Parking Lots and Sidewalks under Winter Snow Events: Classification, Friction Characteristics, and Slipping Risk

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ABSTRACT

Pedestrian safety on parking lots and sidewalks is a main concern under adverse winter conditions due to the reduced friction level caused by snow accumulation and ice formation. While there is an intuitive understanding that the risk of slipping is related to the friction level of a pavement surface affected by snow and ice, there is limited knowledge on the underlying relationship and how friction level is affected by various factors such as contaminant type and amount, pavement type, and other factors. Knowledge on this relationship among the contaminant type, coefficient of friction, and risk of slipping is essential for establishing cost-effective level of service policy and standards for winter maintenance of these transportation facilities. This paper summarizes the results of a field study investigating the friction characteristics and associated slipping risk levels of different contaminant pavement surfaces under a variety of weather conditions. A large number of field tests were conducted on three common pavement structures - asphalt concrete, interlocked brick, and Portland cement concrete, with a variety of surface contaminants such as unplowed snow, plowed snow, slush and ice. It was found that pavement surfaces of major contaminant types have distinctive ranges of friction and slipping risk levels, and they could be inferred from each other, suggesting the feasibility of establishing a friction-based service standard.

1. INTRODUCTION

Pedestrian safety on foot ways, such as sidewalks, transit platforms and parking lots, is always the first concern in winter as they can become slippery due to the presence of snow and ice. Past studies have found that pedestrian injuries are often caused by slips and falls, which is the second leading cause of accidental deaths after motor crashes in the North America (Lin L. et al., 1995). Pedestrian falls are mostly caused by a loss of traction or friction between shoes and pavement surface (Bakken G. et al., 2002). Therefore, the traction or friction levels of a walking surface and the associated risk have become a key consideration for undertaking snow and ice control activities in winter.

To improve the surface conditions (i.e., the friction level), both public and private organizations have put large efforts and resources to make sure the public is safe under winter weather conditions. However, in contrast to highways, parking lots and sidewalks are commonly maintained by small contractors under some ad-hoc contracts with few being regulated by industry wide standards and guidelines for consistent and cost-effective delivery of services. This lack of uniform standards and guidelines have been considered as one of the main factors contributing to significant legal challenges of slip-and-fall cases and over application of salt in fear of the former.

The first step toward establishing a set of comprehensive maintenance service standards is identifying the measures of effectiveness that can be used to gauge the desirable service conditions from a user’s perspective and the performance of the maintenance work being completed. One of the most commonly used, most intuitive indicators used in the road industry is the bare pavement (BP) status (e.g. percent of pavement being bare or clear of snow and ice). This indicator is equally applicable for parking lots and sidewalks and is expected to be adopted
for parking lots and sidewalks. However, BP status is a subjective and partial indicator as it does not provide a full picture of the risk level of different pavement surface conditions that could be experienced in the real world. For example, a pavement surface covered by snow and ice could present totally different levels of safety hazards to the pedestrians depending on the type and nature of the surface contaminants (e.g. snow vs. ice, loose snow vs. bonded snow).

The objective of this research is to address several critical questions concerning the representation and classification of surface conditions of footways in terms of friction and risk of slipping and fall. In particular, the research attempts to answer the following questions: a) how can the winter pavement surface contaminants be classified in a simplistic, tangible and measurable way? b) is there any correspondence between contaminant types, friction levels and slipping risk level? c) how can a quantitative knowledge of slipping risk be used for service agreement between facility user and contractor? d) what are the factors that affect friction?

This paper provides a detailed discussion of the results of a series of field tests conducted during the winter seasons of 2011-2012 and 2012-2013 to identify the friction characteristics of a pavement surface with different types of snow and ice contaminants and develop a risk based classification scheme. This paper is organized as follows. The first section presents an introduction to the research questions. The second section consists of a literature review of the topic. The third section describes the test sites, testing method, data collection procedures and their processing. The classification of pavement contaminant is described in the fourth section, followed by a detailed analysis and discussion of the results in the fifth section. The last section highlights the conclusions and provides recommendations for future work.

2. LITERATURE REVIEW

A number of past studies have been conducted to address issues related to the characteristics of road surface conditions and their relation to the friction level. James et al. (1998) investigated the friction characteristics of both contaminated and non-contaminated surfaces. They found that on surfaces with no contaminants, the tire of the friction device is the sacrificed part for the reduced friction, but on the contaminated surfaces, snow and ice become the sacrificed part, thus the friction depends on the relative resistance between the friction tester and the road surface condition.

Perchanok (2002) undertook a study to classify winter pavement surface conditions corresponding to friction level for highways. The study classified thirteen types of contaminants into six groups. The contaminants included snow covered, bare wet, bare dry, ice covered, slush, thin snow, and compacted snow. The study concluded that the friction value increases when the length of snow cover decreases.

With video data of pavement condition and friction data from field tests, Cloutier & Donaldson (2007) established a contaminant classification system. The classification included wet ice, hard packed, wet bare asphalt, and slush/snow. The wet ice had a friction value as slow as 0.02 to 0.10, while wet bare ranged from 0.53 to .92. However, due to lack of data, they could not quantify the friction values for slush and snow.
Fu & Feng (2008) undertook a study to correlate the friction coefficient for specific road surfaces conditions statistically. A discrete binary logit model was developed to determine the probability that a road surface is in bare and snow covered conditions. It was found that friction and road surface temperature are reliable predictors. A simple model considering friction as the only predictor was also calibrated and evaluated. It was found that a coefficient of friction of 0.67 could be used as a threshold value for distinguishing whether or not a pavement surface is bare. That is, if the average coefficient of friction of a road surface is less than 0.67, it is snow covered, either partially or fully.

Regarding the factors that affect the friction level, many studies have indicated the coefficient of friction of winter pavement is affected by the texture of the road surface, contaminant types, pavement types, humidity, and other elements (e.g., TAC, 2008; Hall et al., 2009).

The relationship between the road surface condition and safety has already been studied extensively. Wallman & Åström (2001) conducted a comprehensive literature review focusing on the relationship between friction and accidents rates. They reported that accident rate was varied with friction for the roadway, for example, the accident was 0.2 injuries per million vehicle km for a friction value more than 0.35, whereas it was 0.8 injuries per million vehicle km for a friction value less than 0.15, based on data from Norwegian road grip project.

Berggard (2010) undertook a research on preventing slip and falls. The study indicated that the risks of slipping on slippery surfaces, such as icy and snowy surface, are higher than on other surfaces. The study indicated that slipping rates have a negative relationship with the friction. The study also reported that pedestrian injuries are more severe on slippery surfaces than those on non-slippery surfaces. Based on hospital based injury statistics, this study also mentioned that, annually, 3.20 slips per thousand inhabitants need treatment for injuries caused from snow and ice conditions in Sweden, similar to those in North America and Finland.

3. DESCRIPTION OF FIELD TESTS AND DATA

In order to determine the friction characteristics of pavement surface types with different contaminants, tests were conducted under a range of weather and contaminant conditions during the winter season of 2011-2012 and 2012-2013. The focus was on asphalt pavement, but tests on other types of pavement were also done to compare the differences. Approximately 150 tests were conducted on three pavement types: asphalt, interlocked brick, and Portland cement concrete. The following section details the test sites, the testing method employed, the data collection, and processing.

Test Sites

To cover the tests on the most common pavement (i.e., asphalt pavement), a large number of the tests were conducted on Parking Lot C at the University of Waterloo, Ontario, Canada. It is paved with regular asphalt concrete in good condition and has good drainage facilities for surface
runoff. Due to its convenient location by the University, the parking lot is heavily used and has a high volume of traffic throughout driveways. It has 900 parking stalls and 8 driveways.

Tests were also performed in other three parking lots located in the Kitchener-Waterloo region: one serving a central fresh market place while the others were at a large financial office building and a community center. These parking lots have about 150, 800 and 250 parking stalls respectively. These sites serve different types of users and have different usages and expectations on friction level. All pavements sections tested are made of asphalt concrete but they have different micro/macro textures and blend.

Interlocked brick and Portland cement concrete pavement are available across the campus of the University of Waterloo. Campus sidewalks are mainly paved with interlocked bricks, and a few with Portland cement concrete. Tests were carried out primarily in the surroundings of several University of Waterloo buildings.

The test sections were selected based on the availability of visible contaminants on the pavement surfaces. Due to the non-uniformity of the contaminant, the length of the test sections ranged from 5.6m to 10m.

**Data Collection and Test Protocols**

As pavement contaminant type varied by many conditions, the following data were collected during tests for analysis:

- Contaminant type (descriptive)
- Snow depth
- Pavement surface temperature (by IR thermometer)
- Coefficient of friction [COF] (by the friction tester)
- Risk of slipping (high, medium, or low-by field observer)
- Weather data from Environment Canada (Region of Waterloo station)

The coefficient of friction of a pavement surface was measured using a device called the T2GO made by ASFT (Airport Surface Friction Tester, Sweden).

In addition to measuring the COF, the risk of slipping (i.e., degree of slipping risk) for each test section was also assessed by the field test team. Risk levels- high, medium and low were assigned according to slipperiness conditions of the pavement sections, i.e., very slippery, slippery, not slippery. This categorization was made and benchmarked based on the comfort level of walking by the observer, during the initial stage of the study. The distinction between risk levels has made it possible to investigate the corresponding relationship between level of risk and the COF under similar pavement conditions. It is important to note that, assessment of risk level is subjected to judgments (Lin et al., 2005). Hence, the risk category which was assigned by the most of the field observers was recorded.
When a test section was selected, the following steps were carried out for each test:

- Initial inspection of the pavement was carried out, and recorded the pavement conditions data along with weather data.
- Traffic cones were placed at the four corners to cordon off the test section.
- Photographs were then taken to keep a record of the particular test.
- T2GO’s wheels were cleaned with a towel prior to each run.
- Multiple runs were done to obtain an average coefficient of friction of the section.
- Test results were then entered into the system.

4. CLASSIFICATION OF PAVEMENT SURFACE CONTAMINANTS

Under the effect of adverse winter events, the dominant factor affecting pavement friction level is surface contaminants, which are defined as substances found on pavement surfaces that prevent the exposure, or direct contact with the bare pavement. In other words, contaminants are the eventualities or products of snow after some external forces and actions. For example, compacted snow after plowing by truck or manual power, slushy snow due to positive thermal changes and traffic actions, and bonded ice due to the temperature falling below freezing point are all types of pavement contaminants.

Based on numerous observations and past studies, winter pavement surface are classified into 8 types, namely, surface with unplowed-unbonded snow, unplowed-bonded snow, plowed-unbonded snow, plowed-bonded snow, slush, ice, wet, and dry surface. A general discussion of each of the surface contaminants is given in the following sections with a pictorial illustration in Table 1. Since the first two types of contaminants can be found when snow is not plowed, and the second two types are observed when snow is plowed, they are discussed as a group.

**Surface with Unplowed Snow: Bonded or Unbonded**

Pavement surfaces become contaminated with newly fallen snow; in addition, the type of snow can vary from very loose to very packed, and thickness can vary from very thin to very thick amounts. A bond can start to form under the top layer of the snow when the pavement temperature is below the freezing point. Friction was measured on top of the snow; friction characteristics of this type of pavement largely depended on the amount and physical properties of the snow (e.g., crust/packed snow vs. loose snow) rather than whether the snow is bonded with the pavement surface underneath or not. Note that, if the snow amount is small, normally it is not plowed in the real world, and therefore the friction levels for unplowed snow under both unbonded and bonded snow are critical to investigate for pedestrian safety.

**Surface with Plowed Snow: Bonded or Unbonded**

This type of contaminant can be observed when snow is present either in compacted form or in patches of snow after snow has been plowed either by truck or manual power. If the initial snow is wet or the temperature is above freezing point, a bond does not form and the snow can be mostly cleared by only plowing, leaving patches of snow; however, in the case of dry snow, both
plowing methods can leave the pavement with compacted snow. Thus, the friction characteristics of this type of pavement can be varied either for initial snow type (e.g., dry snow vs. wet snow) and/or plowing method (manual plow vs. truck plow). It is intuitive that the compacting force by the plowing blades of trucks compresses the dry snow and helps bond snow to pavement surface. However, when snow is plowed by manual power (e.g., shoveling snow in wheel-chair parking stall), this compacting force is marginal, securing a better friction level than mechanical plowing.

**Slush**

Slush is a semi-solid (i.e., slurry) snow that can be found as a mixture of snow, ice, water, and dirt. The pavement can be found contaminated with slush when the ambient temperature is above freezing point, or the snow control chemical is applied, which will start to melt the snow into a liquid. Slush can be observed with very high water content and is in a state of snow just before it completely turns into liquid form.

**Ice**

Ice is crystalized water. The pavement is contaminated with ice when the temperature tumbles below the freezing point and no appropriate snow-melting chemical (e.g. salt) has been applied to control the snow contamination.

In the case of salt being applied on snow, snow-melted solution (i.e., some percentage of brine) can also be formed into ice closing a temperature under eutectic concentration and temperature. In the field tests, the pavement surface turned to icy pavement under temperatures ranging from -9°C to -15°C. In addition to the regular ice, another type of ice was also observed, referred to as ‘black ice’ in Canada. This is a special type of ice that is formed when a very thin film of water on the pavement surface is frozen due to freezing temperature. ‘Black ice’ is less visible than regular ice and has a much smoother surface. It can easily be overlooked and thus more accidents are aroused due to the presence of ‘black ice’.

**Wet Surface**

If the pavement is clear of contaminant types mentioned above, but is damp with a thin film of liquid from snow melted solution, it is considered to be a wet pavement. Note that, in the cases where the puddles of water were present, friction data could not be obtained as an excess amount of water might be splashed onto the electrical component of the friction tester during the operation.

**Dry Surface**

As time elapsed, water evaporates and pavement becomes dry. Contaminants that can typically be found or traced on dry pavements are: deposited fine salts, dissolved salts, and regular dirt and debris from aggregates of the pavements.
<table>
<thead>
<tr>
<th>Pavement Contaminant Type</th>
<th>Pictorial Illustration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unplowed-unbonded snow (e.g. loose snow)</td>
<td></td>
</tr>
<tr>
<td>Unplowed-bonded snow (e.g. icy snow)</td>
<td></td>
</tr>
<tr>
<td>Plowed-unbonded snow (e.g. patches of wet snow after plow)</td>
<td></td>
</tr>
<tr>
<td>Plowed-bonded snow (e.g. compacted snow after plow)</td>
<td></td>
</tr>
<tr>
<td>Slush</td>
<td>![Slush Image]</td>
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<tr>
<td>---------------------------</td>
<td>----------------</td>
</tr>
<tr>
<td>Ice</td>
<td>![Ice Image]</td>
</tr>
<tr>
<td>Wet surface</td>
<td>![Wet Surface Image]</td>
</tr>
<tr>
<td>Dry surface</td>
<td>![Dry Surface Image]</td>
</tr>
</tbody>
</table>
5. DATA ANALYSIS AND RESULTS

This section summarizes data, data analysis, and test results with the objective of examining the feasibility of mutual inference between level of friction, surface contaminant type and associated slipping risks.

Figure 1 shows the total number of tests conducted. It should be noted that, due to an ever changing weather and contaminant state, as well as some contaminant types being harder to find than others, the large amount of data points are unevenly distributed among the 8 contaminant types that were tested.

![Figure 1: Number of Tests for Each Contaminant Type](image)

The COF Stratified by Contaminant Type:

Data stratification by contaminant type was done to investigate the difference in COF across the contaminant types. Figure 2 presents a descriptive statistics (by box plot) of COF data associated with each type of contaminant on an asphalt pavement surface. The box plot shows the median, 1st to 3rd quartile, and the range of data for each contaminant.
Some important observations can be made from the Figure 2.

Firstly, there is a significant amount of variance in COF within a single contaminant type, across the contaminant types. Furthermore, there is an overlap between the ranges of COF between different types of contaminant. The variation and overlap is expected because each test section was unique in terms of the surface conditions and the weather conditions at the time.

Secondly, as expected, the first three surface contaminant types, dry, wet, and plowed-unbonded snow (e.g., patches of snow), surfaces have a relatively higher COF, varying from 0.45 to 0.78 (1st and 3rd quartile). Note that a COF of 0.5 is considered having good traction for the pedestrian traffic (Miller et al., 1983). Also, the sections covered by these three contaminants were also rated as having very low potential for slipping by the field observer, in general.

Thirdly, plowed surfaces with unbonded snow (e.g., patches of snow) and unplowed surfaces with bonded snow (large amount of snow) have very similar mean COF (~0.38), followed by the first three contaminants. It can be found that the average coefficient of friction for ‘unplowed-bonded’ surfaces was found to be slightly higher than that of ‘unplowed-unbonded’ surfaces. It is somehow counterintuitive that bonded unplowed snow can be associated with a lower friction level. When interpreting the results from the friction tester (T2GO), one should clearly keep in mind that the friction value largely depends on snow type and thickness, as the friction tester was run on top of snow. Therefore, snow depth was the principal influencing factor to have similar
ranges of friction coefficient though underneath conditions of snow were different (bonded vs. not bonded) for unplowed conditions.

Lastly, the last three contaminants, plowed-bonded snow (e.g., compacted snow), slush, and ice, have a relative very low COF range (0.15 to 0.22). Surprisingly, ice has a higher mean COF than plowed-bonded snow (i.e., compacted snow), which is slightly higher than slush (liquid snow). This counterintuitive result should be taken with caution. There were two types of ice observed, namely crystalized ice and black ice. When ice was formed with snow patches and debris, the surface was much rougher, which had a positive influence towards a higher friction coefficient, in contrast to black ice, compacted snow and slush (liquid snow). The friction value of ice was calculated by taking the average friction values of black ice and regular ice. Therefore, ice had a slightly higher coefficient than its other group members.

The COF Stratified by Risk Levels:

The COF data which was accompanied by different risk levels (high, medium, and low) during field tests was then analyzed to investigate the general boundary between them. Figure 3 shows the coefficient of friction distributed for the three risk levels. It can be observed, again, there is an overlap between the different risk levels, as the COF ranges for each contaminant type overlapped with another contaminant type. However, there is a clear boundary between the most interesting levels, i.e., high risk (0.06 to 0.45) and low risk COF (0.36 to 0.80) levels.

As expected, the variance of the COF within a risk level is also clearly observed, because the risk category has been gauged after generalizing the test section’s slippery condition first. For example, if a pavement is partially wet or partially slushy, the risk level could either be assigned as low risk or high risk by the observer. Regardless of which risk category that test section is assigned, the COF will not correspond with the other perfectly wet or slushy test samples, leading to the variance observed.

The low risk COF ranged from 0.36 to 0.80, showing a large variance from the safe traction threshold of 0.5. The high risk level COFs varied from 0.06 to 0.45, also showing a large variance. The medium risk level COFs ranged from 0.35 to 0.55, falling mostly within the mediocre safety range with some tests being within the safe safety range.

The peak frequency occurred at the COF of 0.55, showing that this COF was most commonly found for low risk pavement condition. The most common COF within the high risk level is 0.15, showing a very high risk. Whenever a low COF is seen, winter maintenance activity needs to be completed in order to ensure the safety of personnel and vehicles traversing the affected area.
The COF Stratified by Contaminant Types and Risk Levels:

The figure shown above shows the distribution of the COF within the risk levels, but which contaminant types are within what COF ranges? To answer this question, a similar figure is shown below showing the COF data pertaining to each contaminant type as well as the risk level associated with the contaminant type has been shown (Figure 4).

Interestingly, some contaminant types’ COFs are varied greatly while others are concentrated at a certain COF. Ice, for example, is varied greatly from a COF of 0.06 to 0.40, which is large variance for ice, depending on whether it is black ice or crystalized ice as explained before. On the other hand, slush is concentrated between the COF of 0.11 and 0.20, which is a very small range.

Also, the dry pavement surface’s COF varied quite largely. The COF ranged from 0.56 to 0.80, which is a large range for a pavement condition that seems to be quite constant, without large variation. Another example of a large variation in the COF range would be the wet pavement condition, which ranged from 0.31 to 0.75, the largest variance seen. Most of the data samples collected had a COF between 0.56 and 0.60, but other samples spread across this range in small numbers, with at most 4 tests in each COF bin.
Figure 4: Distribution of COF by Contaminant Type and Risk Level

Risk Ranking of Different Surface Contaminants

As previously explained, the knowledge of risk levels associated with contaminant types is necessary in order for appropriate maintenance. After the stratification of data as discussed in previous sections, it can be clearly seen that there is a significant mutual relationship among surface contaminants, the COF and slipping risks. This section has classified and summarized the previously discussed eight surface contaminants into three risk categories. Table 2 shows the three risk levels COF with the example of contaminant types with the mean, median, standard deviation, and range of COF.
Table 2: Risk Ranks of Contaminants and the COF

<table>
<thead>
<tr>
<th>Risk of Slipping</th>
<th>Example of Contaminant Types</th>
<th>Number of Complete Observations</th>
<th>Range of COF</th>
<th>Mean COF</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>Ice, Slush, Plowed-bonded snow (compacted snow)</td>
<td>52</td>
<td>0.06 to 0.45</td>
<td>0.22</td>
<td>0.08</td>
</tr>
<tr>
<td>Medium</td>
<td>Unplowed-bonded snow, Unplowed-unbonded snow</td>
<td>21</td>
<td>0.31 to 0.55</td>
<td>0.41</td>
<td>0.06</td>
</tr>
<tr>
<td>Low</td>
<td>Dry, Wet, Plowed-unbonded snow (patches of snow)</td>
<td>69</td>
<td>0.31 to 0.80</td>
<td>0.57</td>
<td>0.10</td>
</tr>
</tbody>
</table>

**Low Risk Contaminants**

It is generally known that a dry pavement surface has less slipping risk than a wet pavement, which is better than one covered by snow and ice. What is not well known is the range of friction level that discriminates different pavement surface types and risk levels. Note that, when snow is plowed, depending on the snow type (loose snow vs. dry snow), pavement surfaces in winter can be varied from mostly clear pavement to mostly covered with compacted snow. Intuitively, friction level will be higher for the former and will be less risky.

The results from our tests also showed the pavement with dry, wet and plowed-unbonded snow surfaces had the highest ranges of COF and were rated less risky for slipping accidents. The mean COF of this low risk contaminant is 0.57 with a standard deviation of 0.10.

**High Risk Contaminants**

For the worst winter pavement conditions, such as bonded snow (e.g., compacted snow) after plow, slush, and ice, as anticipated, were gauged very slippery by the observers and the friction levels were found to be very low. The mean COF of this very high risk group is 0.22 with a standard deviation of 0.08.

**Medium Risk Contaminants**

When snow is not plowed, it may result in two states of pavement surfaces (‘unplowed-bonded snow’ vs. ‘unplowed-unbonded snow’) which were rated in the middle of the two extremes discussed above. The mean COF of this group is 0.41 with a standard deviation of 0.06.
Factors Influencing the Friction Level of a Pavement Surface

From the above discussion, it can be understood that the surface contaminant affects the COF and the COF could also be affected by other factors such as humidity, snow depth, pavement materials. The following section discusses some of the factors that can affect the COF of a pavement surface.

a) Effect of Humidity

Snow, once reaching the ground, starts absorbing moisture from the air. Hence, as the humidity increases, the moisture content of snow is expected to increase. Water could then act as a lubricating agent between snow particles, resulting in a lower coefficient of friction. To test this hypothesis, this section examines if humidity, relating to the moisture level of snow, has an effect on the friction level of a pavement surface covered by snow. Friction data from days with different humidity levels were extracted and are shown in Figure 5(a). It can be observed that the coefficient of friction generally decreases as the humidity increases, for both snow types, bonded and unbonded. This suggests that humidity plays a role in friction level for plowed snow.

b) Effect of Snow Depth

The amount of snow and ice present on a pavement surface is expected to have a direct effect on the friction level of the pavement surface. Figure 5(b) shows the effect of snow depth on friction level based on the test results. It can be seen that friction level decreases when snow depth increases, in general. When the amount of contaminants is small and unbonded, they can be easily displaced by the tire grooves, and thus the effect on friction is expected to be marginal. However, when the thickness of snow reaches a certain level, the displacement action will yield to compacting action, resulting in a lower traction and friction level.

c) Effect of Pavement Type

As mentioned earlier, in addition to asphalt concrete (AC) pavement, limited number of tests were also conducted on Portland cement concrete (PCC) and interlocked brick (IB). Figure 5(c) shows that all pavements performed similarly in wet condition with friction values greater than 0.5, which is above the generally accepted value and considered as safe. When the pavement is covered with unplowed and unbonded snow, the performance of the three materials displays the same trend when compared to the wet condition. This same trend holds true when pavement is covered with plowed and unbounded (e.g., patches of snow) snow as asphalt concrete performs the best, then interlocked brick and Portland cement concrete. Average snow thickness for AC, IB, and PCC were 0.5cm, 1cm and 0.5cm, respectively. As the snow was loose in all cases, it was possible for the tire of the friction tester to displace the snow and gain contact with the surface; thus, the effect of different materials outplays the effect of snow depth mentioned in the previous section.
Note that, there is a difference in the micro and macro texture of the three pavement types. The rubber of the tires is able to better interlock with the surface of asphalt concrete as it has rougher texture, resulting in a higher friction level than that of Portland cement concrete and interlock brick pavement.

![Graph a) Effect of Humidity on Friction](image1.png)

![Graph b) Snow Depth Effect on Friction Level](image2.png)
CONCLUSION

This paper describes the findings from a series of field tests designed to investigate the friction characteristics of various pavement surface contaminants that could be observed in parking lots and sidewalks during a typical winter. This research is aimed at examining the correspondence between contaminant types, coefficients of friction, and slipping risk levels and identifying the key factors that affect the friction levels. A large number of data was collected from field tests under a wide range of external conditions. An extensive exploratory analysis was performed with the goal of classifying surface contaminants in a simplistic and measurable way and relating the risk levels and coefficient of friction. The key findings are summarized as follows:

- Winter pavement surface contaminants were classified in eight types according to their appearances: surface with unplowed-unbonded snow, unplowed-bonded snow, plowed-unbonded snow, plowed-bonded snow, slush, ice, wet, and dry surface.

- According to the degree of slipping risk, the eight contaminants were grouped into three classes: a high risk group including contaminants such as ice, slush, and plowed-bonded snow/compacted snow, a medium risk group with contaminants such as unplowed-unbonded snow and unplowed-bonded snow, and lastly, a low risk group with plowed-unbonded snow (e.g., patches of snow), wet or dry surfaces. The mean COF of high risk group is 0.22 with a standard deviation 0.08. For the low risk group, the mean COF is 0.57 and the standard deviation 0.10. The medium risk group has a mean COF of 0.41 and a standard deviation of 0.06.
- It was found that, humidity has a negative relationship on COF. That is, the higher the humidity, the more slippery the pavement surface with winter contaminant.

- Snow depth was found to play an interesting role in determining the COF. When the amount of snow is small and unbonded, its effect on friction was found to be marginal. However, when the thickness of snow reached a certain level, the displacement action of the tire changed to a compacting action, resulting in lower traction and friction levels.

The research can be further extended to several directions. A modeling effort can be made for predicting the friction and risk level for a given contaminant type and weather conditions. The results could be applied to develop friction and safety based service policy and standards for snow and ice control of parking lots and sidewalks.

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