Multiphysics based Analysis of Materials for Roads in Cold Regions to Prevent Ice Adhesion and Low-Temperature Crack Developments

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ABSTRACT
Roads constitute a significant hazard if the effects of wintertime are not handled well. After a heavy snowfall, the most dangerous factor is a slippery surface due to ice adhesion with the asphalt pavement. The ice on roads increases the risk of road accidents and, upon melting, contributes to the formation of Low-Temperature Cracks (LTCs) and potholes. This research explores the physical principle that could remove the ice from concrete roads by investigating whether road ice is susceptible to self-separation upon loading when the road surfaces in cold regions are coated with a polymer-based material such as polyurethane. This study conducted an experimental and numerical analysis of ice-polyurethane and ice-concrete separation under tensile load and calculated the Von-Mises stresses on the surfaces. Results revealed higher Von-Mises stresses on ice when the base material is polyurethane compared to concrete, indicating ice is more prone to self-separation when adhered to polyurethane than concrete. These results are important for increasing the operational life of roads in cold regions and reducing the number of road accidents. In addition, polyurethane is a potential material for pre-emptive road measures, such as repairing cracks before they become potholes.

1. INTRODUCTION

1.1. Asphalt Pavement Deterioration

A typical asphalt pavement consists of layers, starting from natural ground, ballast, core/lining, filter, shoulder/erosion protection, embankment, subbase, base course, asphalt binder course, and asphalt wearing course, as shown in Figure 1. There are various causes of pavement deterioration such as overloading, seepage, improper or poor road surface drainage, insufficient road maintenance, poor design, and adverse climatic conditions [1]–[3].

Cold weather accelerates the deterioration of the transportation infrastructure system, particularly roadways. The pavements are subject to extremely cold weather conditions because of environmental factors such as oxidation, thermal cracking, subgrade softening, freeze-thaw damage, joint deterioration (spalling), and scaling [4]. Due to differential thermal contraction, the severe cold weather is responsible for Low-Temperature Cracks (LTCs) on the asphalt pavement as shown in Figure 2 [3]. It has been observed that an instant drop in surface temperature of more than 9.5°C (15°F) can result in the development of cracks, due to surface contractions [5], [6]. LTCs are common in Alaska, Canada, Norway, Russia, the United States, Arctic regions, and other locations experiencing severely cold weather.

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LTCs are the result of thermal contractions, which build transverse stresses exceeding the tensile strength of the pavement's material, leading to failures such as LTC. The daily temperature cycle accompanying the repeated heating and cooling also aids LTC formation across the road and down the pavement structure. LTC forms even when traffic load and volume are not high. LTC is just the initiation, helping water to seep through into the pavement structure, causing a reduction in subbase strength and the loss of fines. This further leads to deterioration to the extent that potholes are formed [6] and [7] as shown in Figure 3. In addition, the freezing temperature of the surrounding air causes surface deterioration [8]. Furthermore, the fluctuation in temperature enhances the development of LTCs. Researchers have reported that de-icing materials (such as salts and others) cause water seepage through the LTC and defrost the subgrade [9]. The fine grain material in the subgrade mixes with water, creating a gap. This results in a depression, hence reducing the service life of the pavement.

Figure 1: A typical asphalt pavement.

Figure 2: Low-Temperature Cracks (LTCs) on the asphalt pavement

Figure 3: Potholes on asphalt pavement

1.2. Icing

The icing phenomenon is referred to when water droplets are cooled below the freezing temperature (0°C) and freeze upon impact with a structure [10][11]. Ice exists in several different crystal structures, as well as two amorphous states [12]. The ordinary ice we find in our freezer is a hexagonal crystal structure called ice – 1h, where the numbers refer to individual water molecules. The physical properties and the appearance of accreted ice vary widely [13]. It is known from published work that young's modulus of ice varies between 4 GPa to 9 Gpa [14]. In addition, it has also been reported that the value of young's modulus for ice is related to temperature, grain size, density, and sample volume. Icing causes many serious problems; for example, icing causes aircraft and road accidents, the icing on ship hulls creates navigational difficulties, and the icing on wind turbines has many negative consequences [15]–[19]. These challenges are associated with the ice adhesive behavior [20], [21]. There is no direct correlation to calculate the ice adhesion force [21]. However, researchers have given a number of theories. The theories divide the force of adhesion into four categories: electrostatic adhesion [22], diffusive adhesion [23], mechanical adhesion, and chemical adhesion [24][25].

The most common reason for ice adhesion is mechanical. The ice adheres when water seeps into the microscopic pores of the material substrate and freezes, thereby forming an interlocking mechanism [26]. Therefore, surface roughness has a significant effect on ice adhesion. For example, in general, ice adhesion on the surface of unpolished stainless steel is up to 1.65 MPa, while the ice adhesion on polished stainless steel is only 0.07 MPa [21]. In the given study, ice is frozen over a polyurethane surface. Polyurethane is a polymer-based structure, and its mechanical properties may vary based on the curing process [27]. In addition, additives can be added to obtain a range of mechanical properties [28].

2. MATERIALS

This study uses anti-seepage and anti-abrasion polyurethane [29]. Anti-seepage polyurethane is suggested as a sealant in either chemical tanks, as it has good resistance to chemical corrosion, or in dams to prevent water leaks through the concrete. Anti-abrasion polyurethane can be used in locations where high corrosion is expected. Locations of such can be water ducts from dams, on ships, due to the force of water while the ship is in transit, and so forth. Both variants of polyurethane are used in this study.

3. METHODOLOGY

This study is meant to explore the physical principle that could remove the ice from the roads. This study investigates whether ice on roads is susceptible to self-separation upon loading when the road surfaces in cold regions are coated with a polymer-based material such as polyurethane. This is assumed due to the underlying principle: "If a hard and brittle material is in direct contact with a softer material that easily deforms, the hard and brittle material will take the load." In this research work, simulations were performed to calculate the stresses when the load was applied to ice-polyurethane and ice-concrete materials.

3.1. Experimental Study

An experiment was performed by producing ice on anti-seepage and anti-abrasion polyurethane in the lab, as shown in Figure 4. Ice and road temperatures was measured by using FLIR TG165 thermal camera [30], shown in Figure 5. The ability of ice to separate from the surface was tested by moving a vehicle over the ice on the road, as shown in Figure 6.

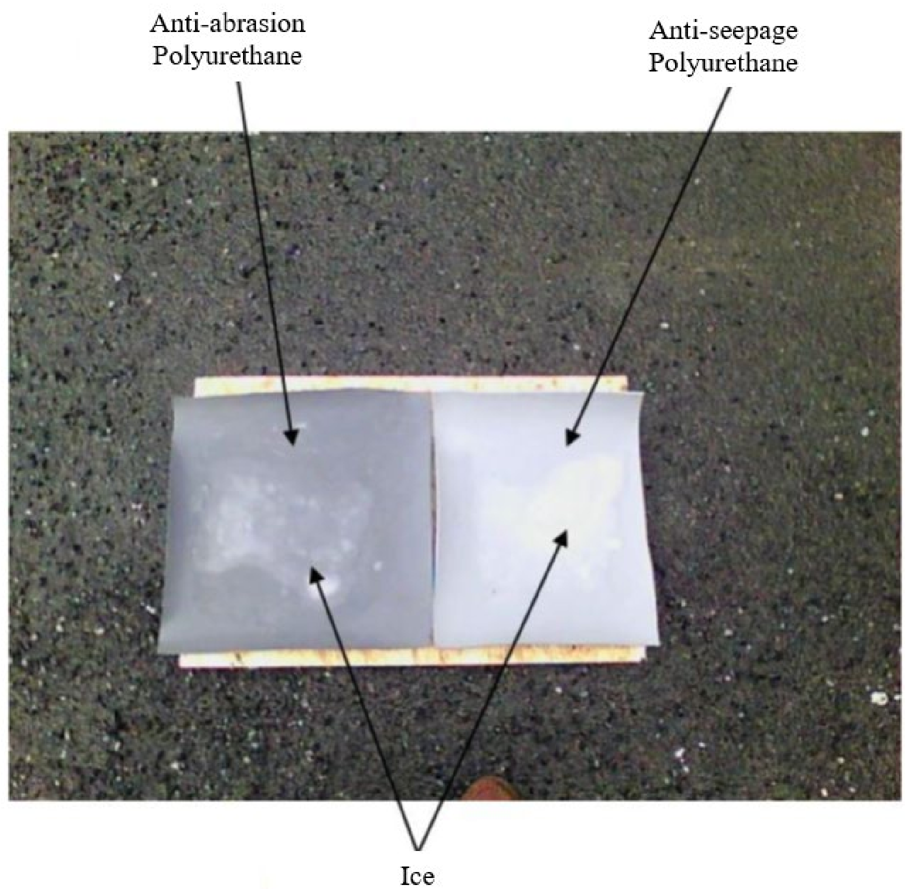

Figure 4: Ice on Anti-abrasion and Anti-seepage polyurethane

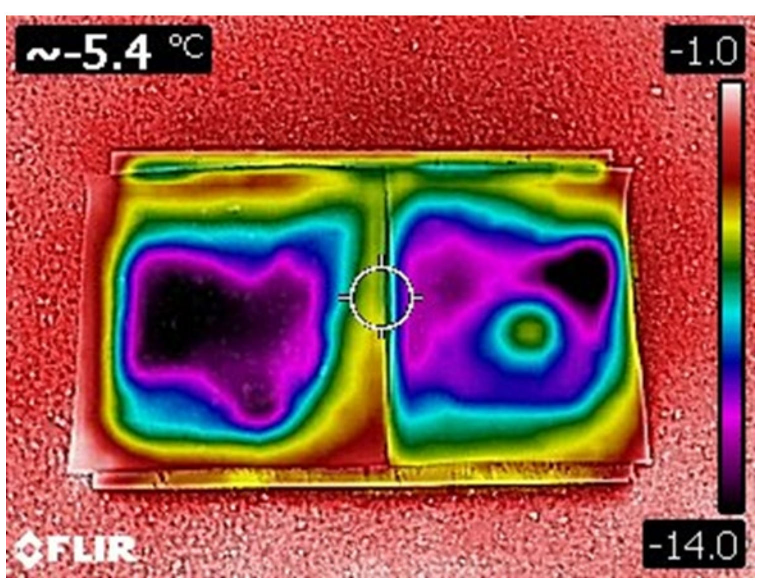

Figure 5: Temperature of Ice blocks and road, captured by a thermal camera

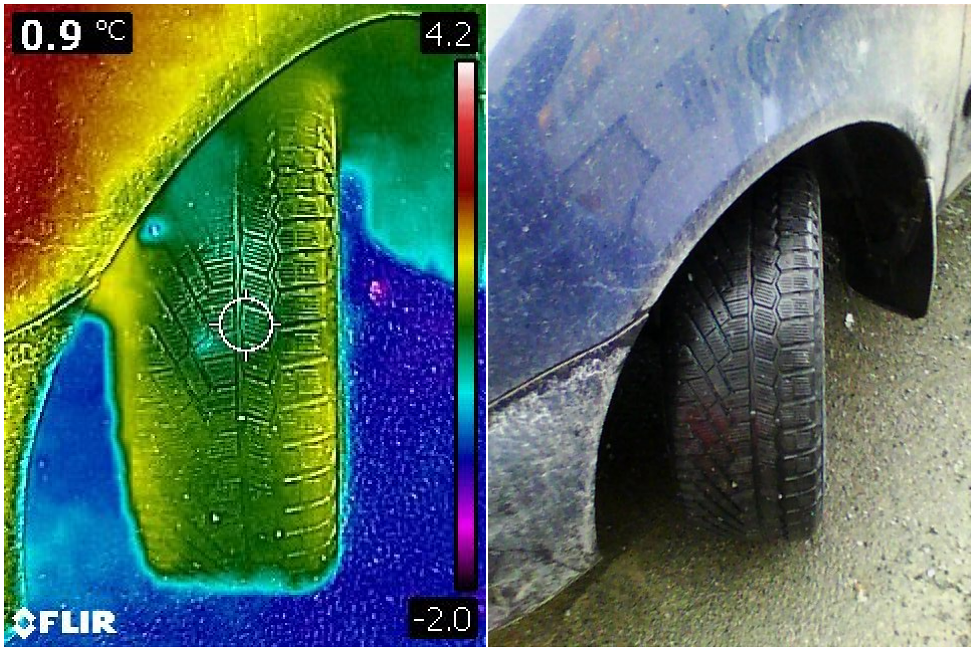

Figure 6: Vehicle used to apply load on the blocks of ice

3.2. FEA (ANSYS® Workbench)

The simulations were performed to generate observations of ice separation since pulling sideways induces longitudinal and shear stresses. Two simulations were carried out to obtain the required stresses, as explained in sections 3.1.1.

3.1.1. Ice Polyurethane/Concrete Separation

The structural analyses were performed in ANSYS® Workbench [31]–[35] module to simulate the ice-polyurethane separation under tensile loading. The materials assigned were Linear Isotropic with young's modulus, as given in Table 1. Mesh sensitivity analysis was performed to optimize the mesh. The model dimensions under investigation were 100 mm × 100 mm with 5 mm thick polyurethane/concrete with a layer of 75 mm × 75 mm with 5 mm thick ice. Uniform pull of 1MPa was applied, as shown in the geometric model given in Figure 7.

Table 1: Young's Modulus and Tensile Strength of Ice, Concrete, and Polyurethane Materials

Materials	**Young's Modulus**	**Tensile Yield Strength**
Ice	1-4 GPa	2 MPa
Concrete	14-41 GPa	5 MPa
Polyurethane	0.069-0.69 GPa	69 MPa

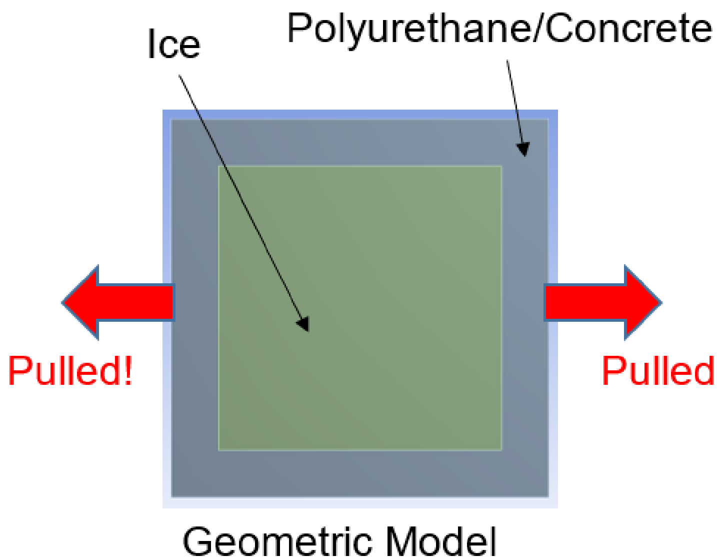

Figure 7: Geometric model showing ice-polyurethane sheet under tensile loading

4. RESULTS AND DISCUSSION

The results reveal that once the load is applied on ice attached to a polyurethane surface, ice being stiffer (higher young's modulus) and having a higher young's modulus, takes up the load and breaks, eventually separating from the surface.

4.1. Experimental Results

The experimental results showed that ice fractured and separated from the surface when a five-door sedan car equipped with non-studded tires drove over the samples at dead-slow speed. Both anti-seepage and anti-abrasion polyurethane behaved in a similar manner, as shown in Figure 8.

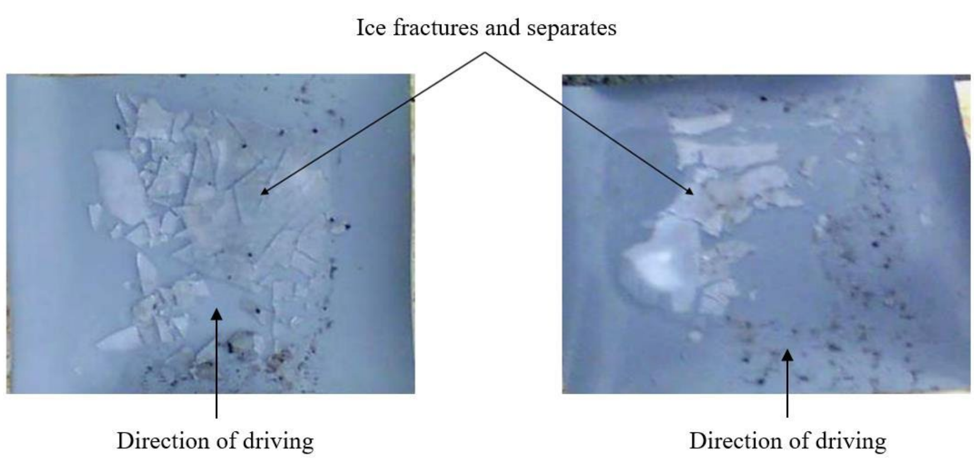

Figure 8: Ice fractures and separates when the car drives over the ice adhered with anti-seepage and anti-abrasion polyurethane.

4.2. Ice Polyurethane Separation - FEA Results

The ANSYS® simulated results in the are presented in Figure 9. The ANSYS® results exhibited the lowest stresses on the polyurethane surface while high stresses of around 1.0117 MPa on the ice surface. High stresses on ice would result in its breakage and separation from the surface, hence self-deicing.

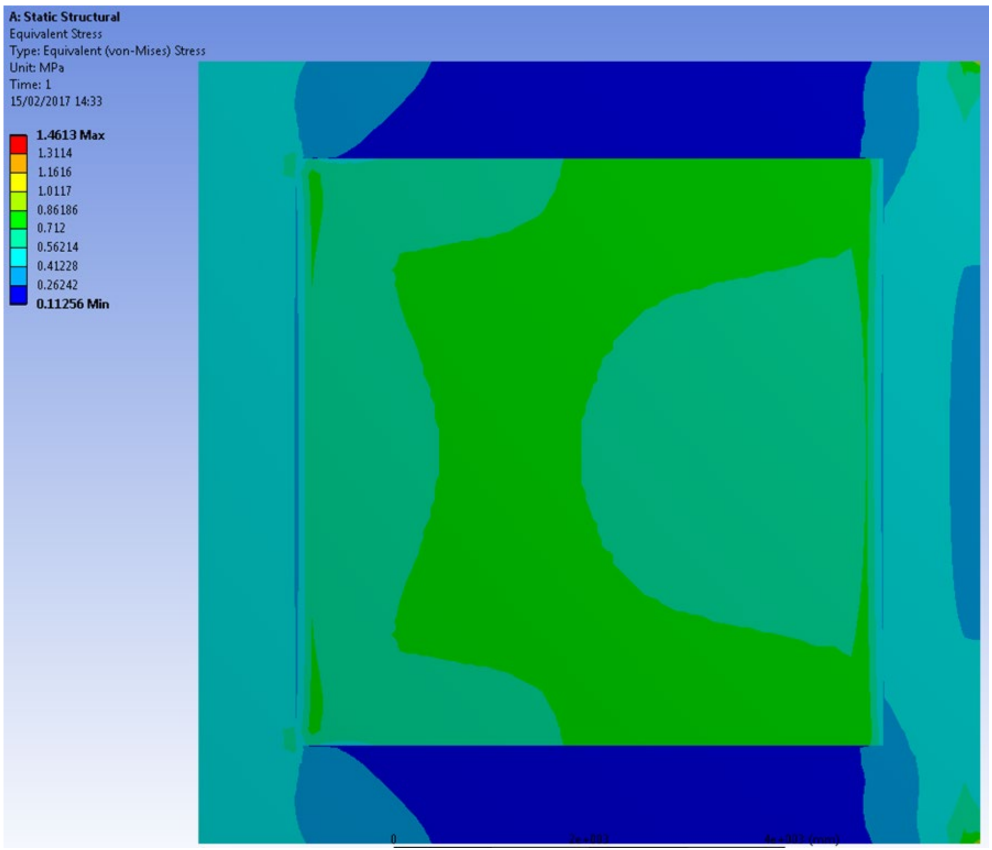

Figure 9: Von-Mises Stresses on Ice-Polyurethane Adhered Sheets under Tensile Loading

4.3. Ice Concrete Separation - FEA Results

The ANSYS® simulated results are presented in Figure 10. The ANSYS® results exhibited the lowest stresses on the ice surface while higher stresses of around 1.1528 MPa on the concrete surface. Lower stresses on ice mean ice will remain solid and in contact with the road surface for a long time, eventually forming LTC and potholes.

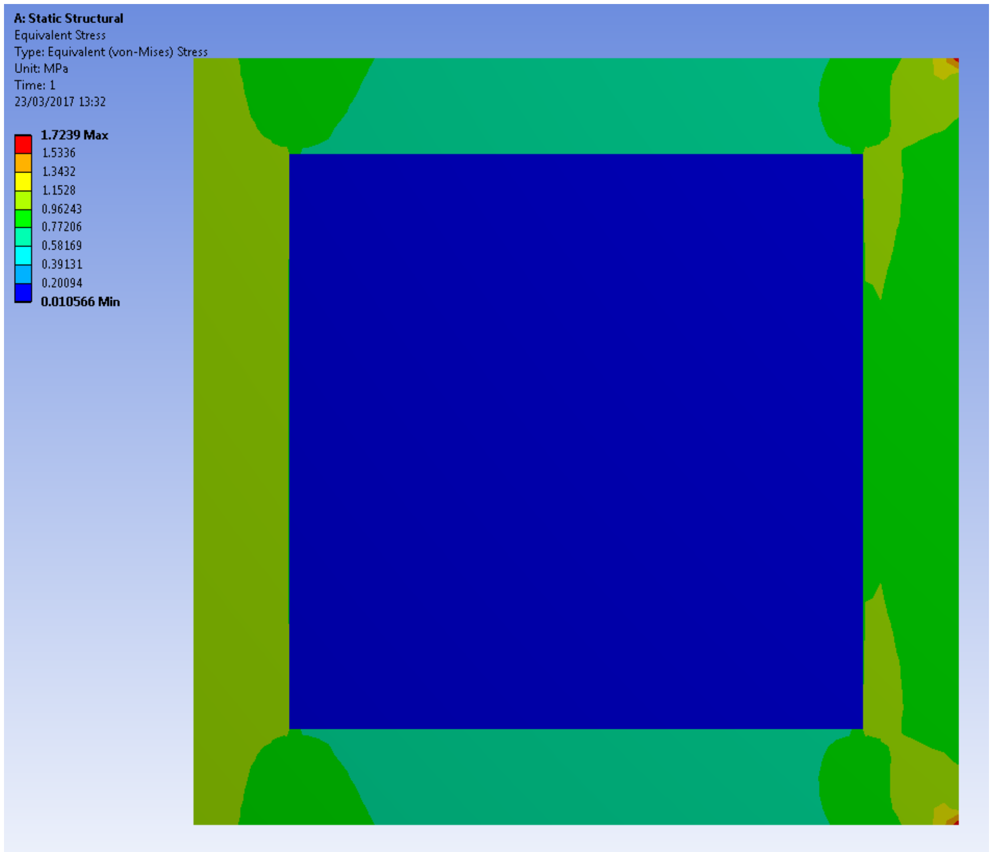

Figure 10: Von-Mises Stresses on Ice-Concrete Adhered Sheets under Tensile Load

4. CONCLUSIONS

Ice adhesion is a concerning phenomenon for roads in cold regions. This study conducted experimental and numerical analysis of ice-polyurethane and ice-concrete separation under tensile load and calculated the Von-Mises stresses on the surfaces. Results revealed higher Von-Mises stresses on ice when the base material is polyurethane compared to concrete. These results are important for increasing the operational life of roads in cold regions and reducing the number of road accidents. In addition, polyurethane is a potential material for pre-emptive road measures, such as repairing cracks before they become potholes. However, further studies will be required to investigate the longevity of polyurethane road repair and the interactional behavior of the tires.

ACKNOWLEDGEMENT

The publication charges for this article have been funded by a grant from the publication fund of UiT The Arctic University of Norway.

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