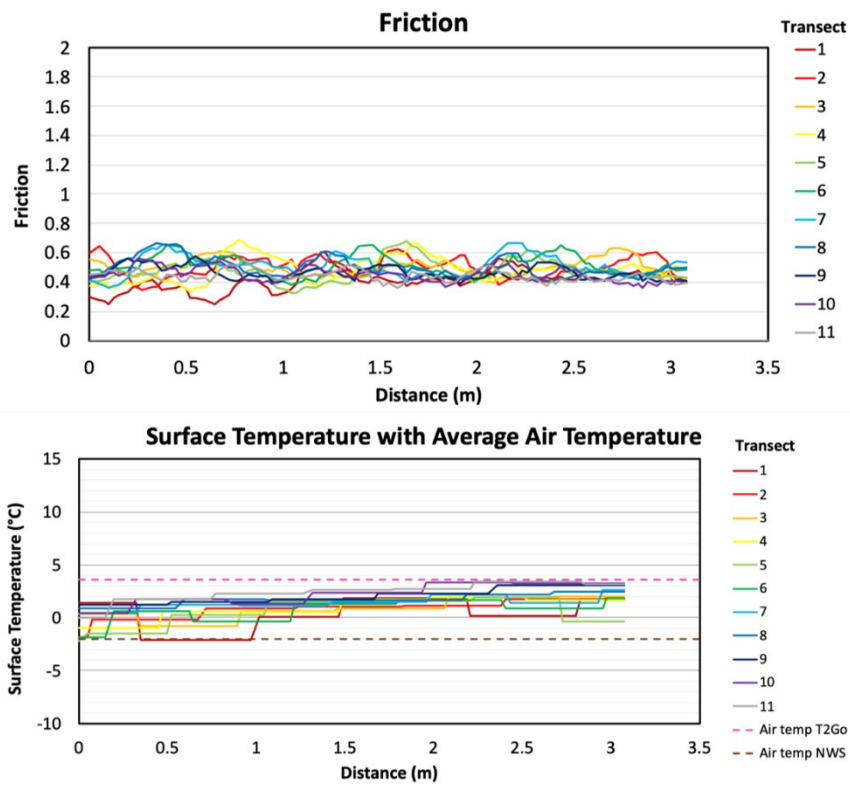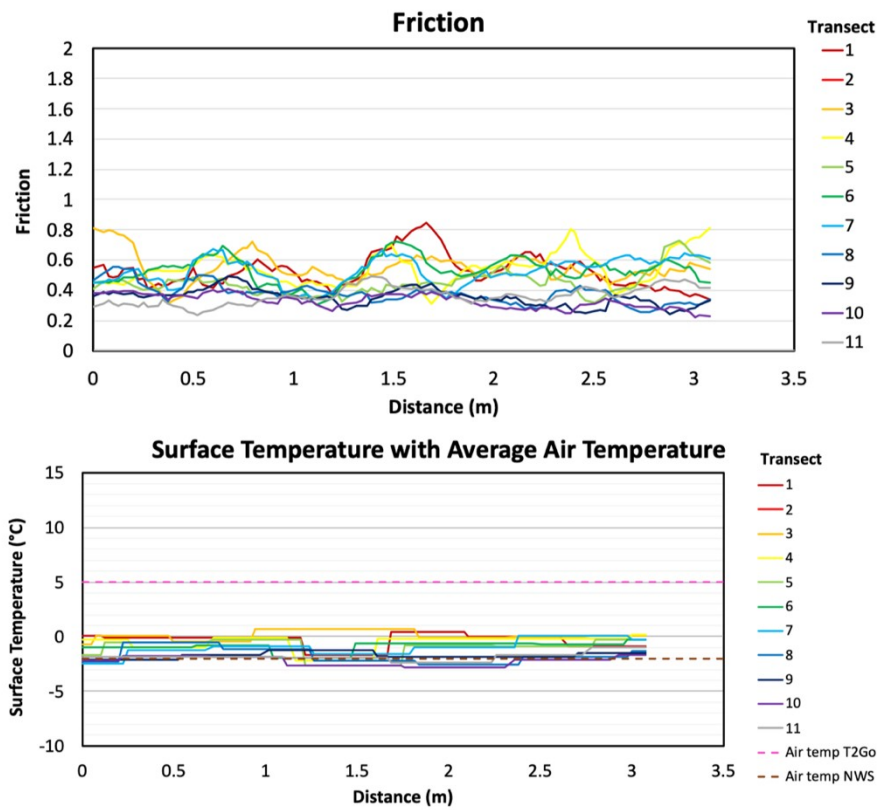
Impermeable Pavement

Figure 3.46 Surface friction, surface temperature, air temperature, and photo of testing space for Impermeable Pavement at Janice Street in Shoreview, MN. (Note: Photo was taken 8 days after friction and temperature measurements and may not accurately illustrate the pavement conditions when measured. Transect locations are approximate.)

Permeable Pavement
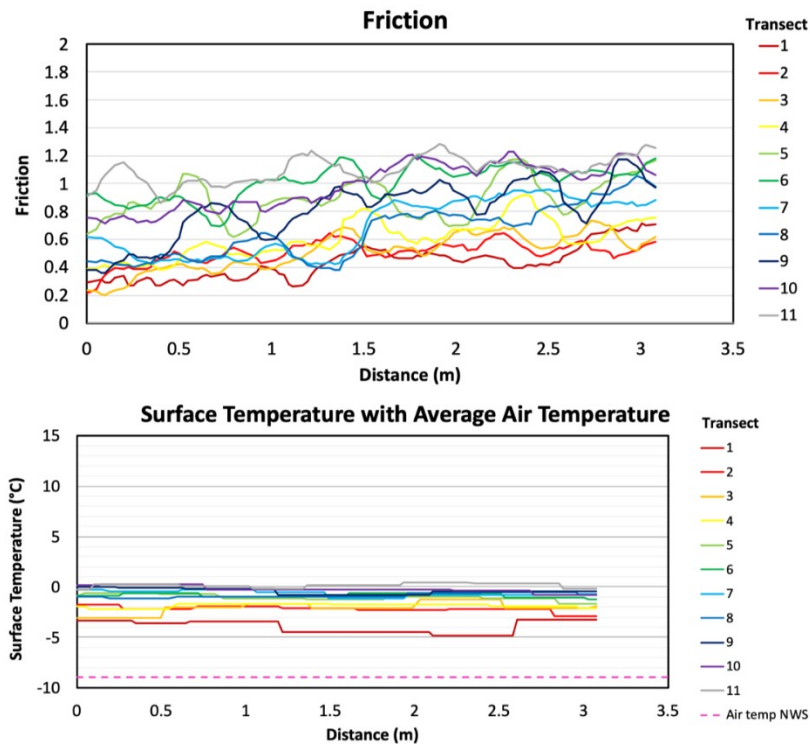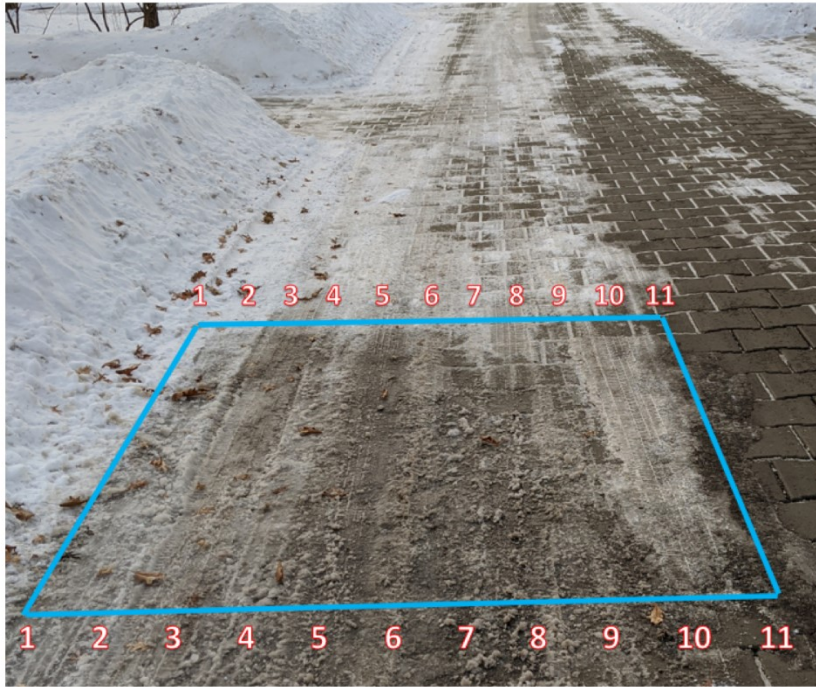
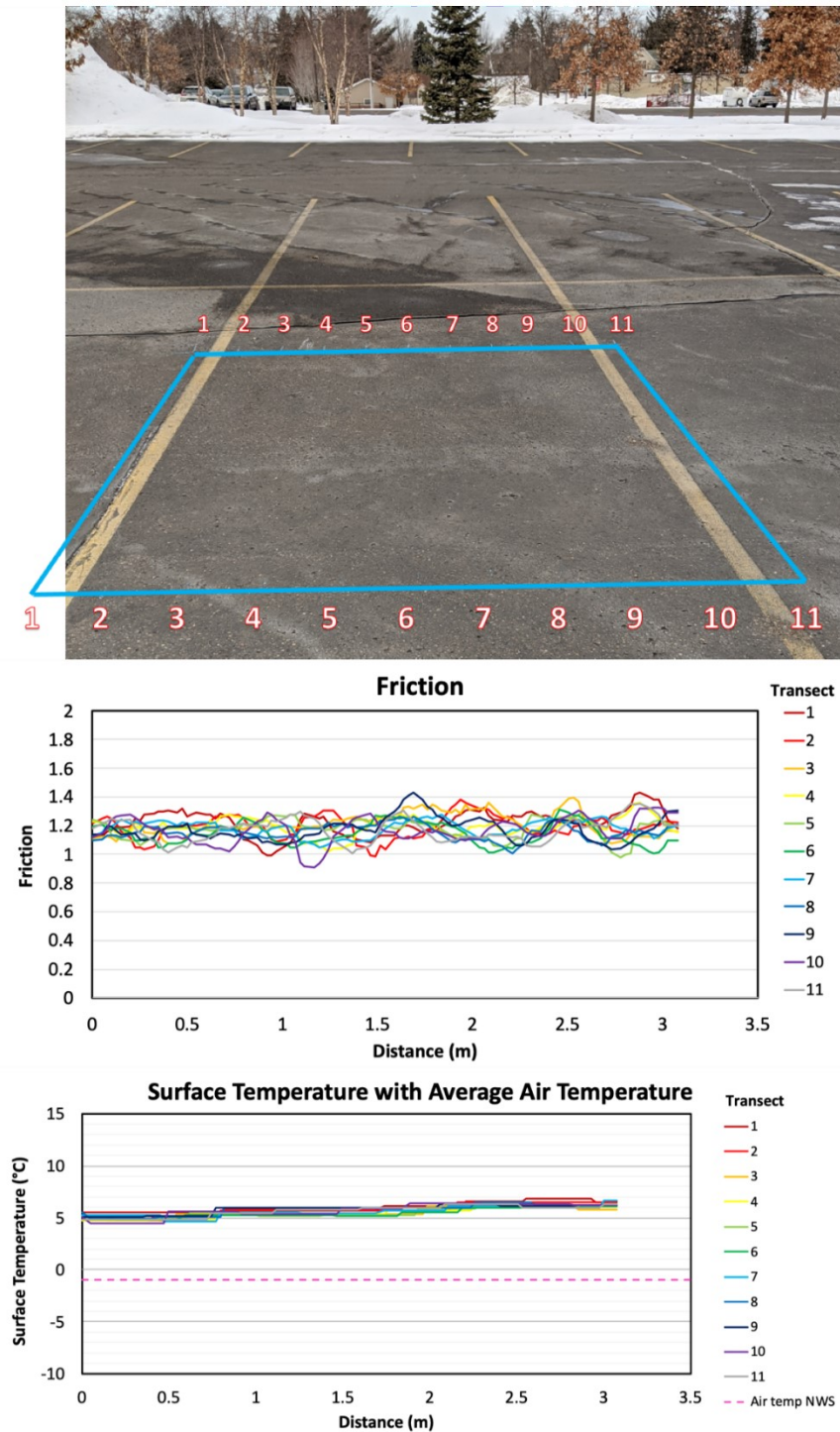**Figure 3.47 Surface friction, surface temperature, air temperature, and photo of testing space for Permeable Pavement at Janice Street in Shoreview, MN. (Note: Photo was taken 8 days after friction and temperature measurements and may not accurately illustrate the pavement conditions when measured. Transect locations are approximate.)**
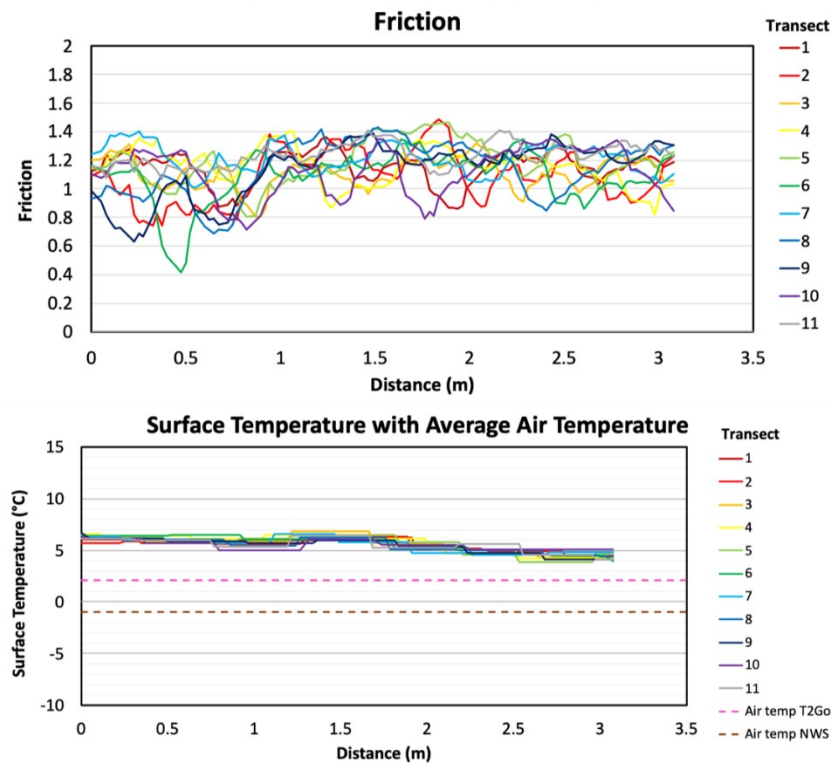
When comparing the friction, the impermeable section has more friction (average μ = 1.24) and warmer surface temperature (average T = 5.67°C) compared to the permeable pavement (average μ = 0.75, average T = -1.26°C). The photos illustrate that the impermeable section has minimal or no snow or ice cover whereas permeable sections has some snow and ice. The ice in permeable section is evident from the friction data in Figure 3.47, as shown by some transects with friction values of 0.2 throughout the distance. Friction values below (μ < 0.25) are categorized as unsafe for pedestrian travel according to the manufacturer recommendations. By contrast, the impermeable pavement has bare pavement and friction values of 0.65 to < 1.0 (Figure 3.46).

The difference in temperature (impermeable average T = 5.67°C vs. permeable average T = -1.26°C) can be explained by the difference in pavement color and the presence of snow and ice cover. The permeable paver blocks are lighter in color compared to impermeable asphalt, and thus likely absorbs less solar radiation. In addition, snow and ice on the surface of the pavement will keep the surface below freezing temperatures, as evidenced by the consistent negative measured surface temperatures (Figure 3.47) and below freezing average temperature (average T = -1.26°C).

3.3.17 Shoreview Oakridge Avenue

The City of Shoreview, MN has several residential streets of permeable interlocking block pavers, one of which is along Oakridge Avenue. Friction and surface temperature were measured on a 10ft x 10ft section of the permeable pavers and another 10ft x 10ft section on nearby impermeable asphalt (Hansen Road), as shown in Figures 3.48 and 3.49.

Impermeable Pavement

Figure 3.48 Surface friction, surface temperature, air temperature, and photo of testing space for Impermeable Pavement at Hansen Road (near Oakridge) in Shoreview, MN.

Permeable Pavement

Figure 3.49 Surface friction, surface temperature, air temperature, and photo of testing space for Permeable Pavement at Oakridge Avenue in Shoreview, MN.

When comparing the friction, the impermeable section has less friction (average μ = 0.30) and warmer surface temperature (average T = -1.21°C) compared to the permeable pavement (average μ = 0.35, average T = -2.79°C). The photos illustrate that the impermeable section has snow and ice cover for most transects and the permeable pavement is completely covered with snow. The snow and ice on the impermeable section is evident from the friction data in Figure 3.48, as shown by transects 3 - 11 with friction values of 0.1 to 0.4 throughout the distance. By contrast, the permeable pavement has snow cover for all transects, but friction values of 0.35 to 0.4 for nearly all transects and distance (Figure 3.48). The packed snow on the permeable pavement appears to have more friction than the ice on the impermeable pavement. Both pavements, however, are categorized as unsafe (μ < 0.25) or cautious (μ < 0.35) according to the manufacturer recommendations.

The difference in temperature (impermeable average T = -1.21°C vs. permeable average T = -2.79°C) can be explained by the difference in snow and ice cover. The permeable paver blocks are covered in a layer of snow and ice which will keep the surface below freezing temperatures. The impermeable asphalt section is covered in ice, compared to snow, and has a few sections with patches of bare pavement (e.g., transect 1). In addition, the weather was overcast and cloudy, and thus solar radiation was minimal.

3.3.18 Shoreview Ramsey County Library

The City of Shoreview, MN has several parking areas of permeable interlocking block pavers, one of which is near the Ramsey County Library. Friction and surface temperature were measured on a 10ft x 10ft section covering approximately 2/3^{rds} of one stall in each of the permeable block pavers and impermeable asphalt areas, as shown in Figures 3.50 and 3.51.
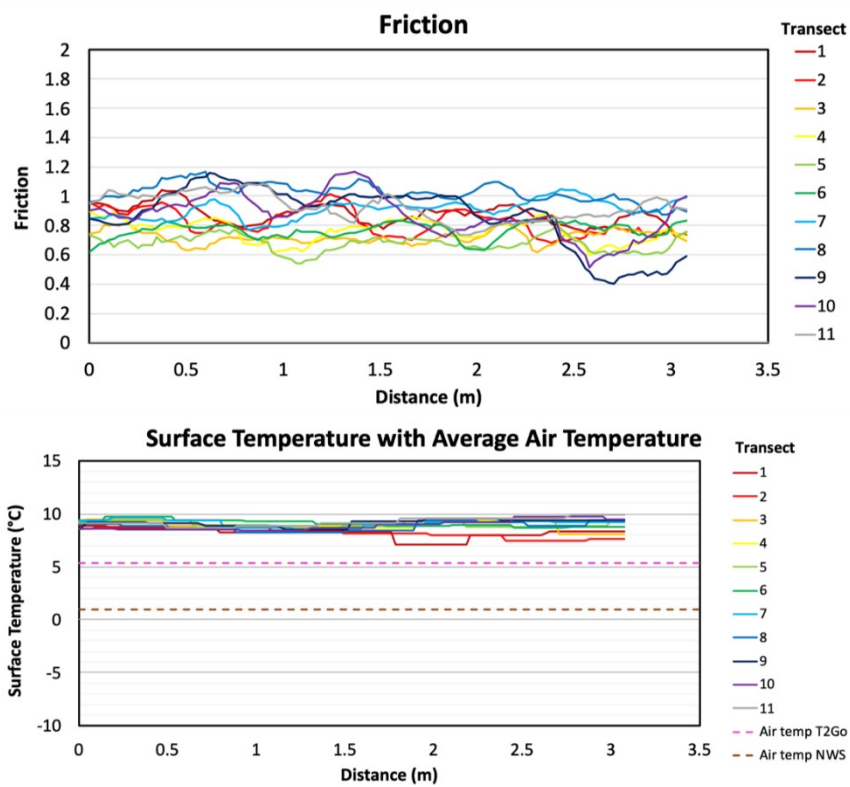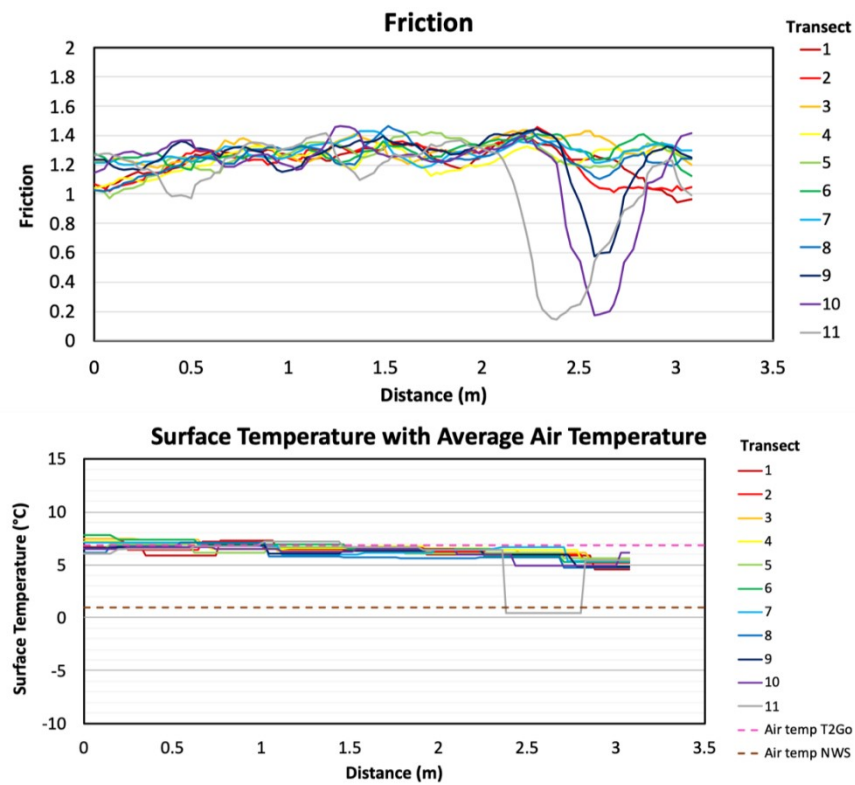
Impermeable Pavement

Figure 3.50 Surface friction, surface temperature, air temperature, and photo of testing space for Impermeable Pavement at Ramsey County Library in Shoreview, MN.
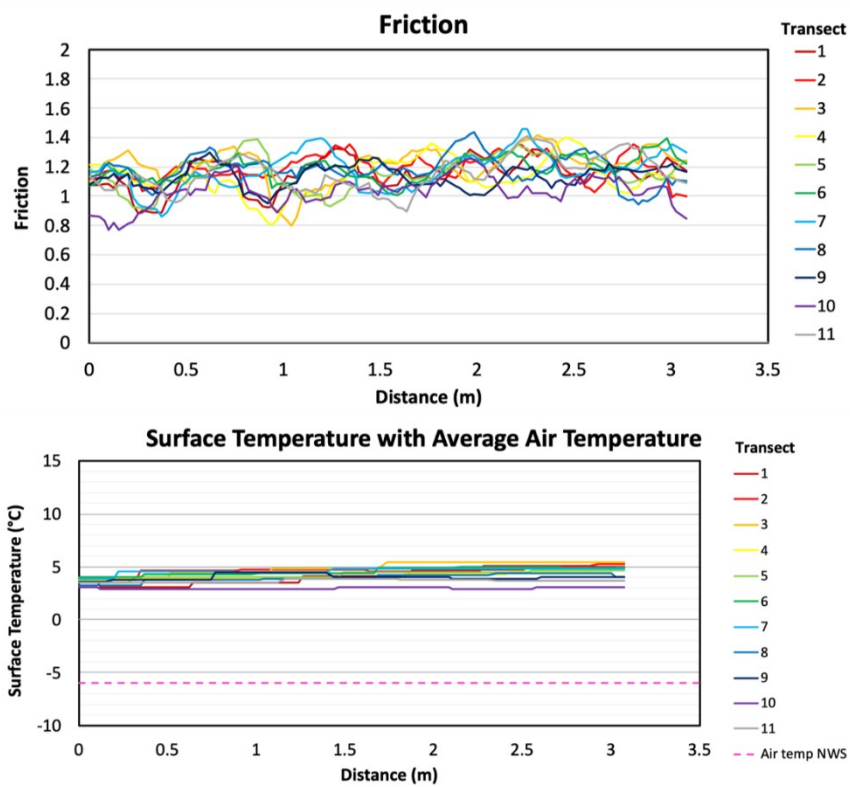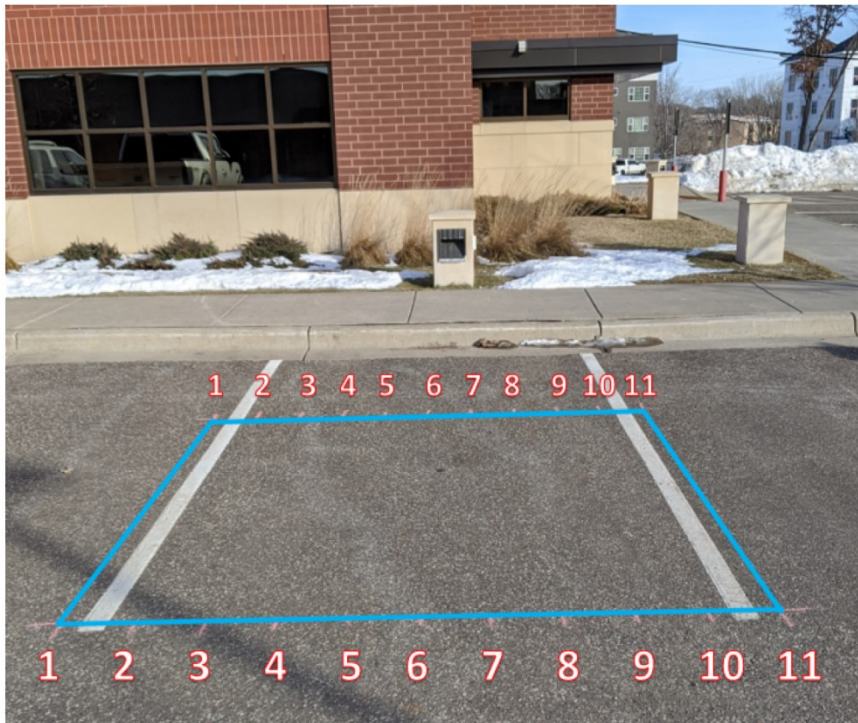
Permeable Pavement
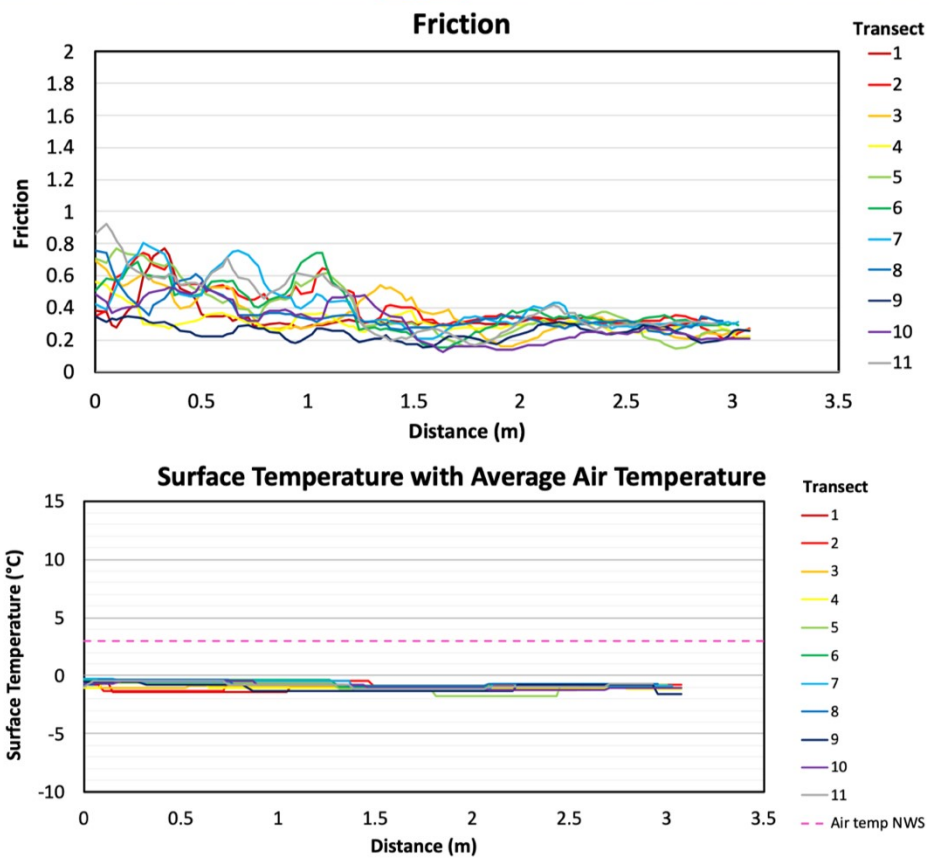
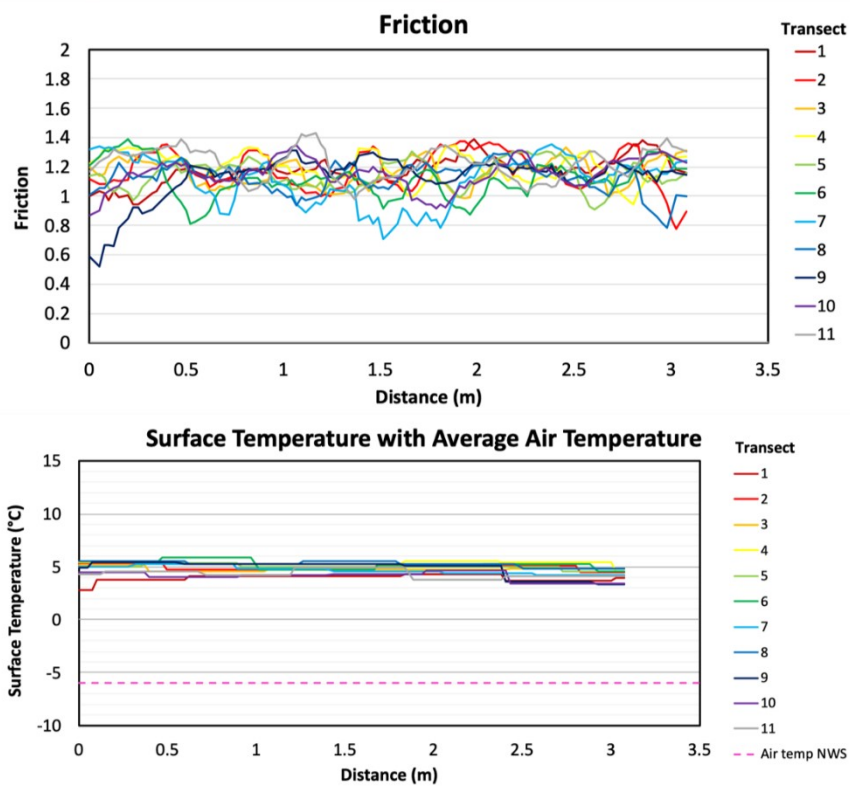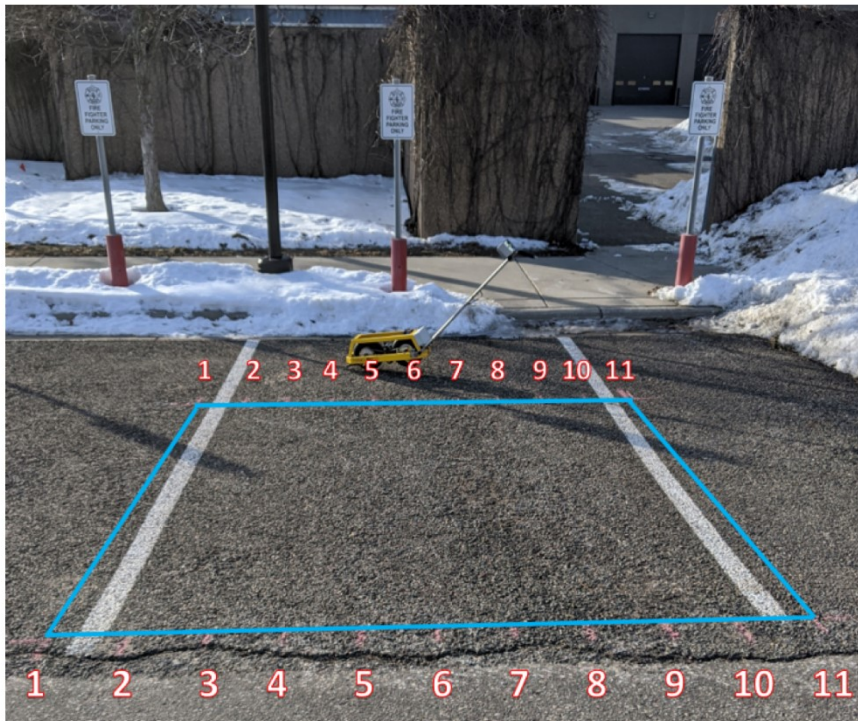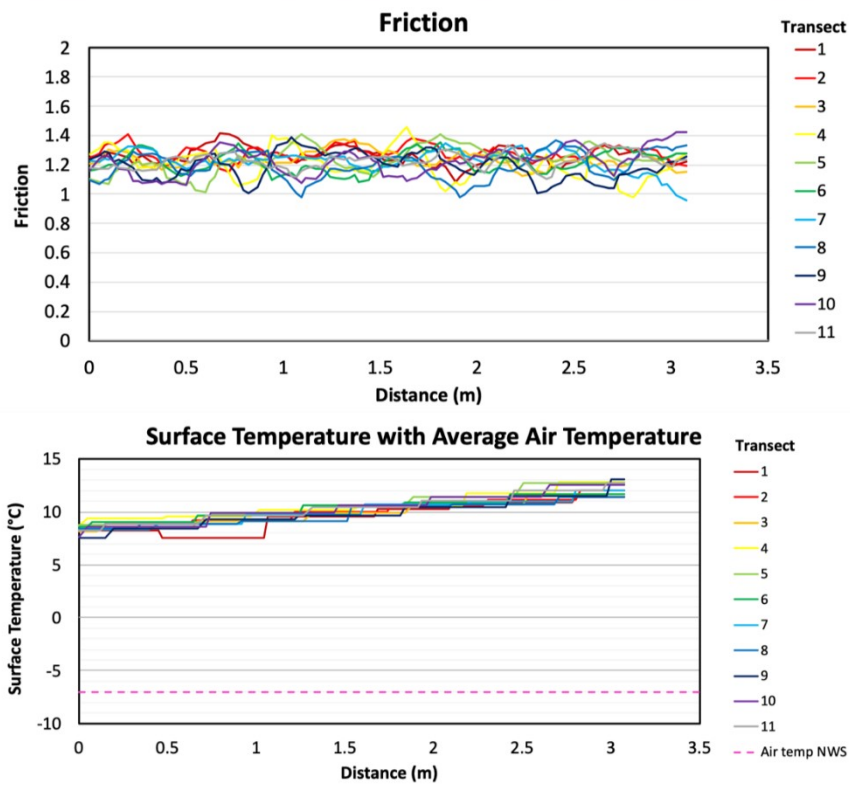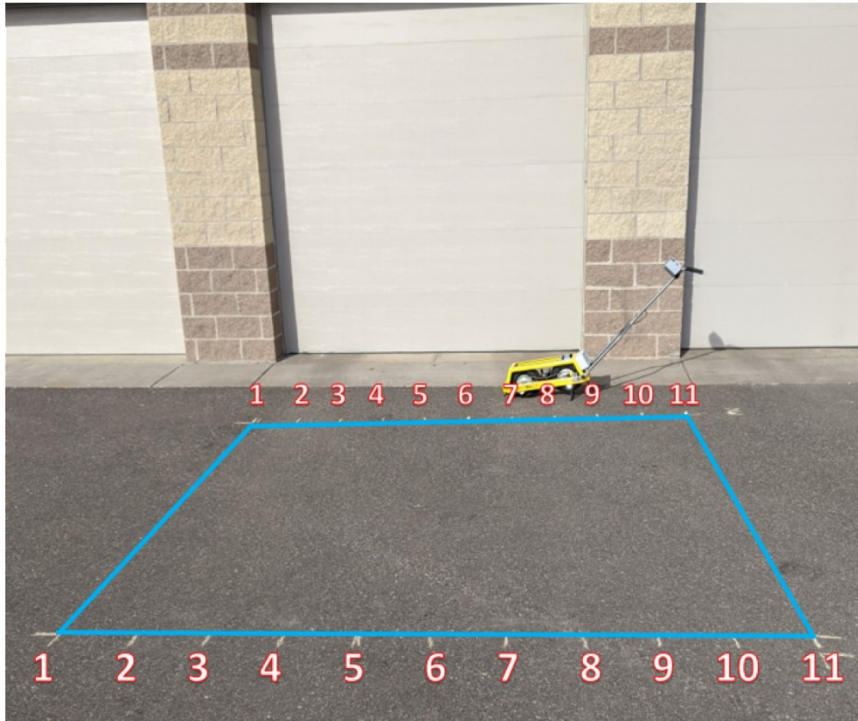**Figure 3.51 Surface friction, surface temperature, air temperature, and photo of testing space for Impermeable Pavement at Ramsey County Library in Shoreview, MN.**

When comparing the friction, the impermeable section has more friction (average μ = 0.70) and similar surface temperature (average T = -0.50°C) compared to the permeable pavement (average μ = 0.36, average T = -0.90°C). The photos illustrate that the impermeable section has bare pavement with small patches of ice cover. The ice on the impermeable section is evident from the friction data in Figure 3.50, as shown by transects 7 - 10 at distances of 0.5 - 1m and 2 - 3m with friction values of 0.2. By contrast, the permeable pavement has snow cover for all transects, especially for distances greater than 1.5m with friction values of 0.2 to 0.4 (Figure 3.51). Portions of both pavements are categorized as unsafe (μ < 0.25) or cautious (μ < 0.35) according to the manufacturer recommendations. The surface temperature is similar for both pavements.

3.3.19 Stillwater First Presbyterian Church

The First Presbyterian Church in Stillwater, MN has a pedestrian walkway constructed of permeable block pavers immediately adjacent to impermeable asphalt drive lanes. The permeable walkway is separated from the impermeable asphalt by a 1ft wide strip of impermeable concrete. Friction and surface temperature were measured on a 10ft wide x 20ft long section covering a 6 ft length of impermeable asphalt, 1 ft of impermeable concrete, 6 ft of permeable block walkway, 1 ft of impermeable concrete, and 6 feet of impermeable asphalt, as shown in Figure 3.52.
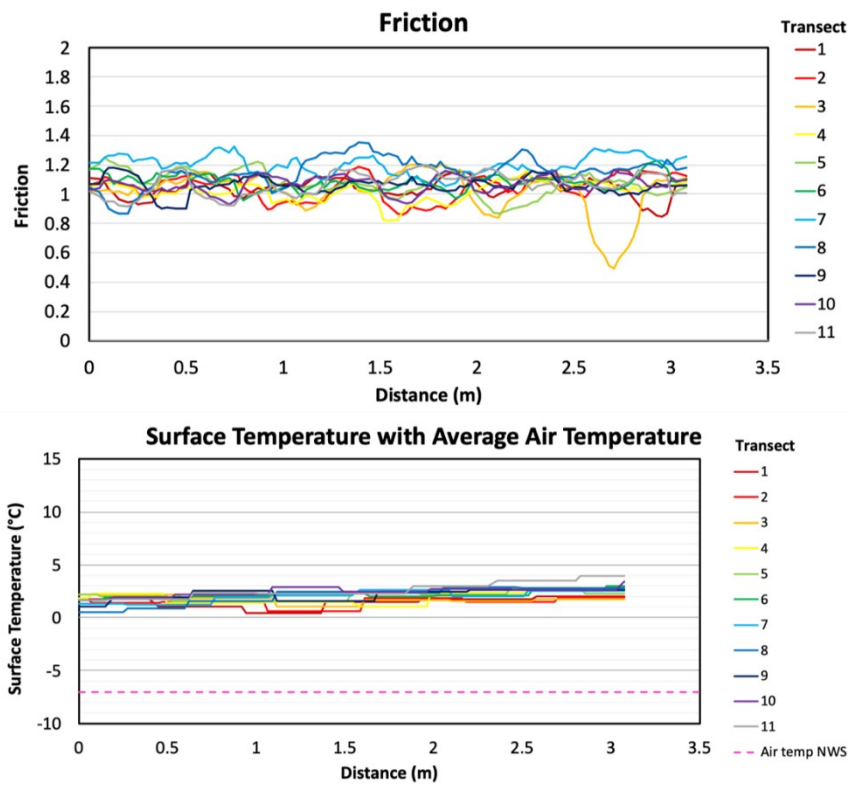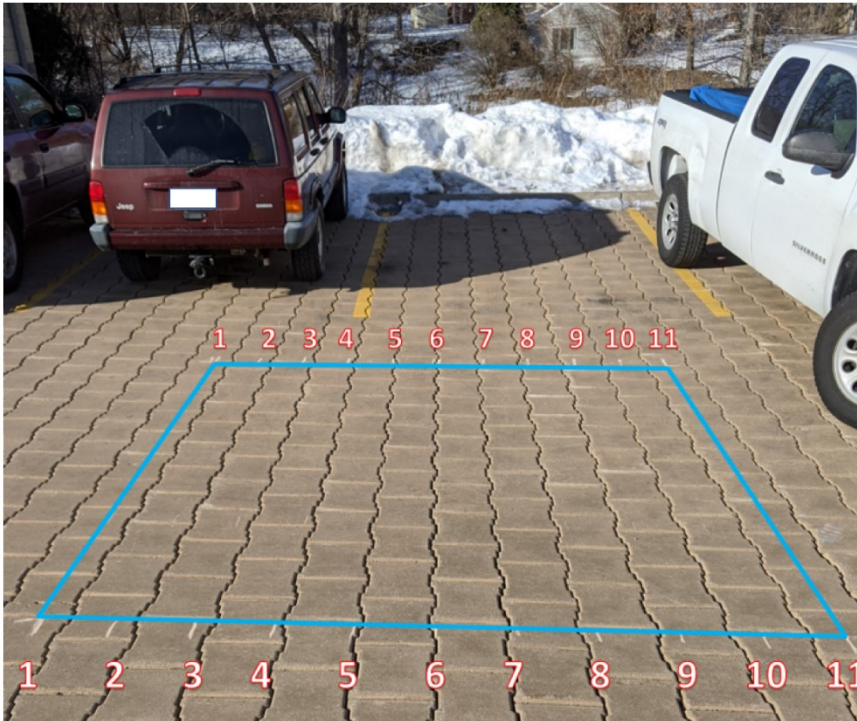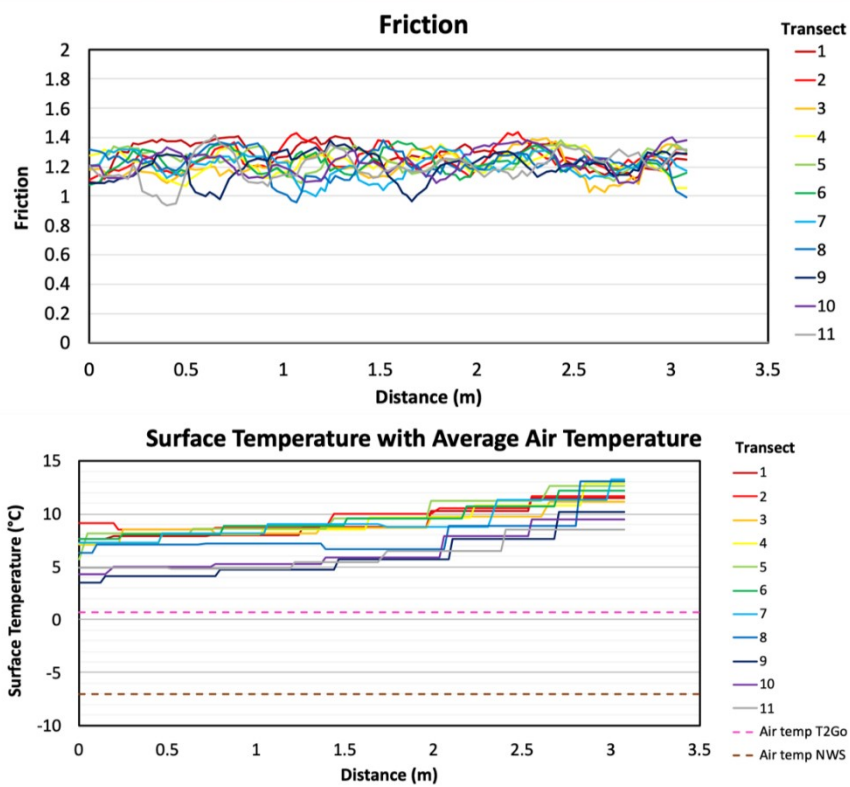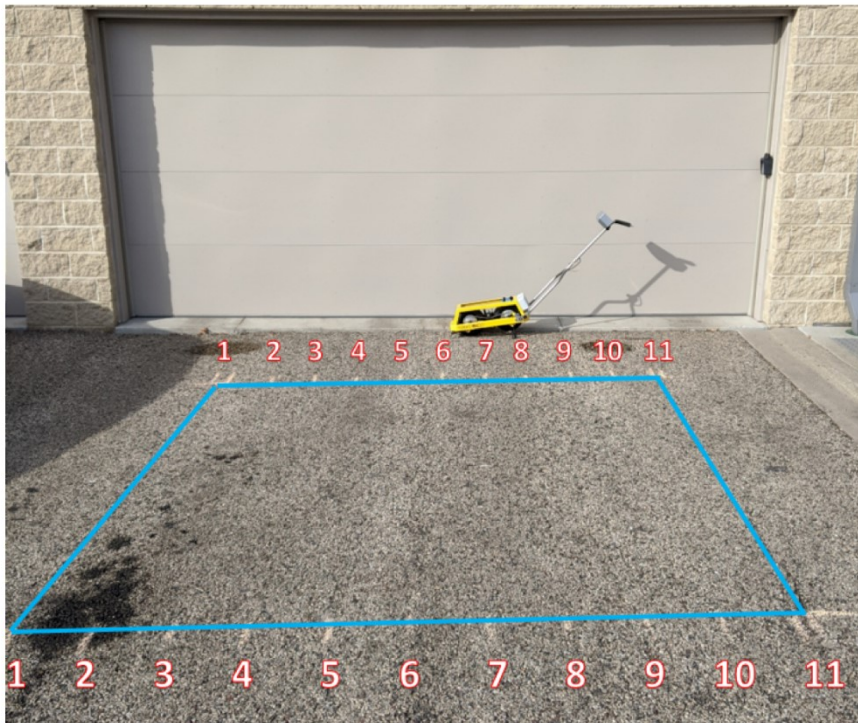
Impermeable and Permeable Pavement
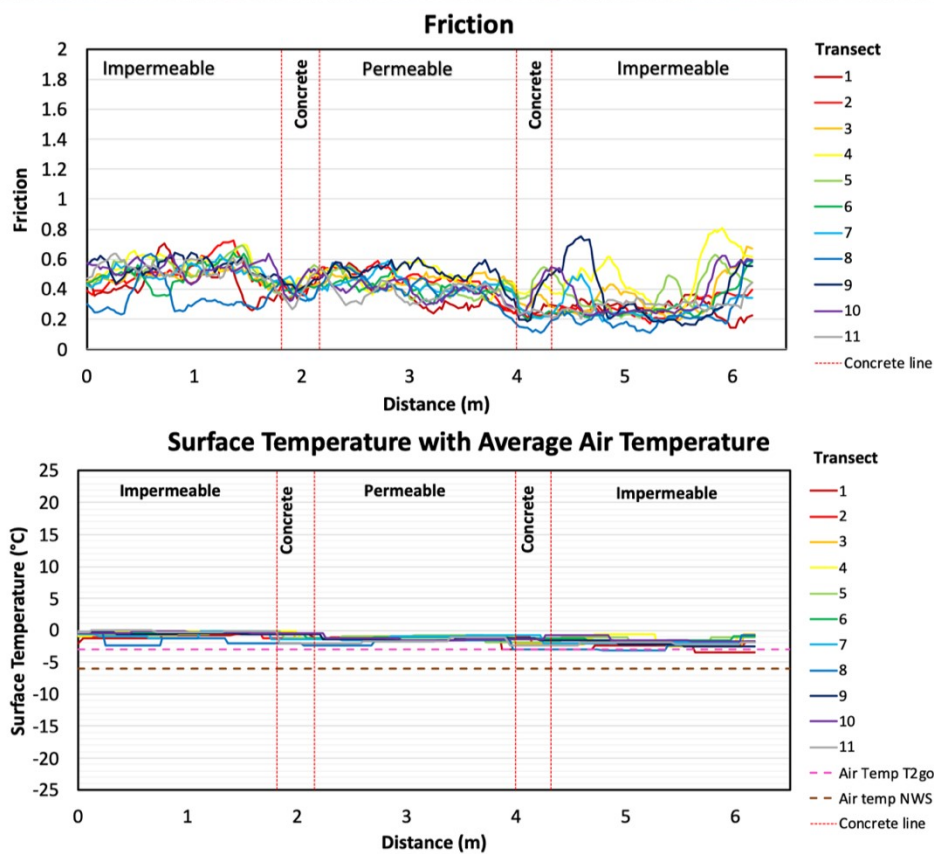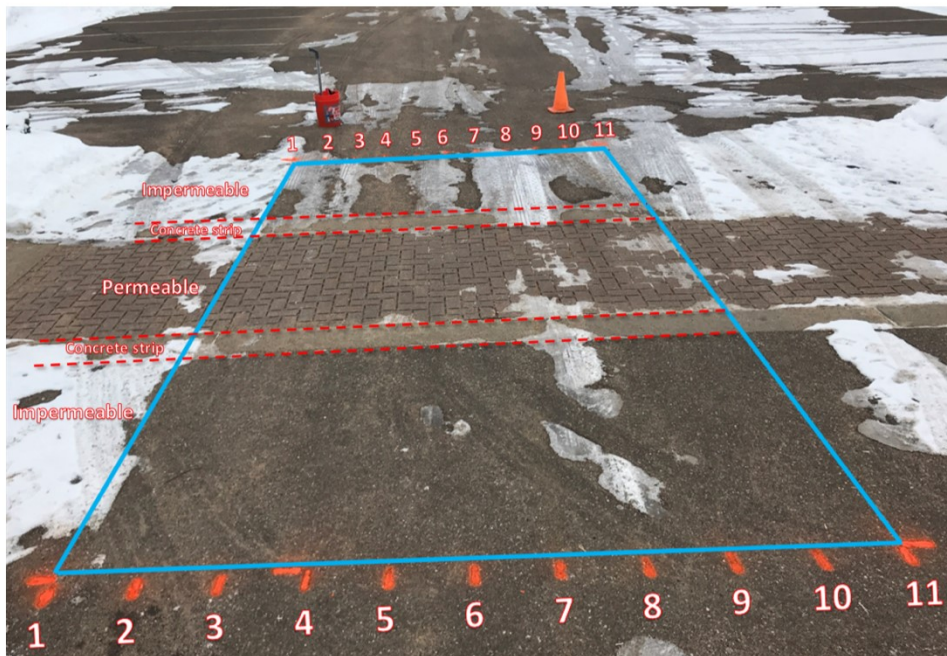
Figure 3.52 Surface friction, surface temperature, air temperature, and photo of testing space for Impermeable and Permeable Pavement at First Presbyterian Church in Stillwater, MN.

When comparing the friction, the impermeable asphalt sections have similar overall friction (average μ = 0.41) and similar overall surface temperature (average T = -1.26°C) compared to the permeable pavement (average μ = 0.43, average T = -1.21°C). The photos illustrate that a portion of the impermeable section has bare pavement (foreground portion) and the other impermeable section (background portion) has snow and ice cover for most transects. The lack of snow and ice on the foreground impermeable section is supported by the friction values varying from 0.4 - 0.6 for most transects at distances of 0 - 1.8m. The average friction for the foreground section is average μ = 0.50 and average T = -0.59°C. The friction values for the foreground portion of impermeable pavement were less than friction values measured on other bare impermeable pavements because sand was applied throughout the parking lot to increase traction on icy portions. The friction values exceed the manufacturer recommendations for caution (μ < 0.35).

The snow and ice on the background impermeable section is evident from the friction data in Figure 3.52, as shown by most transects with friction values of 0.1 to 0.4 at distances of 4.3 - 6.2m. The average friction for this section is average μ = 0.29 and average T = -1.92°C. These values are less than the friction and surface temperature for the foreground of the impermeable section, demonstrating the impact of the snow and ice cover. Most of the background portion of impermeable pavement is categorized as unsafe (μ < 0.25) or cautious (μ < 0.35) according to the manufacturer recommendations.

The permeable pavement has small portions of snow and ice for a few transects. Friction values for this portion are 0.25 to 0.6 for all transects at distance 2.2 - 4m (Figure 3.52) with an average μ = 0.43. The friction values exceed the manufacturer recommendations for unsafe (μ < 0.25) but some portions are recommended as cautious (μ < 0.35) according to the manufacturer recommendations.

3.3.20 Woodbury Christ Episcopal Church

The Christ Episcopal Church in Woodbury, MN has portions of the parking lot constructed with permeable interlocking block pavers immediately adjacent to impermeable asphalt. Friction and surface temperature were measured on a 10ft x 10ft section covering a 5 ft length of impermeable asphalt (foreground) and 5 ft of permeable block pavers (background), as shown in Figure 3.53.
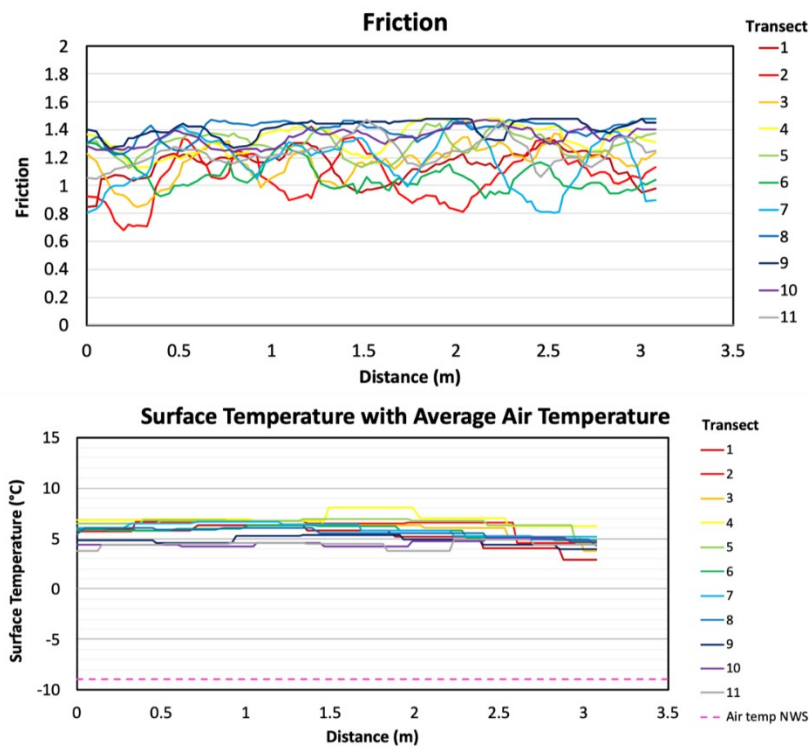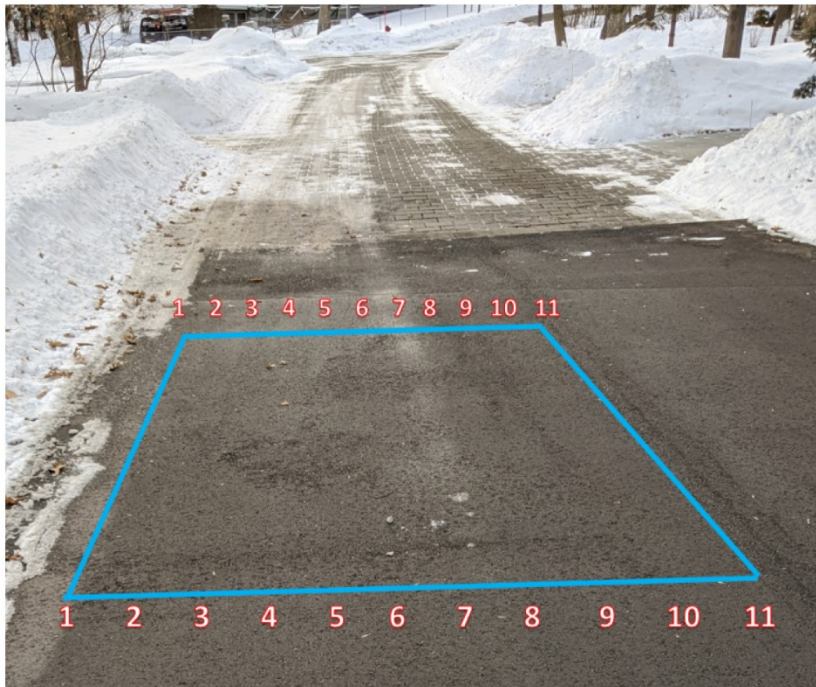
Impermeable and Permeable Pavement
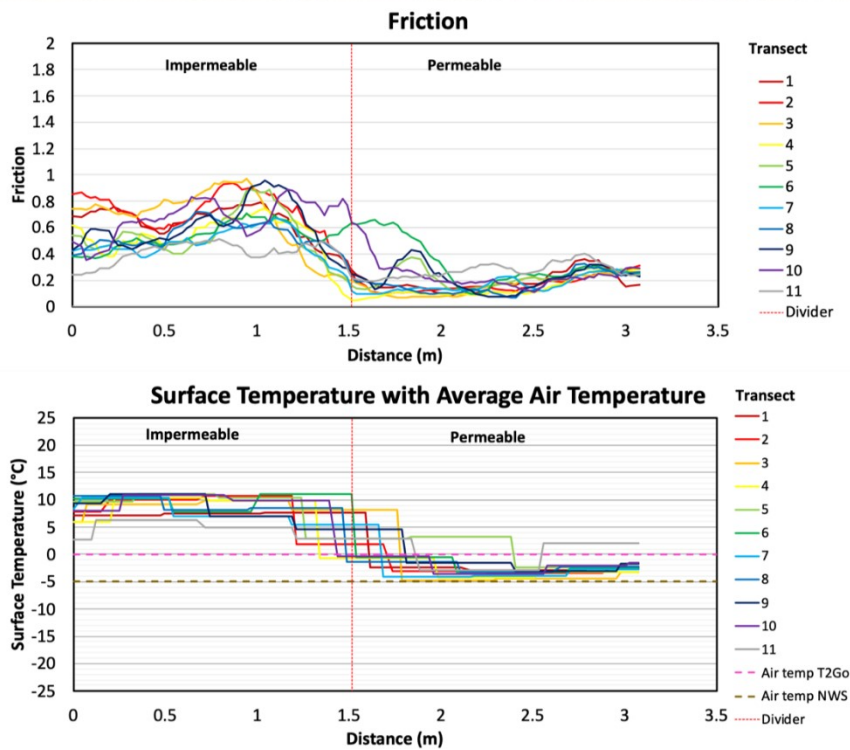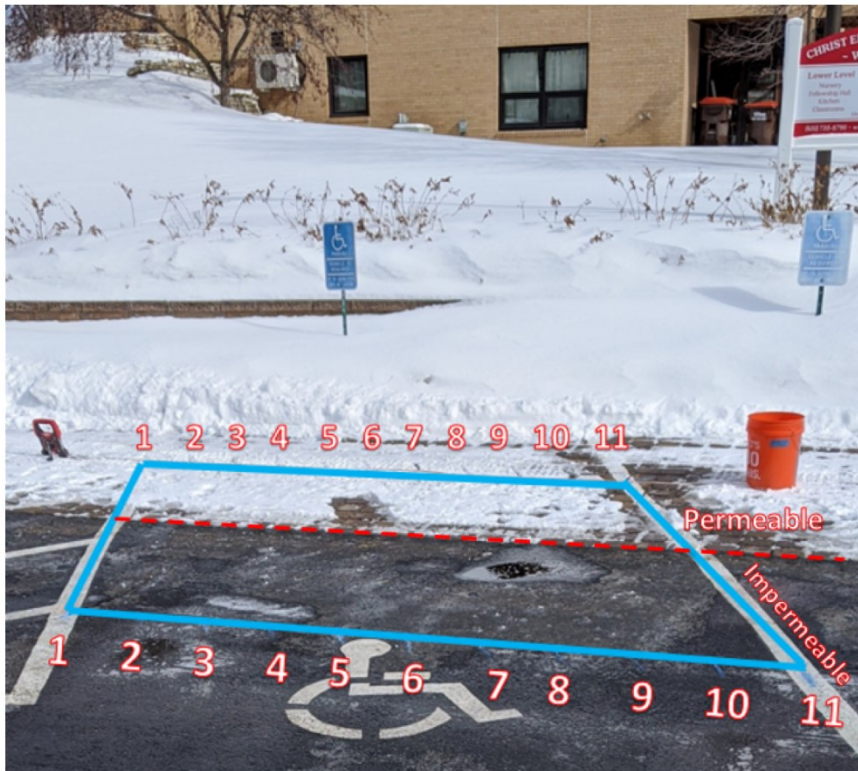
Figure 3.53 Surface friction, surface temperature, air temperature, and photo of testing space for Impermeable and Permeable Pavement at Christ Episcopal Church in Woodbury, MN.

When comparing the friction, the impermeable asphalt section has more friction (average μ = 0.57) and warmer surface temperature (average T = 8.21°C) compared to the permeable pavement (average μ = 0.21, average T = -1.80°C). The photos illustrate that the impermeable section has bare pavement (foreground portion) and the permeable section (background portion) has snow and ice cover over most of the surface. The lack of snow and ice on the foreground impermeable section is supported by the friction values varying from 0.8 - 1.0 for most transects at distances of 0 - 1.5m. The friction values exceed the manufacturer recommendations for caution (μ < 0.35).

The snow and ice on the permeable section is evident from the friction data in Figure 3.53, as shown by most transects with friction values of 0.1 to 0.4 at distances of 1.5 - 3m. The average friction for this section is μ = 0.21 and average T = -1.80°C. These values of friction and surface temperature are explained by the snow and ice cover. The surface temperature for the permeable is similar to the ambient air temperature (NWS) due to the snow and ice. Most of the permeable pavement is categorized as unsafe (μ < 0.25) or cautious (μ < 0.35) according to the manufacturer recommendations.

3.3.21 Woodbury Public Works

The Woodbury Public Works Facility in Woodbury, MN has a section of permeable asphalt parking. Friction and surface temperature were measured on a 10ft x 10ft section covering approximately 2/3rds of one stall in each of the permeable asphalt and impermeable asphalt, as shown in Figures 3.54 and 3.55.

Impermeable Pavement
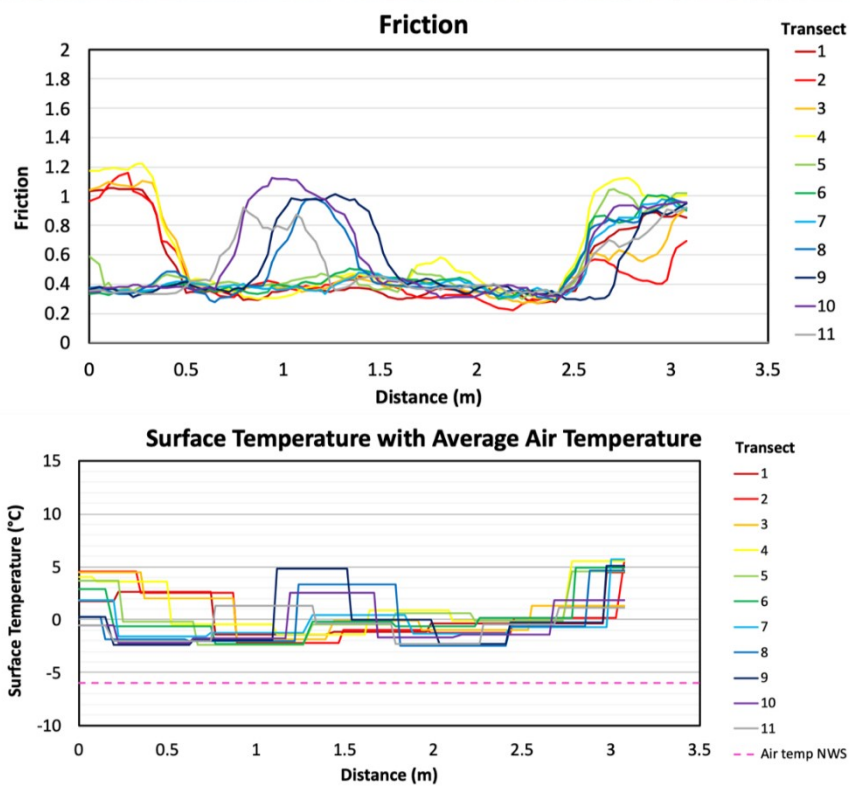
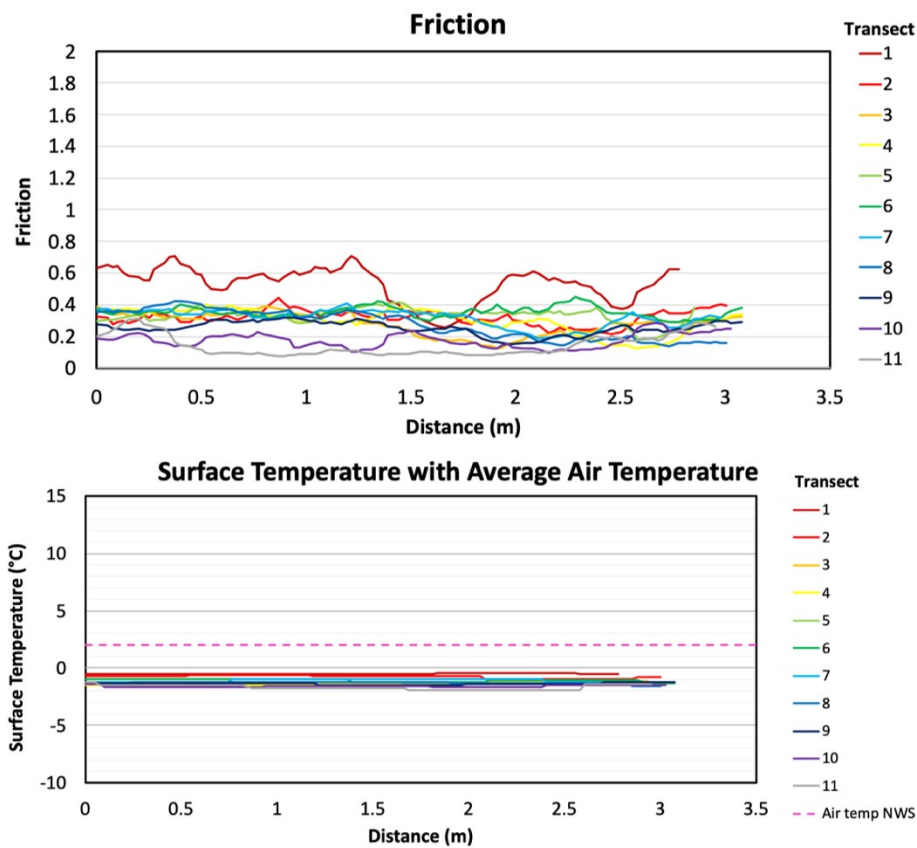**Figure 3.54 Surface friction, surface temperature, air temperature, and photo of testing space for Impermeable Pavement at Woodbury Public Works Facility.**
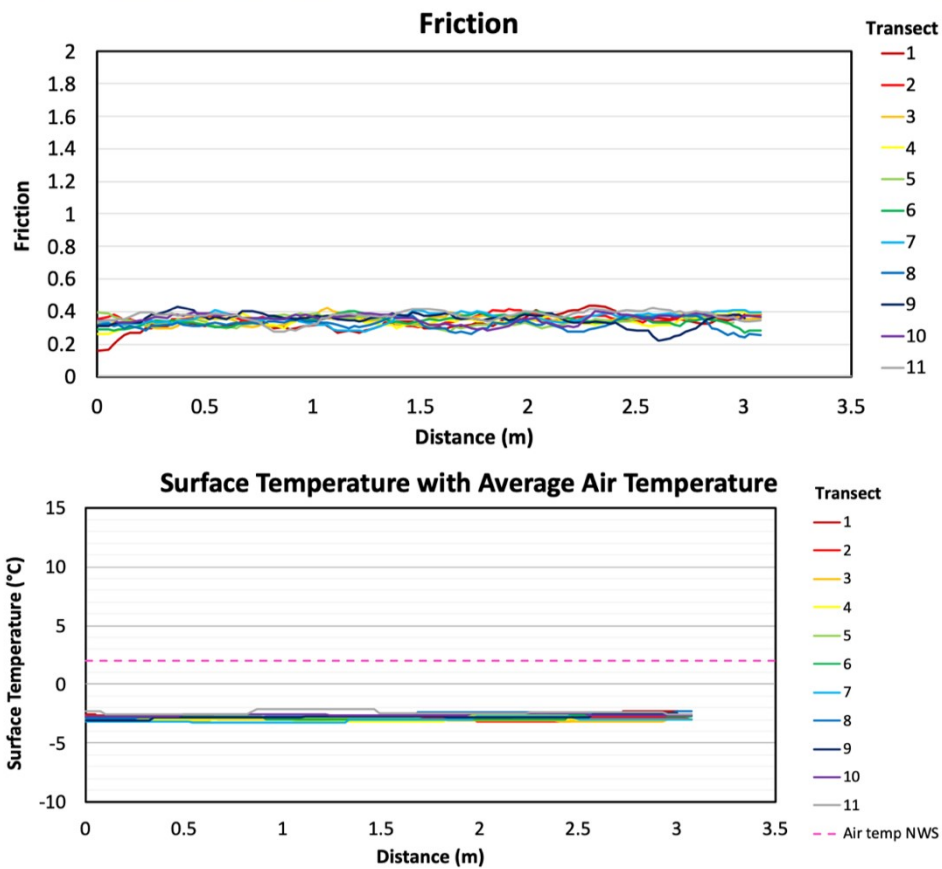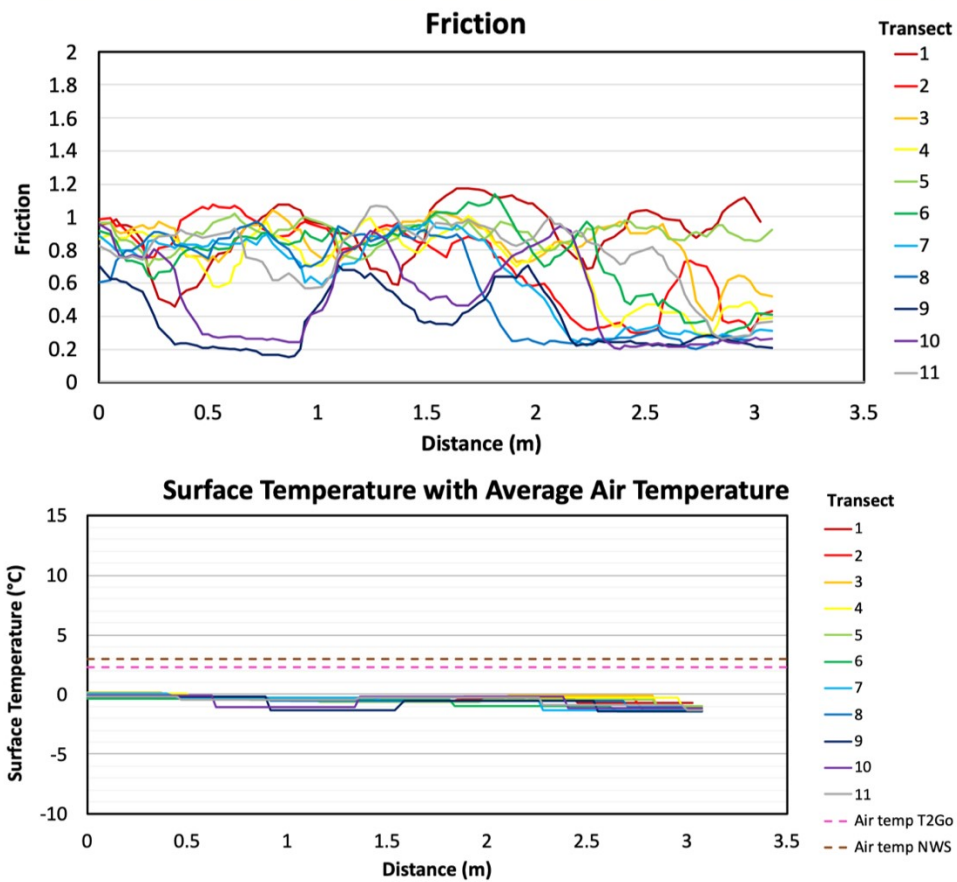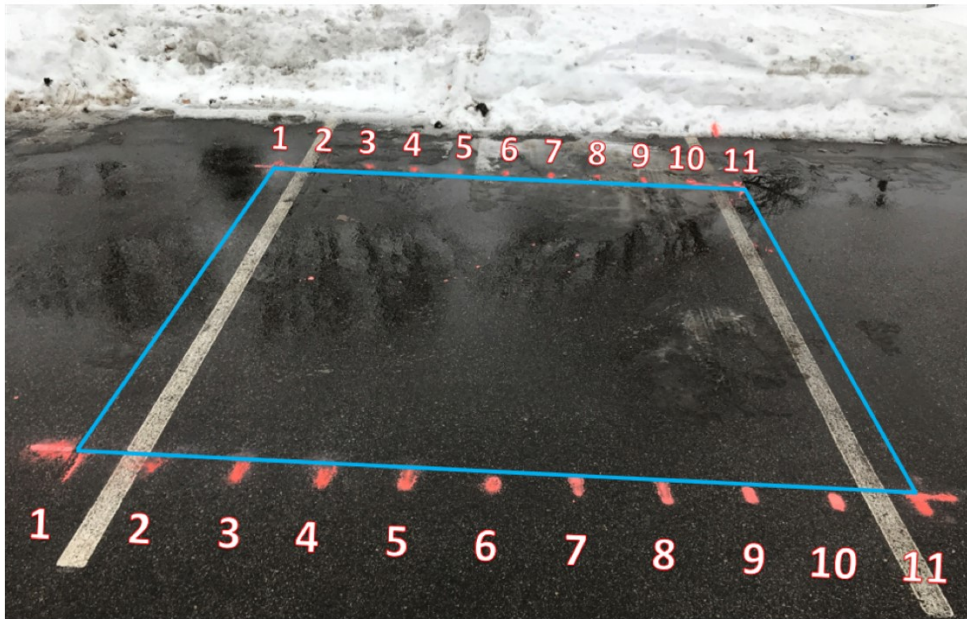
Permeable Pavement
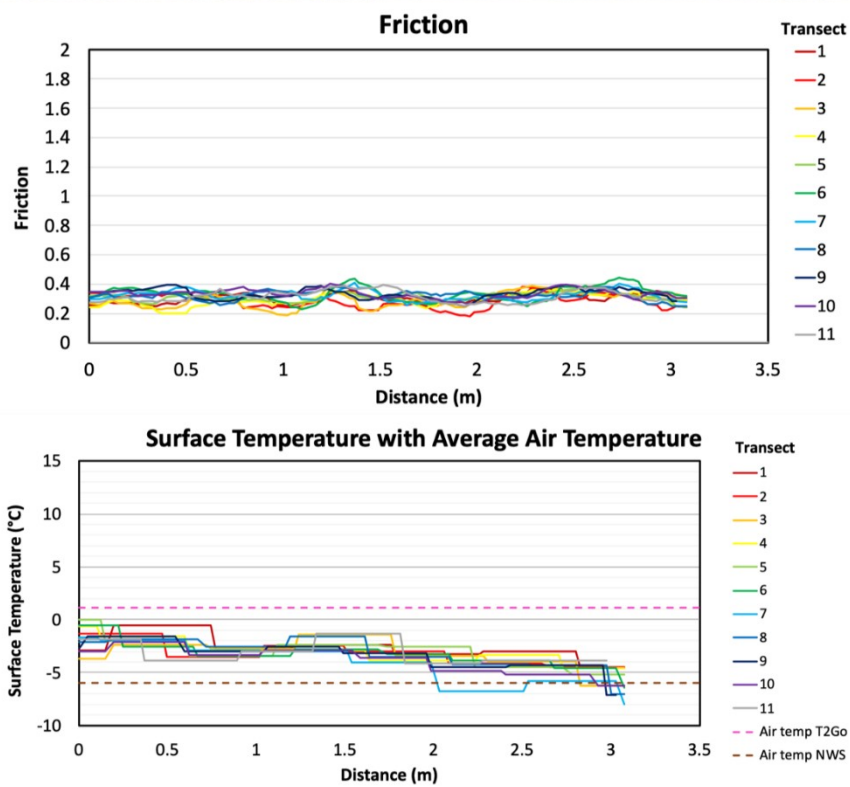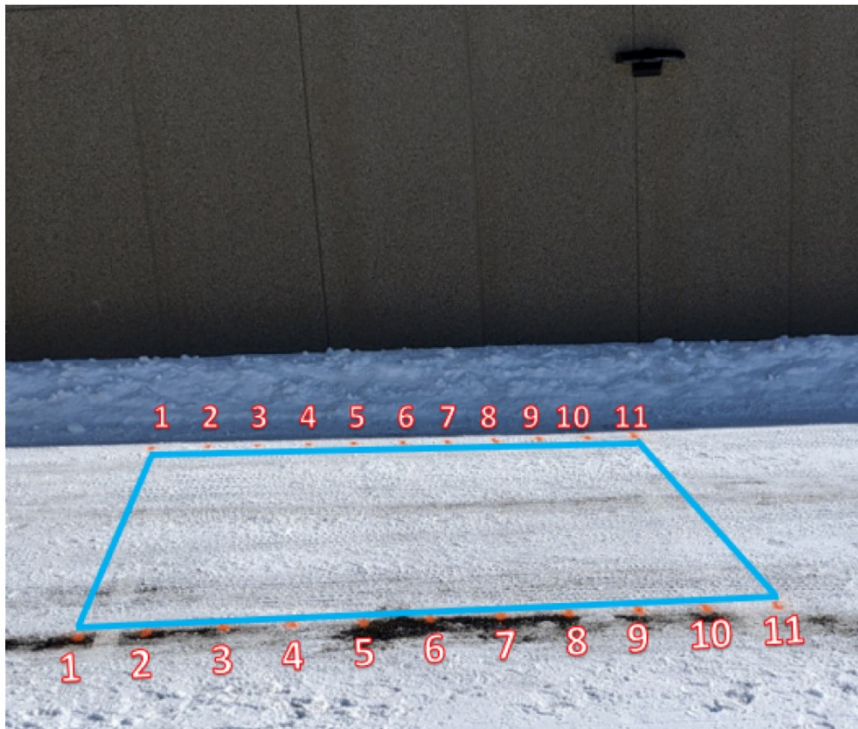
Figure 3.55 Surface friction, surface temperature, air temperature, and photo of testing space for Impermeable Pavement at Woodbury Public Works Facility.

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When comparing the friction, the impermeable section has more friction (average μ = 0.52) and warmer surface temperature (average T = 0.03°C) compared to the permeable pavement (average μ = 0.33, average T = -3.23°C). The photos illustrate that the impermeable section has some snow and ice cover with small patches of bare pavement. The bare pavement on the impermeable section is evident from the friction data in Figure 3.54, as shown by some transects at distances of 0 - 0.5m, 0.75 - 1.5m, and 2.5 - 3m with friction values greater than 0.5. For most transects at distances of 0 - 2.5m, the friction is roughly 0.4, which is greater than but close to manufacturer recommendations for caution (μ < 0.35).

By contrast, the permeable pavement has snow cover for all transects and all distances, with friction values of 0.2 to 0.4 (Figure 3.55). Most of the measurements of the permeable pavement are categorized as unsafe (μ < 0.25) or cautious (μ < 0.35) according to the manufacturer recommendations.

The difference in temperature (impermeable average T = 0.03°C vs. permeable average T = -3.23°C) can be explained by the difference in snow and ice cover. The impermeable asphalt has some patches of bare pavement that exhibit greater friction and higher temperature (Figure 3.54) compared to the areas of snow and ice cover. This is supported by the observation that the surface temperature in areas of snow and ice are similar to ambient air temperature (NWS) whereas the portions of bare pavement are warmer (~5°C). The overall surface temperature on the permeable pavement colder than the impermeable pavement because the surface is completely covered in snow an ice, which no visual evidence of bare pavement.

3.3.22 Conclusions from Year 4

Table 3.1 below summarizes measurement data of existing conditions for multiple sites in year 4, including friction, surface and air temperature, and presence of snow and/or ice. Note that there were 21 locations and 22 "sites" including the two permeable pavement sites at Ramsey Washington Metro Watershed District (15 and 16 in Table 3.1 below; discussed in section 3.2.15 above).

Table 3.1 Summary of Existing Conditions Measurements of average friction, average surface temperature, air temperature, and presence of snow and/or ice. Note: comparison cells are shaded orange when impermeable values are greater than permeable values and shaded green when impermeable values are less than permeable values.

Site	Friction (μ)			Surface Temperature (°C)			Permeable Surface vs. Air Temp	T2Go Air Temp (°C)	NWS Air Temp (°C)	Snow or Ice[1]			Pooled Water[2]		
	Impermeable	< = >	Permeable	Impermeable	< = >	Permeable				Impermeable	< = >	Permeable	Impermeable	< = >	Permeable
1 Blaine Fire Department	1.18	>	0.39	7.43	>	-0.29	≃	0.42	-1	None	<	Snow/Ice	None	≃	Snow
2 Blaine Lakeside Commons Park	1.17	≃	1.18	-1.12	≃	-1.54	≃	N/A	-5	None	≃	None	None	≃	None
3 Blaine Public Works Facility	1.36	>	1.01	5.93	>	3.98	>	2.02	-2	None	≃	None	None	≃	None
4 Falcon Heights City Hall	0.70	>	0.55	-0.12	<	0.44	≃	N/A	0	Some	<	More	Some	>	Snow
5 Inver Grove Heights, Target Parking Lot	0.92	>	0.72	1.72	>	0.05	≃	N/A	0	Some	<	More	Some	≃	Some
6 Mahtomedi Century College	1.23	>	1.02	3.82	<	4.74	>	2.11	-2	None	≃	None	None	≃	None
7 Mahtomedi District Education Center	0.61	>	0.39	-0.34	>	-2.50	≃	-2.24	-2	Some	<	More	Some	>	Snow
8 Mahtomedi Public Works	0.94	>	0.75	1.46	<	3.23	>	0.53	-1	Some	<	More	Some	>	Snow
9 Mahtomedi Universalist Church	1.15	>	1.01	3.09	<	4.29	>	1.61	-4	None	≃	None	None	≃	None
10 Maplewood Public Works	0.90	<	1.17	8.67	<	11.72	>	3.46	1	None	≃	None	None	≃	None
11 Minneapolis Pearl Park	0.48	≃	0.45	1.31	>	-1.12	≃	3.57	-2	Some	<	More	None	≃	Snow
12 North St. Paul Church of St. Peter	1.18	≃	1.15	5.67	≃	5.55	>	N/A	-1	None	<	Some	None	≃	Snow
13 North St. Paul Preservation Park	0.84	>	1.24	8.90	>	6.27	>	5.35	1	Some	<	Some	Some	>	None
14 Roseville Fire Department	1.16	≃	1.16	4.17	<	4.78	>	N/A	-6	None	≃	None	None	≃	None
15 Ramsey Washington Metro Watershed District (Perm Concrete)	1.23	≃	1.08	10.17	>	2.01	>	N/A	-7	None	≃	None	None	≃	None
16 Ramsey Washington Metro Watershed District (Perm Pavers)	1.23	≃	1.23	10.17	>	8.40	>	N/A	-7	None	≃	None	None	≃	None
17 Shoreview Janice Street	1.24	>	0.75	5.67	>	-1.26	>	N/A	-9	None	<	Some	None	≃	Snow
18 Shoreview Oakridge Avenue	0.30	<	0.35	-1.21	>	-2.79	<	N/A	2	Most	<	All	Some	>	Snow
19 Shoreview Ramsey County Library	0.70	>	0.36	-0.50	≃	-0.90	<	2.25	3	Some	<	More	Some	>	Snow
20 Stillwater First Presbyterian Church	0.41	≃	0.43	-1.26	≃	0.43	>	-2.90	-6	Some	≃	Some	None	≃	None
21 Woodbury Christ Episcopal Church	0.57	>	0.21	8.21	>	-1.80	>	0.02	-5	None	<	All	Some	>	None
22 Woodbury Public Works	0.52	>	0.33	0.03	>	-3.23	>	N/A	-6	Most	<	All	Some	>	Snow

Friction (μ)			Surface Temperature (°C)		
Imp > Perm	13	59%	Imp > Perm	12	55%
Imp ≃ Perm	7	32%	Imp ≃ Perm	4	18%
Imp < Perm	2	9%	Imp < Perm	6	27%

Snow or Ice[1]			Pooled Water[2]		
Imp > Perm	0	0%	Imp > Perm	8	36%
Imp ≃ Perm	9	41%	Imp ≃ Perm	14	64%
Imp < Perm	13	59%	Imp < Perm	0	0%

[1]Snow or Ice cover describes the amount of snow and/or ice on the surface during measurements. None = bare pavement; Some = less than half of the pavement covered; More = more than the other pavement type; All = completely covered with snow and/or ice.

[2]Pooled water describes the presence or absence of pooled water on the pavement surface. None = no standing water. Some = Some standing water. Snow = No standing water, but snow covered.

Of the 22 sites in which friction and surface temperature were measured, 13 sites (59%) had more friction on the impermeable pavement compared to the permeable pavement; 7 sites (32%) had similar friction (typically bare pavement), and 2 sites (9%) had less friction on the impermeable pavement compared to the permeable. This suggests that under typical mid-late winter conditions, more sites of impermeable pavement had more friction than permeable pavements.

Of the 22 sites, 12 sites (55%) had warmer surface temperatures on the impermeable pavement compared to the permeable pavement; 4 sites (18%) had similar temperatures ($\Delta T < -0.5°C$), and 6 sites (27%) had cooler surface temperatures on the impermeable pavement compared to the permeable pavement. Similar to surface friction, more sites of impermeable pavement had warmer surface temperatures compared to permeable pavements. Warmer temperatures typically indicate less snow and ice cover at the time of measurement and higher potential to melt snow and ice when ambient air temperature is near freezing. In general, more friction should correlate to warmer surface temperatures. In contrast to the friction data, however, more permeable pavement sites had warmer temperatures (n = 6) compared to the permeable pavement sites with more friction (n = 2). All six of these measurements occurred when the pavement surface temperature was above, but near freezing temperature. If precipitation or snowmelt occurred at the time of measurement, the warmer permeable pavement could infiltrate the precipitation before the air (and pavement) temperature decreased enough to freeze the precipitation to the surface. If the same precipitation fell on an impermeable pavement, it's possible that it would not runoff and thus be susceptible to freezing when the ambient air (and surface temperature) decreased below freezing. Thus, permeable pavements may have more potential to melt snow and ice than unsalted impermeable pavements.

Of the 22 sites, 13 sites (59%) had less snow and/or ice cover on the impermeable pavement compared to the permeable pavement; 9 sites (41%) had similar snow/ice cover on both pavements, and none of the sites had more snow/ice on the permeable pavement compared to the impermeable pavement. Visual observations mimic the friction measurements described above in that the same number of sites (n = 13) had more friction and less snow on the impermeable compared to the permeable. The sites that had more friction, however, did not correspond exactly with the sites that have less snow.

Finally, of the 22 sites, 8 sites (36%) had more pooled water on the impermeable pavement compared to the permeable pavement; 14 sites (64%) had similar or no pooled water on both pavements, and none of the sites had less pooled water on the impermeable pavement compared to the permeable pavement. This demonstrates the primary winter benefit of permeable pavements: meltwater can infiltrate through permeable pavements and prevent refreezing. Refreezing of meltwater on impermeable pavements creates dangerously slippery conditions which can be avoided with functional permeable pavements.

3.4 SUMMARY OF RESULTS - YEAR 4 - JAY PLACE, EDINA, MN WATER DISSIPATION TEST

Similar to the test conducted at the Maplewood Public Works Facility in Year 2, one site was selected in Year 4 to measure the dissipation of cold water added to frozen pavement surfaces, both impermeable and permeable. The site for Year 4 was on Jay Place in Edina, MN. The friction and surface temperature of the existing conditions (bare pavement) were measured first, then about 6 L of cold water was added to approximately ½ of each of the 10ft x 10ft (3m x 3m) pavement sections and allowed to freeze or infiltrate. The friction and surface temperature were measured again to determine how much of the water froze on the surface and decreased friction. Any ice on the surface was then melted with a flame torch to restore the pavements to bare pavement condition. The friction and surface temperature were measured for the existing conditions and after water was added and allowed to freeze on both the impermeable asphalt and the permeable interlocking concrete paver blocks, as shown in Figures 3.56 - 3.59.

Impermeable Pavement – Existing Conditions
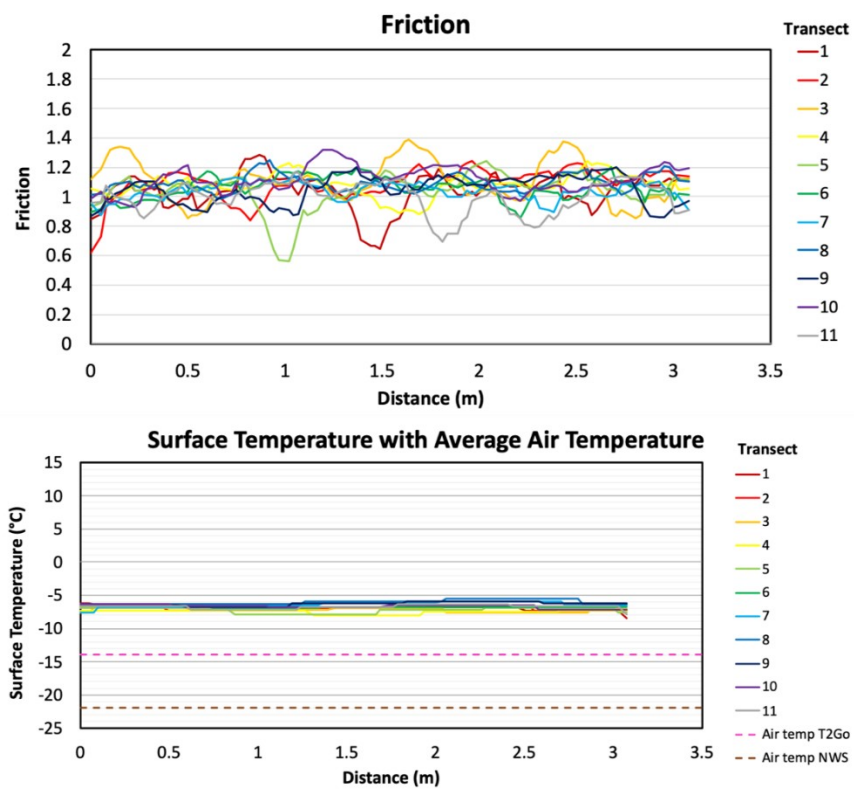
Figure 3.56 Surface friction, surface temperature, air temperature, and photo of testing space for Impermeable Pavement, prior to adding water, on Jay Place in Edina, MN.

Impermeable Pavement:
Cold Water Added, Allowed to Freeze
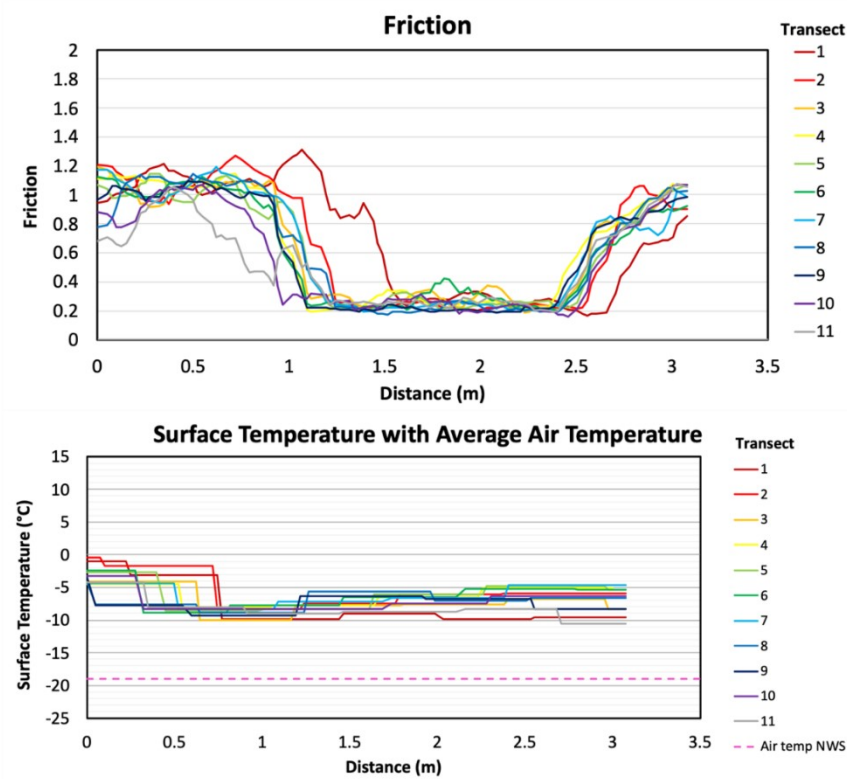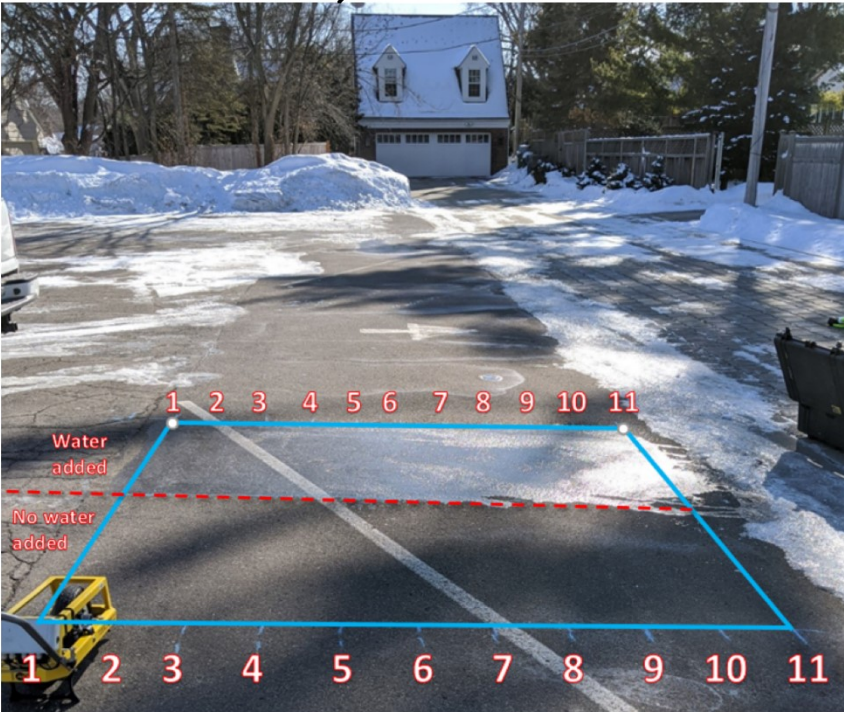
Figure 3.57 Surface friction, surface temperature, air temperature, and photo of testing space for Impermeable Pavement, after adding water, on Jay Place in Edina, MN.

When comparing the friction, the impermeable section prior to water being added (Figure 3.56) has more friction (average μ = 1.07) and warmer surface temperature (average T = -6.77°C) compared to the impermeable pavement after water was added (average μ = 0.61, average T = -6.89°C, Figure 3.57). The photos illustrate that there was bare pavement throughout the surface prior to water being added. After water was added to half of the surface, the temperature and friction decreased on the portion in which the water froze into ice. Friction values were μ = 0.2 on the ice portion (distance = 1 - 2.5m) for all transects.

Permeable Pavement – Existing Conditions
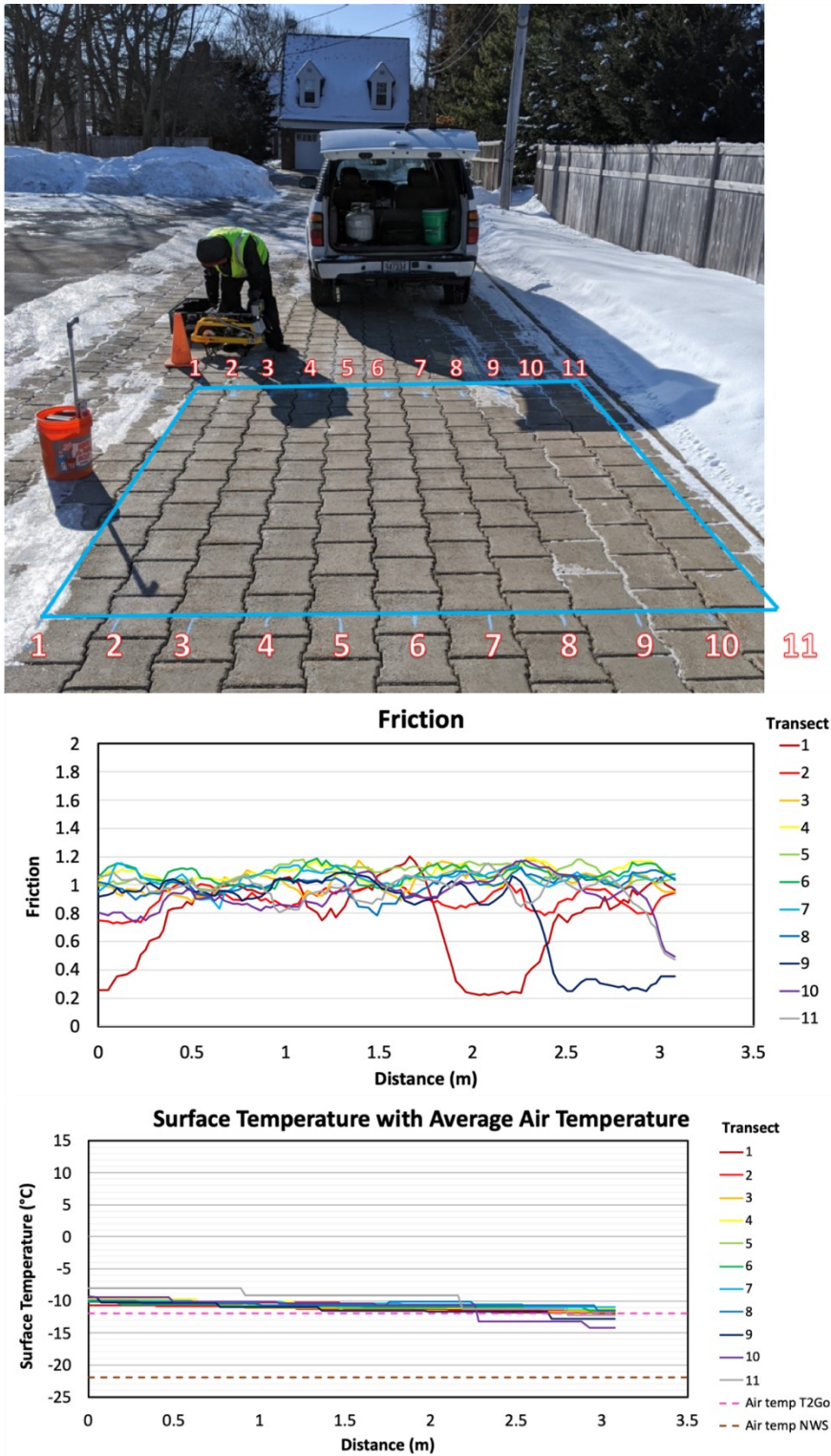
Figure 3.58 Surface friction, surface temperature, air temperature, and photo of testing space for Permeable Pavement, prior to adding water, on Jay Place in Edina, MN.

When comparing the friction, the impermeable section prior to water being added (Figure 3.56) has similar friction (average μ = 1.07) and warmer surface temperature (average T = -6.77°C) compared to the permeable pavement prior to water being added (average μ = 0.97, average T = -10.72°C, Figure 3.58). The photos illustrate that there was bare pavement throughout the impermeable surface prior to water being added and a small amount of ice present on the permeable pavement prior to water being added. The ice is evident in the friction values for transects 1 and 9 of μ = 0.2 for distances 2 - 2.5m and 2.5 - 3m, respectively. After water was added to half of the surface, the temperature and friction decreased on the portion in which the water froze into ice. Friction values were μ = 0.2 on the ice portion (distance = 1 - 2.5m) for all transects.

Permeable Pavement:
Cold Water Added, Allowed to Freeze
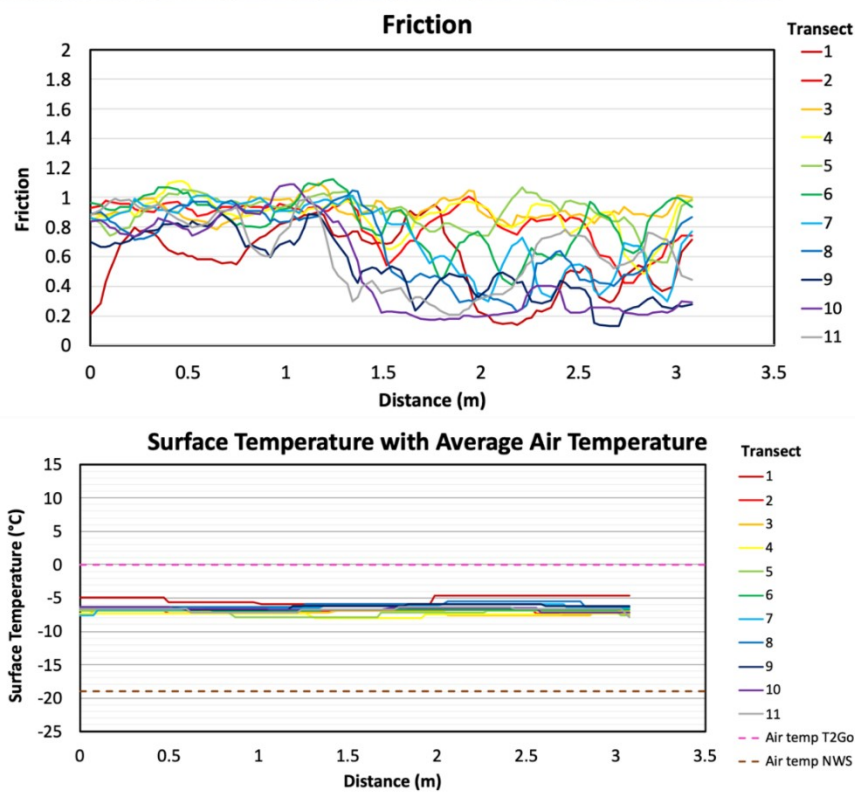
Figure 3.59 Surface friction, surface temperature, air temperature, and photo of testing space for Permeable Pavement, after adding water, on Jay Place in Edina, MN.

When comparing the friction, the impermeable section after water was added (Figure 3.57) has less friction (average μ = 0.61) and similar surface temperature (average T = -6.89°C) compared to the permeable pavement after water was added (average μ = 0.73, average T = -6.64°C, Figure 3.59). The photos illustrate that there after water was added to half of the impermeable surface, the temperature and friction decreased on the portion in which the water froze into ice. After water was added to the permeable pavement, only some of the transects exhibited a decrease in friction. This is likely due to water seeping into the pore spaces between the interlocking paver blocks, reducing the amount of water available to freeze on the surface. Where ice did form on the permeable pavement, the friction values were μ = 0.2 which was similar to the impermeable pavement in areas in which ice formed.

This test demonstrates that when cold water (e.g., freezing rain) is applied to impermeable and permeable pavements when below freezing, the liquid may freeze to the permeable pavement faster if the surface is colder, but may also be infiltrated into the open pore spaces. For this water dissipation test, this resulted in overall more friction on the permeable pavement where water was added compared to the impermeable pavement onto which water was added. This demonstrates the capability of permeable pavements to infiltrate meltwater even when the air and pavement surface temperatures are below freezing.

CHAPTER 4: MODELING

The goal of the Task 4 modeling effort is to use computer models to help determine the physical mechanisms that cause permeable and impermeable pavements to behave differently in winter conditions. Questions we aim to address in this task include:

1) How are the thermal properties of permeable and impermeable pavements different and how does this affect the road surfaces during winter precipitation events?
2) We know that permeable pavement infiltrates rainfall in above-freezing conditions, but how does permeable pavement behave during snowfall events, and how does this affect the need for road de-icing?

The modeling effort in Task 4 built upon previous pavement temperature models developed at SAFL for MnDOT (Herb et al. 2006). The pavement temperature models simulate the variation of pavement temperature over time and depth, based on the thermal properties of the pavement and base layers, and the local weather conditions. The models are one-dimensional, simulating temperature over a series of discrete layers (Figure 4.1) extending from the pavement surface to 10 meters depth. The heat transfer processes included in the models include surface heat transfer with the atmosphere and vertical heat conduction through the pavement and base layers (Figure 4.2). The surface heat transfer processes include solar radiation, long wave radiation, convection, and evaporation. The output of the models is the temperature of each pavement and base layer at 15-minute intervals. The models are currently written in Fortran and run on a laptop PC.
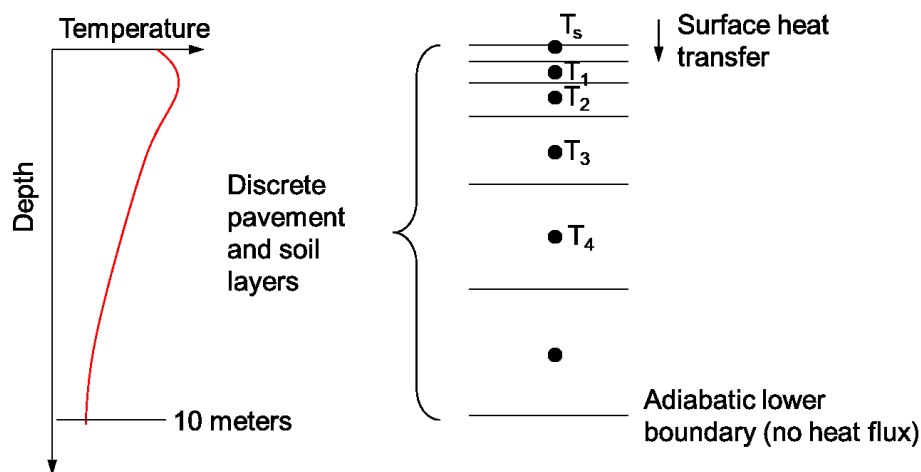
Figure 4.1 Schematic of the one-dimensional pavement temperature models.
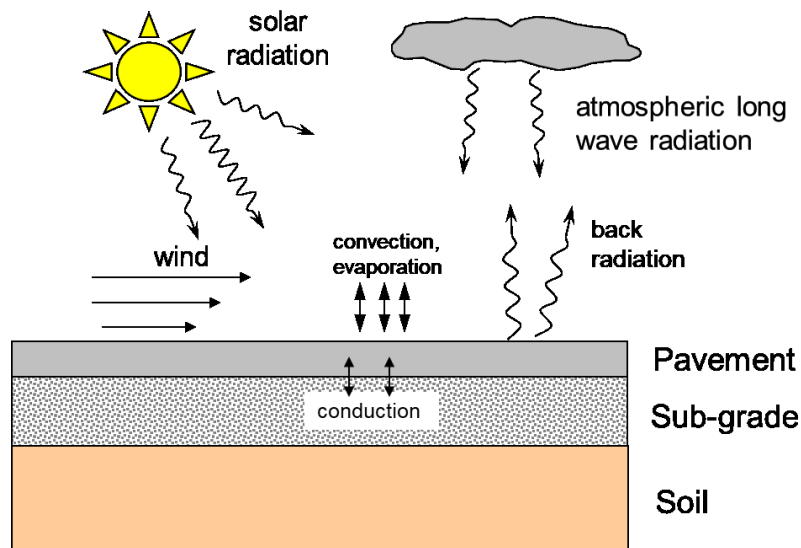
Figure 4.2 Illustration of the heat transfer processes included in the pavement temperature model.

4.1 PAVEMENT TEMPERATURE MODEL MODIFICATIONS FOR PERMEABLE PAVEMENT

To simulate temperature in permeable pavements, the pavement temperature models required several modifications. To help bound the bulk and surface heat transfer properties of permeable pavement, a literature search was conducted. Data were compiled for both asphalt and concrete permeable pavement. Based upon this literature search, the bulk heat transfer properties (thermal conductivity, density, specific heat) and the surface heat transfer properties (surface roughness, albedo, emissivity) in the pavement model were set to values appropriate for permeable pavement (Table 4.1, from Hu et al. 2017), and the heat transfer associated with rainfall infiltration through the pavement was added.

The pavement temperature model was also modified to include water infiltration through the pavement and base layers. Previously developed models for water infiltration through soil were used (Herb et al. 2009). Literature on the hydraulic properties of permeable pavement (e.g. Izevbekhai 2011) document high infiltration rates (0.1-4 cm/s), so that for typical rainfall events, the infiltration rate is equal to the rainfall rate. The calculated flux of infiltrating water through the porous pavement is used to calculate a corresponding advective heat flux, based on the temperature of the water and the temperature of the pavement.

The revised temperature model for permeable pavement was calibrated and tested using pavement temperature and climate data from the MnROAD facility. Most of the modeling effort to date has focused on a pervious concrete section (MnROAD cell 85). Initial model runs focused on simulating temperatures in summer, to calibrate the pavement thermal properties. An example of simulated and observed summer pavement temperatures for cell 85 is given in Figure 4.3. The accuracy of the temperature simulation was measured as the root-mean-square error, about 1.8 °C for the simulation for May-October, 2010.

Table 4.1 Variability of several bulk and surface heat transfer properties with porosity for conventional and permeable concrete pavement, from Hu et al. (2017). PCC=Portland cement concrete, PPCC=pervious Portland cement concrete.

Type	Particle Size (mm)	Porosity (%)	Apparent Density (kg/m³)	Albedo	Emissivity	Thermal Conductivity (W/m²/°C)	Specific Heat (J/kg/°C)
PCC	0.075–16.0	0.8	2100	0.432	0.96	1.4	1050
PPCC	2.36–4.75	15.1	2048	0.3557	0.95	1.28	920
PPCC	4.75–9.50	18.2	1974	0.3401	0.94	1.26	900
PPCC	9.50–13.2	20.1	1928	0.3305	0.94	1.23	870
PPCC	13.2–16.0	21.8	1887	0.3219	0.93	1.22	860
PPCC	16.0–19.0	24.9	1812	0.3063	0.92	1.2	840
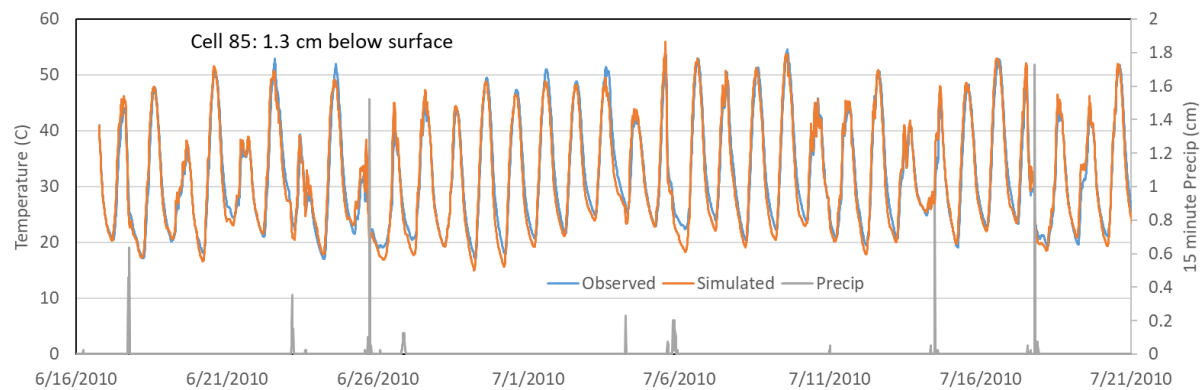
Figure 4.3 Time series of observed and simulated pavement temperature for MnROAD cell 85 (permeable concrete), 1.3 cm below the surface.

4.2 MODELING WINTER CONDITIONS

With a calibration for permeable pavement temperature in summer conditions, the next step was to add features to the model to enable better simulations of winter conditions with snow and ice cover. The different summer and winter precipitation conditions that need to be handled are summarized in Table 4.2. To handle the snow accumulation case, a separate layer for snow cover was added to the pavement temperature model – this layer is active when there is a snow cover on the pavement and is inactive for bare or wet pavement. Conduction between the snow layer and the pavement is simulated, and surface heat transfer between the snow layer and the atmosphere is simulated using the same methods as bare pavement. Precipitation input is assumed to be either rain or snow based on an air temperature threshold, currently set to 1.5 °C. Based on snowfall data from the Minneapolis/St. Paul airport, snowfall depth is assumed to be 13.3 times the measured precipitation depth from the heated rain gage at MnROAD. This factor of 13.3 is also used to set the density and thermal conductivity of the snow layer. The relationship between snow density and thermal conductivity is set using data from Yen (1981).

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Information on the timing of snow plowing events was added to the weather data input file – when a plowing event is indicated, the snow is assumed to be completely removed.

Preliminary winter simulations were performed for MnROAD cell 85. The results to date indicate that for dry snow on pavement, the pavement surface temperature is relatively constant over time (Figure 4.4), likely because 1) the snow acts as a thermal insulator and 2) it reflects most of the incident solar radiation.

Table 4.2 Summer and Winter Precipitation Cases

	Air Temp < 0 °C	**Air Temp > 0 °C**
Pavement Temp < 0 °C	Snow accumulation	Freezing rain
Pavement Temp > 0 °C	Snow melting	Rain
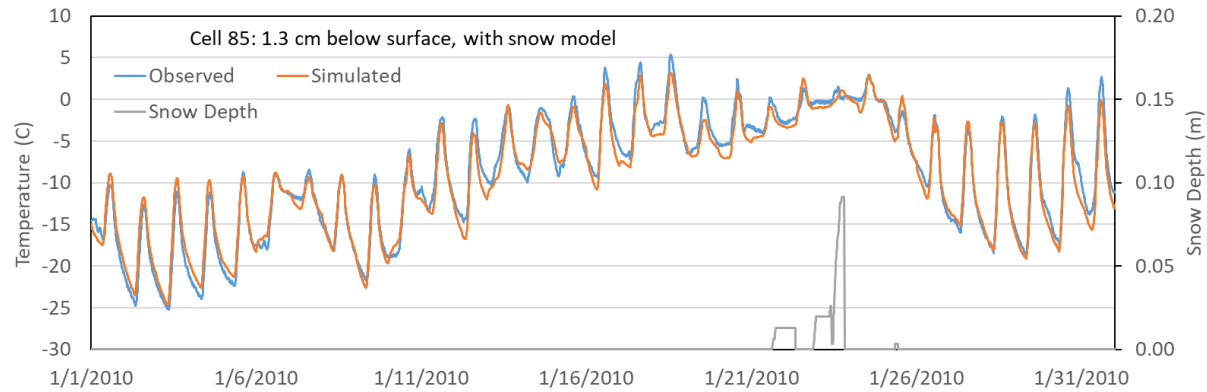
Figure 4.4 Time series of observed and simulated pavement temperature for MnROAD cell 85 (permeable concrete), 1.3 cm below the surface, in January 2010.

CHAPTER 5: PUBLIC OUTREACH AND ENGAGEMENT

Public outreach and civic engagement were achieved via oral presentations, publications, meetings/workshops, and a municipal survey.

5.1 ORAL PRESENTATIONS

The project team gave oral presentations at several venues that communicated the goals or the project or presented preliminary results. These presentations include the following:

1. Erickson, A.J. October 24, 2019. Invited to present "Recent, in progress, and future research on salt pathways, pavements, water softening, and all things chloride." Oral Presentation. 20th Annual Minnesota Road Salt Symposium. Vadnais Heights, MN.
2. Erickson, A.J. October 16, 2019. "The Challenge of Maintaining Stormwater Treatment Practices: A Synthesis of Recent Research and Practitioner Experience." Oral Presentation. Minnesota Water Resources Conference 2019. St. Paul, MN.
3. Gulliver J.S. April 25, 2019, "Investigation of Road Salt Alternatives and Pavement Innovations," co-presented with B.N. Wilson, CTS Environment and Energy in Transportation Council.
4. Weiss, P.T. October 30, 2018. "Permeable Pavements in Cold Climates: Lessons Learned from Practice and Research" at the 2018 Ohio Stormwater Association Watershed Workshop in Columbus, OH.
5. Erickson, A.J. August 13, 2018. "Permeable Pavement for Road Salt Reduction." Oral Presentation. 2018 ASCE/EWRI Low Impact Development Conference. Nashville, TN.
6. Erickson, A.J. July 26, 2018. Invited to present "Road Salt Research at UMN." Oral Presentation. Legislative Water Commission. St. Paul, MN.
7. Weiss, P.T. April 26, 2018. "Permeable Pavements in Cold Climates" at the Indiana Association for International Erosion Control Associations (Great Lakes Chapter) Great Connections Conference in Dubuque, Iowa.
8. Erickson, A.J. March 8, 2018. Invited to present "Permeable Pavement, Winter, and Roadsalt" Webcast, co-presented with Ryan Winston, Ohio State University. Chesapeake Stormwater Network. https://cwp.adobeconnect.com/_a1124522395/pkvxxe16bmx3
9. Erickson, A.J. February 22, 2018. Invited to present "Chloride accumulation and transport research in Minnesota" Webcast, co-presented with William Herb and Benjamin Janke. Chesapeake Stormwater Network. http://epawebconferencing.acms.com/p1txow4jjxu/
10. Weiss, P.T. September 7, 2017. "Permeable Pavements in Cold Climates" at the Indiana Association for Floodplain and Stormwater Management Annual Conference, South Bend, IN.
11. Weiss, P.T. August 21, 2017. "Permeable Pavements in Cold Climates" at the Permeable Pavement Success Workshop. Hosted by MS Consultants, Columbus, OH.
12. Weiss, P.T. (presenting), Gulliver, J.S., Kayhanian, M., and Khazanovich, L. June 1, 2017. "Permeable Pavements: Lessons learned from practice and research," at the Great Lakes and St. Lawrence Green Infrastructure Conference, May 31 – June 2, 2017.
13. Erickson, A.J. March 10, 2017. "Recent, Current, and Developing Stormwater Research at the University of Minnesota." Oral Presentation. 2017 CCWMO Stormwater Workshop. Chaska, MN.
14. Loida, B., B. Neuendorf, and J.S. Gulliver, August 29, 2016, "Stormwater Systems and Other Innovative Stuff," 2016 Public Works Stormwater Summit, American Public Works Association PWX Conference, Minneapolis, MN.

5.2 PUBLICATIONS

1. "Groundwater Impacts from Stormwater Infiltration Practices," by M. D. Trojan, J. S. Gulliver, and D.J. Fairbairn, in *Encyclopedia of Water: Science, Technology and Society*, P. A. Maurice, Ed., John Wiley & Sons, Inc., 2020.
2. Erickson, A.J., V.J. Taguchi, and J.S. Gulliver. (2018). "The Challenge of Maintaining Stormwater Control Measures: A Synthesis of Recent Research and Practitioner Experience." Journal of Sustainability Special Issue, 10, 3666. http://dx.doi.org/10.3390/su10103666.

5.3 MEETINGS/WORKSHOPS

1. Erickson, A.J. August 20, 2018. "LRRB: Permeable Pavement for Road Salt Reduction." Oral Presentation. Technical Advisory Panel for Permeable Pavement for Road Salt Reduction. Mn/DOT Waters Edge, Roseville, MN.
2. Erickson, A.J. April 19, 2018. "LRRB: Permeable Pavement for Road Salt Reduction." Oral Presentation. Technical Advisory Panel for Permeable Pavement for Road Salt Reduction. Mn/DOT Waters Edge, Roseville, MN.
3. Weiss, P.T. Permeable Pavement Road Map Workshop, University of California-Davis, November 14-15, 2017.

5.4 MUNICIPAL SURVEY

1. Erickson, A.J., and J.S. Gulliver. Survey of Minnesota Cities Stormwater Coalition members for "Permeable Pavement Sites in Minnesota." Distributed January 16, 2018. Twenty responses identifying 44 locations.

CHAPTER 6: CONCLUSIONS

This report describes research that investigated the use of permeable pavements that are not treated with road salt as an alternative to impermeable pavement surfaces that are treated with road salt. The primary research question is this: Do unsalted permeable pavements have more, the same, or less snow and ice than salted impermeable pavements during winter conditions in cold climates? To answer this question, the research project included a review of the existing literature to identify methods in which snow and ice could be quantifiably and repeatably measured on various pavement surfaces. Then, various methods were used to quantify the snow and ice cover on permeable pavements under various conditions and compare the results to snow and ice cover on impermeable pavement surfaces under near-identical environmental conditions. The methods employed included photographic, temperature (air, surface, and in-pavement), and surface friction measurements.

Research data prior to the current project by Wenck (2014) were evaluated and the following conclusions about permeable and impermeable pavements during mid-winter (e.g., January or February) were observed:

- During mid-winter (e.g., January or February) when the pavement surface temperature is warmer than the subbase temperature (e.g., at 18"), the permeable pavement surface is warmer than the impermeable pavement surface. Conversely, when the pavement surface temperature is colder than the subbase temperature (e.g., at 18"), the permeable pavement surface is colder than the impermeable pavement surface.
- During mid-winter (e.g., January or February), the difference in temperature between the surface and approximately 18" below the surface is greater in the permeable pavement compared to the impermeable pavement, regardless of the pavement surface temperature. In addition, the subbase temperature at 18" below the surface is warmer in the permeable pavement compared to the impermeable pavement. This suggests that permeable pavements and the porous subbase beneath them function as thermal insulators, preventing heat transfer from the surface to below or vice versa.

During the current research project, photographic methods determined that the presence of snow could be easily identified, and time lapse comparisons could demonstrate when impermeable pavements had snow and permeable pavements did not, or vice versa. Unfortunately, photographic methods were not able to distinguish between ice and water on the pavement, and thus were not adequate for determining if the pavement surface was slippery.

The air temperature, pavement surface temperature, and in-pavement temperature profiles were measured for a number of sites for the purpose of predicting surface conditions without other technology. As identified in the literature, a difference between the air temperature, surface temperature, and in-pavement temperature can be used to predict the pavement surface conditions. We found that a comparison of temperature alone was not sufficient or consistent to predict whether the surface was covered or what covered the pavement (e.g., snow, ice, water, etc.).

Finally, surface friction was measured on various pavement types for various conditions and determined to be the most reliable method for comparing the surface conditions. While other methods could determine when snow and/or ice were present on the surface, only surface friction could quantifiably determine if the surface was slippery and unsafe for travel. In several cases (see Chapter 3), snow and/or ice were present on the pavement surface, but the friction was such that pedestrian traffic was recommended as cautious or safe.

A survey was conducted in January 2018 of local municipalities and at least 44 locations around the Twin Cities metro area were identified as possible permeable pavement measurement sites, including locations of permeable asphalt, permeable concrete, and permeable block pavers. These sites were evaluated and 22 were found to be suitable for data collection during winter 2019-2020 (Year 4). Of the 22 sites in which friction and surface temperature were measured, 13 sites (59%) had more friction on the impermeable pavement compared to the permeable pavement; 7 sites (32%) had similar friction (typically bare pavement); and 2 sites (9%) had less friction on the impermeable pavement compared to the permeable. This suggests that under typical mid-late winter conditions, more sites of impermeable pavement had more friction than permeable pavements.

Of the 22 sites, 12 sites (55%) had warmer surface temperatures on the impermeable pavement compared to the permeable pavement; 4 sites (18%) had similar temperatures ($\Delta T < -0.5°C$); and 6 sites (27%) had cooler surface temperatures on the impermeable pavement compared to the permeable pavement. Similar to surface friction, more sites of impermeable pavement had warmer surface temperatures compared to permeable pavements. In contrast to the friction data, however, more permeable pavement sites had warmer temperatures (n = 6) compared to the permeable pavement sites with more friction (n = 2). All six of these measurements occurred when the pavement surface temperature was above but near freezing temperature. If precipitation or snowmelt occurred at the time of measurement, the warmer permeable pavement could infiltrate the precipitation before the air (and pavement) temperature decreased enough to freeze the precipitation to the surface. If the same precipitation fell or snowmelt ran onto an impermeable pavement, it's possible that it would not runoff and thus be susceptible to freezing when the ambient air (and surface temperature) decreased below freezing. Thus, permeable pavements may have more potential to melt snow and ice than unsalted impermeable pavements.

Of the 22 sites, 13 sites (59%) had less snow and/or ice cover on the impermeable pavement compared to the permeable pavement; 9 sites (41%) had similar snow/ice cover on both pavements; and none of the sites had more snow/ice on the permeable pavement compared to the impermeable pavement. Visual observations mimic the friction measurements described above in that the same number of sites (n = 13) had more friction and less snow on the impermeable compared to the permeable. The sites that had more friction, however, did not correspond exactly with the sites that had less snow.

Of the 22 sites, 8 sites (36%) had more pooled water on the impermeable pavement compared to the permeable pavement; 14 sites (64%) had similar or no pooled water on both pavements; and none of the sites had less pooled water on the impermeable pavement compared to the permeable pavement. This demonstrates the primary winter benefit of permeable pavements: Meltwater can infiltrate

through permeable pavements and prevent refreezing. Refreezing of meltwater on impermeable pavements creates dangerously slippery conditions which can be avoided with functional permeable pavements.

It must be noted, however, that impermeable pavements are typically managed with road salt and permeable pavements are not. Therefore, this evaluation is likely comparing salted impermeable pavements to unsalted permeable pavements. Regardless, the following conclusions can be drawn from previous research and data collected during this project:

- Permeable pavements provide warm weather hydrologic and water quality benefits.
- Permeable pavements that are clogged due to sediment accumulation or collapsed pores provide no benefit.
- Snow and ice cover are sensitive to the weather conditions (temperature, sunlight, etc.), surface albedo, snow removal, and traffic.
- Meltwater on impermeable pavement can refreeze into ice, whereas permeable pavements infiltrate meltwater.
- Permeable pavements insulate and "spread the heat" less than impermeable pavements.
  - Patches of bare pavement on impermeable asphalt can spread quickly as snow/ice melts (but can refreeze).
  - Block pavers are can be slow to melt snow and ice, but may benefit from flexible plow blade edges or brushes.

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