Frost Heaves: A Problem That Continues To Swell

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ABSTRACT

A frost heave distress on a roadway is caused by the upward movement of the pavement resulting from expansion of trapped water beneath the roadway. A significant heave can result in permanent damage of deformations and cracking with varying severities. These distresses can greatly affect the ride quality and leave motorists with an uncomfortable and unsafe ride.

Pavement distresses caused by frost heave action are usually unpredictable and can be very costly to repair. In order to mitigate frost heave action, designers must understand the different conditions in which water can become trapped within the frost depth. The presence of highly frost susceptible materials and improper drainage are key contributors to frost heaves, but other conditions such as the existing terrain and constructed cut-to fill transitions can also lead to potential frost heaves problems.

The objective of this paper is to investigate the causes of frost heaves and how to mitigate these effects during design and construction stages to avoid costly repairs down the road. It will also review the techniques for a frost heave field investigation and what rehabilitation techniques can be used to improve the frost heave protection.

Key Words: frost heaves, frost action, investigation, rehabilitation, mitigation,

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INTRODUCTION

Pavement distresses observed in flexible pavements caused by frost heaves continue to cause problems for Canadian transportation agencies. They are usually unforeseen distresses that make it difficult to estimate in yearly budgeting for maintenance and repairs. Frost heave is the rise of the ground surface due to frost action. The volume increase associated with freezing water can result in movement at the ground surface; however, a much greater increase in the volume can occur due to the formation of ice lenses within the soil [1]. When frost action takes place under a pavement structure, distresses in the form of distortions and swelling occurs. These distortions typically lead to cracking on the pavement surface, which in turn allows surface water to penetrate into the pavement structure. Distresses in the pavement can lead to a reduction in the service life, as well as providing a poor ride quality for road users [2]. In some cases, severe frost heave distresses may require a motorist to slow down as they approach an area in order to prevent damage to their vehicle.

The prediction of frost heaves and their effect on the deterioration of a pavement structure can be very complex. The development and impact of frost heaves is contingent on a number of factors including the type, porosity, permeability, consolidation and hydraulic conductivity of the soil, temperature gradient, depth of frost penetration, depth of the water table and general sources of water [3,4]. The impact of frost heaves can be measured by extent and severity or by using various indices to determine their impact on the driving public [5,6].

The purpose of this paper is to review the various frost heave mechanisms and the techniques used to investigate them. It will also discuss mitigation techniques through design, construction, and rehabilitation alternatives.

FROST HEAVE MECHANISMS

There are several mechanisms in which moisture can become trapped beneath a pavement. In order to prevent distresses due to frost heaves, the objective for designers is to eliminate these mechanisms and provide proper drainage away from the pavement. The following section highlights some of the key mechanisms likely to result in frost heaves.

Frost Susceptible Soils

The depositional environment surrounding a roadway plays a significant role in the potential for frost heave action. When the water in a soil freezes, a 9 percent volume increase can be expected which can result in an overall increase in the volume of soil between 2.5 and 5 percent depending on the void ratio of the soil. For areas with coarse-grained soils with little or no fines (particle size <75μm), the majority of the voids are large enough to accommodate the increase in volume and therefore minimal heaving can be expected. Fine-grained soils such as very fine sand and silt that have significantly smaller void ratios are typically more affected by frost action than coarser-grained soils [1]. These materials in conjunction with the presence of moisture are considered major contributors to frost action damage.

The Ministry of Transportation, Ontario (MTO), considers a soil to be moderate to highly frost susceptible when the very fine sand and silt content (grain size between 5-75μm) is in excess of 40 percent by mass [7]. Frost heaves can be especially detrimental to a pavement surface when frost susceptible materials are found in ‘pockets’ within the frost penetration depth. These pockets or abrupt changes in soil type can lead to a non-uniform heave. When a frost susceptible material is found more evenly throughout a section, the pavement can rise and fall more uniformly with less risk of permanent damage.

Bedrock

Roadways constructed in areas of bedrock can also lead to the potential for frost heaves if proper design and construction practices are not considered. Bedrock, or shallow rock, can provide good subgrade support for a pavement structure; however, if not constructed properly, it can become an impermeable barrier that can trap water beneath the pavement. Undulating rock peaks beneath a pavement structure can lead to pockets of pooled water. This varying rockline can be naturally occurring or the result of the rock-blasting operation during construction. Without proper drainage, this undulating rockline can create a ‘bathtub effect’ that can lead to pavement surface damage if there is not enough space for the increase in volume under freezing conditions. Figure 1 depicts an example of a cross section with the bathtub effect.

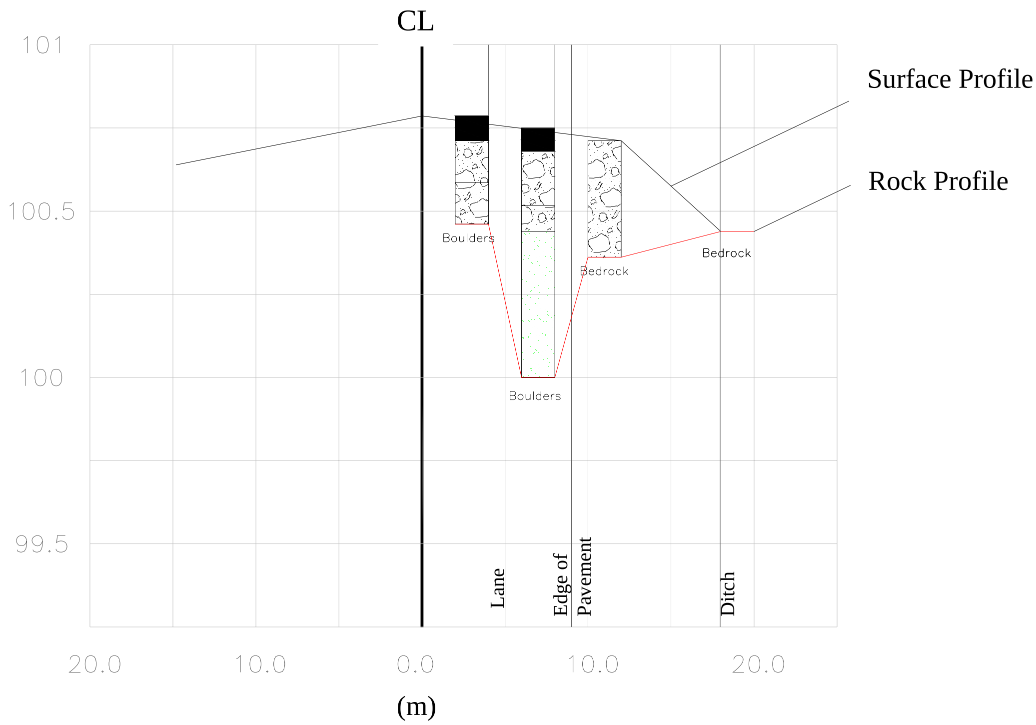

Figure 1. Cross Section of a “bathtub effect”

In many instances these shallow rock areas are also found where rock faces are immediately adjacent to the pavement shoulder edge. The combination of a shallow rock beneath a pavement structure as well as inadequate drainage along the ditches can lead to frost related distresses at the pavement surface. Figure 2 illustrates a rock face that is considered too close to the shoulder edge and therefore not providing appropriate ditch drainage. Transitions that involve surface, or shallow, rock require special design and construction considerations.

Figure 2. Poor pavement structure drainage in a rock cut area.

Transition Treatments

Grade transitions can play a significant role in the occurrence of frost heave action. Pavement structures within cut to fill transitions can increase the potential for frost heaves at the transition points if not properly designed and constructed. In addition to the cut and fill transition, transitions in subgrade material type (sands to silts or earth to rock) have also been observed to be common problem areas. Many agencies have developed specifications and transition details to minimize the impact of frost action in grade transition areas which will be discussed in later sections.

MITIGATION OF FROST HEAVES

The mitigation of frost heave potential in new construction must begin during the detailed design and investigation stage. If one of the three items outlined above (frost susceptible soil, water or frozen conditions) is not present, there will not be any potential for frost heaving. Therefore, frost heaves can be eliminated by either removing frost susceptible materials within the frost penetration depth, eliminating sources of water or by eliminating the penetration of the frost into the pavement structure.

A thorough geotechnical investigation should be completed to determine the level of frost susceptible subgrade soils along the proposed alignment and whether this material will remain within the frost penetration depth of the new pavement structure. The proposed alignment should be reviewed to address the potential mechanisms (as stated above) that may occur and affect the long-term performance of the roadway.

Frost Susceptible Soils

For newly constructed roadways, the management of frost susceptible soils is very important in the prevention of differential distortions. Ideally, frost susceptible materials should be avoided or removed from within the frost penetration depth. In fill sections this would include limiting the top part of the embankment (within the frost penetration zone) to non-frost susceptible material, while in cut areas, subexcavation of frost susceptible materials may be required.

Many agencies have developed their own procedures for handling frost susceptible material in their area [8]. In the Province of Alberta, all new alignment construction requires the undercut of 600 mm beneath the pavement structure, with the replacement of the removed material [9]. This process is an attempt to mix the subgrade soils within this zone to make for a more uniform subgrade platform.

Bedrock

Proper drainage in rock areas is critical for mitigating the potential of frost action. Surface water infiltrating the pavement needs to be channelled away. To help design proper ditches, exposed rock faces should be removed far back from the edge of pavement. Setting back the exposed rock face can also be helpful in reducing the potential for rockfall hazards intruding into the driving lane.

To prevent water from being trapped in undulating rock areas, many agencies have taken the approach of over shattering the underlying rock platform prior to the construction of the pavement structure. In Ontario, MTO Specification (OPSD 205 series) require over shattering the underlying rock to a minimum depth of 300 mm beneath the granular subbase. In recent years this rock over-shatter depth has been increased to depths as much as 1.5 m, with the rock removed and replaced in certain instances. Similarly, in the Province of New Brunswick, it is a standard practice to undercut 600 mm of rock below the top of design subgrade [10]. The depth of undercut is typically dependent on the frost penetration depth for the region.

Transition Treatments

Properly designed and constructed transitions are a critical component of roadway and pavement design. A common oversight is the provision of continuous pavement drainage through transition areas. Proper drainage can be especially critical when grades transition between material types (ie. rock to earth). In these scenarios, designers and constructors need to pay particular attention to ensure that surface water is not channelled into potentially frost susceptible areas.

Several agencies have typical transition details to reduce the potential for frost heave action. For all transitions that involve bedrock, the Province of New Brunswick requires that an additional 500 mm be undercut (in addition to the 600 mm undercut stated above) for a total 1.1 m cut below the top of subgrade [10]. Figure 3, shows a typical standard drawing taken from the New Brunswick Department of Transportation Standard Specifications.

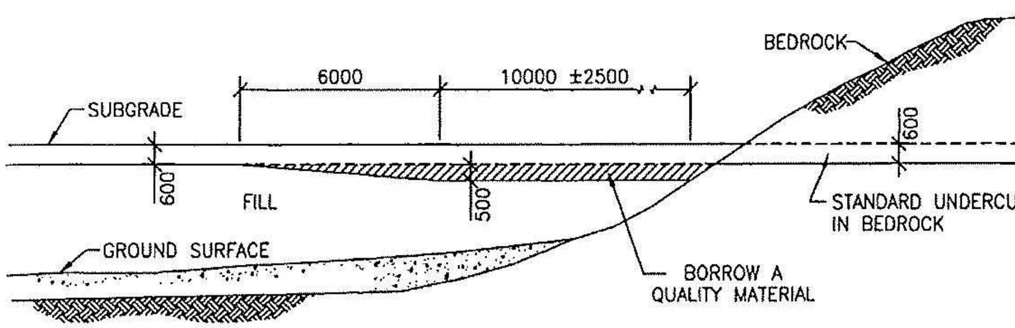

Figure 3. New Brunswick Department of Transportation Transition in Fill Condition (Standard Drawing 108-1, dated January 2006).

In Ontario (Figure 4), rock cut to earth fill transition treatments require a 300 mm of rock shatter in the cut section as well as additional subgrade subexcavation and replacement with rock or granular fill within the fill section to a transition treatment depth (t). In many cases, the transition treatment depth is typically equal to the frost penetration depth for the given area.

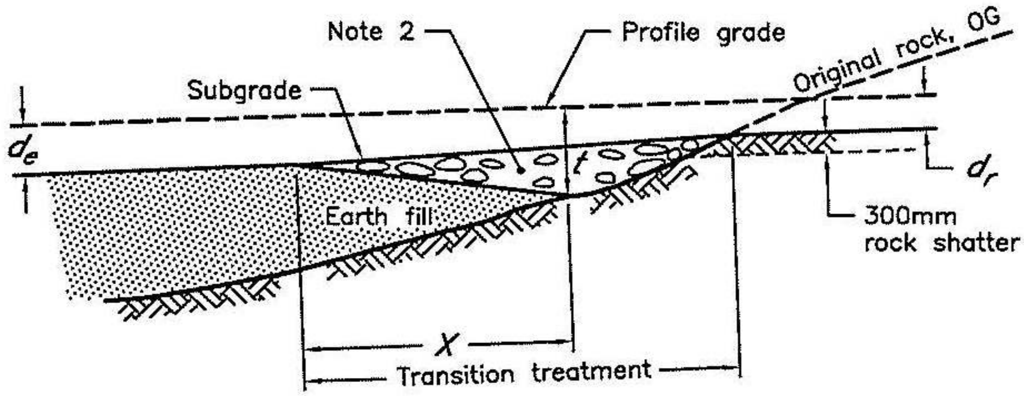

Figure 4. Ontario Provincial Standard Drawing 205.030, Transition Treatment Rock cut to Earth Fill, (Dated Nov 2009).

Transition treatments between cuts and fills in Alberta are treated similar to their typical highway construction, except that the depth of the undercutting is increased from 600 mm to 1.0 m, below the pavement structure.

Drainage

Proper drainage is a key element to the prevention of frost heave distresses. In rural sections, appropriate ditch design and construction are critical to minimize the impact of frost action. Poorly constructed ditches can lead to a ‘bathtub effect’ as stated above. This can occur when the ditches are constructed shallower then the bottom of the pavement, as seen in Figure 2. Trapped water also creates unstable granular bases and subbases near saturation levels that can lead to additional distresses in the form of wheel track rutting.

Drainage consideration is also required in any area where subexcavation of unsuitable subgrade soils is required. Typically required in cut sections, areas of subexcavation may require the ditch depths to be deepened, which may not always be possible due to other geometric constraints. If adequate drainage is not provided for the subexcavated area, ponding water could occur, which in turn could result in differential heaving.

INVESTIGATION OF FROST HEAVES DISTRESSES

It is expected that for new pavement and highway design projects, designers would take into consideration frost mitigation techniques and provide adequate frost heave protection. However, many agencies continue to have problems with frost heaves on existing roadways. In order to provide appropriate rehabilitation recommendations, agencies should complete thorough field investigations focused in understanding the mechanisms that created the problem.

Pavement Condition Survey

A roadway that has been subjected to frost heave action can result in a variety of pavement distresses including: distortions (bumps/dips), wheel-path rutting, cracking (transverse, longitudinal meandering, centre line, map and edge), or combinations of distresses [7]. Figures 5 and 6 illustrate typical distresses due to frost heave action.

Figure 5. Transverse Frost Heave -Severe Distortion and Cracking

Figure 6. Frost Heave - Severe Meandering Crack

Pavement distresses that result from frost action are typically at their peak during spring-thaw conditions, therefore the location, severity, and extend of distresses should be recorded during this time. As temperatures begin to rise during the spring months, many of these distresses become less profound and may become difficult to identify.

Once the general area of the frost heave has been determined, a thorough investigation methodology should be developed to determine the in-situ conditions throughout the distressed area, as well as in the adjacent non-distressed pavement sections. It is imperative in a frost heave investigation to have a comparison between the poorly performing areas and the good areas of the pavement. Key components of an investigation include: pavement structure thicknesses, subgrade soil type and moisture condition, pavement drainage conditions, and roadway cross slope.

Drainage Condition Survey

Prior to completing any destructive testing (ie. a core/borehole investigation), a visual condition survey including a ditch survey should be completed to assess the surrounding area. A ditch survey should include both a general condition assessment, as well as bottom of ditch elevation measurements. Signs of drainage impedance would include shallow exposed bedrock, standing water, or excessive vegetation growth. Each of these can impede the flow of water away from the roadway. Observations of pavement surface drainage are also important to note. The investigation of the surface drainage should consist of transverse and longitudinal cross fall measurements as it is important to determine if water is draining toward the pavement structure or away from it.

Destructive Pavement Investigation

In order to determine the composition and thickness of the pavement structure and subgrade conditions, pavement cores and borehole auger sampling techniques are typically used. Borehole locations should be located to provide both a transverse and longitudinal cross-sectional profile throughout the distressed area. Boreholes should be advanced within the lanes, shoulders, and ditches in order to determine transverse cross sections. In the longitudinal direction, boreholes should be advanced in both the distressed area, and beyond. The total number of test holes will vary as it will be based on the length, and severity, of the distressed area. Isolating the limits of the distresses is important for the determination of appropriate rehabilitation strategies, as well as the limits of repair. The depth of the test holes should be at a minimum the depth of frost penetration for the particular site.

Non-Destructive Testing

To supplement the borehole investigation, non-destructive testing can be completed to provide additional site information. Falling weight deflectometer (FWD) testing is a pavement/load deflection test method which provides an overall indication of the structural characteristics of the in-situ pavement structure, as well as strength measurements of the underlying subgrade soils. The testing frequency will largely depend on the length of the distressed area; however, testing intervals should be a small as practical to identify potential ‘soft spots’ that may require additional remedial action. A key benefit of using FWD testing is to assess the suitability of the current pavement structure by providing comparative deflection measurements in good performing areas and the distressed areas. FWD testing should be completed prior to the destructive drilling, as borehole locations can be modified to be positioned in high and low deflection areas.

Ground penetrating radar (GPR) is another form of non-destructive testing that may also be used to provide additional pavement structure information. GPR is a pavement investigation tool that uses electromagnetic technology to provide subsurface pavement information. If used in conjunction with traditional investigation techniques, a GPR survey can provide pavement layer thicknesses between borehole locations. Other potential benefits of a GPR survey include identifying existing granular frost tapers and areas of high ground water or ponding water.

In developing the methodology for the GPR survey, it is important to select an appropriate antenna frequency, or combination of antenna frequencies, to optimize the clarity of the survey images. Higher frequency antennas provide better resolution near the pavement surface (ie. asphalt thicknesses), while lower frequency antenna’s penetrate deeper into the pavement structure. Similar to the FWD testing, the GPR data should be collected prior to the completion of the drilling operation. A preliminary analysis of the GPR data could provide valuable information that may require additional boreholes to properly investigate the existing conditions.

REHABILITATION ALTERNATIVES

The type of rehabilitation alternative appropriate for the treatment of a frost heave is largely dependent on the type of frost heave mechanism [11]. In severe cases, full pavement reconstruction is usually required as most of the causes of frost heaves are typically found at the pavement-subgrade interface. On account of the costly nature of pavement reconstruction, many agencies will adopt a minimum rehabilitation strategy to improve the rideability through the distressed area. This typically includes removal of the distressed asphalt surface and drainage improvements followed by the replacement of new hot mix asphalt. This repair alternative is often considered to be a short term holding strategy, until funding can be secured for a more thorough rehabilitation.

Frost Susceptible Soils

If moderate to highly frost susceptible soils are present beneath the pavement structure, a typical frost heave treatment would involve the removal of the existing asphalt and granular material, with subexcavation of the subgrade soil to below the frost penetration depth. The subexcavation would be full-depth within the limits of the frost heave, before being tapered back a longitudinal distance on either side of the distressed area. The subexcavated area should be replaced with suitable non-frost susceptible material followed by the placement of new granular and asphalt materials. To ensure proper drainage, where subgrade excavation and replacement has been completed, ditches may need to be deepened. Ditch depths should be designed to be a minimum of 0.5 m below the subexcavation depth of the roadway, to promote drainage away from the pavement structure. In areas where deepening the ditches may not be feasible due to geometric, or other constraints, subdrains should be installed to assist in the removal of water.

In areas where subexcavation to the frost penetration depth is not practical, styrofoam blocks can be used to insulate the underlying frost susceptible material, and reduce the frost action on the underlying subgrade soils.

Insulation

Reducing the depth of frost penetration can also be an effective treatment for frost heaving. Typically, this is completed by including a layer of insulating material within the pavement. While this has been effective, careful attention must be paid to the transition treatment between the insulated and non-insulated pavement to endure that differential frost heaving or icing of the pavement does not occur.

Bedrock

Frost heaves found in bedrock areas can be very costly to rehabilitate. If the roadway geometrics and profile can allow for grade raises, the first alternative would be to remove the asphalt and increase the granular thickness above the bedrock. This strategy would provide a more cost effective alternative to provide separation between the pavement surface and the rock subgrade. If grades raises are not feasible, rock blasting can be completed to create deeper rock shatter to improve pavement structure drainage. Subsequent line blasting could be completed along the edge of pavement and ditchline to ensure proper drainage from beneath the pavement structure. This alternative can be very costly, with significant disruptions to the travelling public.

Recent innovation techniques have attempted to use a polyeurathane foam injection process to fill rock areas with ponding water. The intent of this rehabilitation process is to use the expanding foam material to fill in rock shatter areas where bathtub type conditions exist, preventing water from accumulating. Although trials using foam injection in rock shatter have been completed, the effectiveness of this process for frost mitigating purposes is yet to be verified.

Transition Treatments

Rehabilitation alternatives in transition areas are somewhat limited and usually include full reconstruction. Often problems arise from water draining from a rock cut area into an earth fill with frost susceptible material. In this scenario, a proper transition from rock to earth will be required to ensure that water is able to drain away from the earth fill embankment. Simply removing the frost susceptible material may address the immediate problem area, but care must be taken from creating future problems adjacent to the excavation area.

Drainage

Lack of proper drainage is one of the most significant contributors to frost heave distresses. Minimizing the infiltration of surface water through the pavement structure, and allowing the water to effectively channel away from the pavement, will reduce the potential of frost action in most distressed areas.

CONCLUSIONS

Distresses due to the action of frost heave can result in severe pavement distresses and substantially shorten the service life of a pavement. Frost heave damage decreases rideability of a roadway and can be extremely costly for roadway agencies to address.

To prevent frost heave action, it is important to understand the mechanisms which allow frost heaves to occur. Frost susceptible soils, the presence of water, and freezing temperatures all contribute to the formation of frost heaves. Once these mechanisms are understood, designers and constructors should implement mitigation techniques to ensure that the roadways are properly designed and constructed to minimize the impact of frost heave on the performance of the pavement. The freezing temperatures of cold regions cannot be controlled; however, the materials on which they are constructed on and drainage systems can be designed to reduce the potential for frost heaves.

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