STIFTELSEN BERGTEKNISK FORSKNING
ROCK ENGINEERING RESEARCH FOUNDATION

FREEZING TEMPERATURE FLOWS IN RAILWAY TUNNELS AND ITS CONSEQUENCE ON THE ROCK SUPPORTING STRUCTURE, THE ROCK AND THE REINFORCING ELEMENTS

Anna Andrén

BeFo Report 238

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Temperaturflöden i järnvägstunnlar och dess konsekvens på det bärande systemet, berget och de förstärkande elementen

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BeFo Report 238
Stockholm 2023
ISSN 1104-1773
ISRN BEFO-R-238-SE

PREFACE

The degradation of the main load-bearing system in tunnels, because of low temperatures, temperature changes and ice formation, has been studied in this research project which was already started in the second half of the 1990s.

The overall aim of the research has been to create basics to reduce the operating and maintenance costs required to secure tunnels for traffic, prevent traffic disruptions, damage to vehicles and installations caused by ice and falling rock and shotcrete. To reduce maintenance, improved knowledge is required about the degradation processes that low temperatures and freezing cause in our tunnels and thus relevant design tools can be developed, materials, systems and construction methods can be developed and selected that enhance sustainability and lower life cycle costs. Studies regarding the effect of temperature changes on the properties of shotcrete have been carried out, as well as measurements and analyzes of temperature flows in several of the Swedish Transport Agency's tunnels.

Results from the research are already considered within the framework of the Swedish Transport Administration's various governing documents.

The research reported is co-financed by BeFo, Formas and the Swedish Transport Administration.

The reference group that assisted the project was made up of Tommy Ellison, Thomas Dalmalm, Johan Funehag and Per Tengborg. Their in-kind efforts have contributed to the project's success, but it is the work of Anna Andrén, with the supervision of Lars-Olof Dahlström and Erling Nordlund, and the financiers' enabling of this *long-term effort* that has created an almost world-unique empiricism and data.

Stockholm

Patrik Vidstrand

FÖRORD

Den nedbrytning av det bärande huvudsystemets i tunnlar, som är en konsekvens av låga temperaturer, temperaturväxlingar och isbildning har studerats i detta forskningsprojekt som påbörjades redan under andra halvan av 1990 talet.

Det övergripande syftet med forskningen har varit att skapa grundförutsättningar för att minska de drift- och underhållskostnader som krävs för att säkerställa tunnlar för trafik, förhindra trafikstörningar, skador på fordon och installationer som orsakas av is och nedfallande sten och sprutbetong. För att reducera underhållet krävs förbättrad kunskap kring de nedbrytningsprocesser som låga temperaturer och frysning orsakar i våra tunnlar och därmed kan relevanta designverktyg utvecklas, material, system och byggmetoder utvecklas och väljas med hänsyn till hållbarhet och livscykelkostnader. Studier avseende temperaturväxlingars inverkan på sprutbetongens egenskaper har utförts liksom mätningar och analyser av temperaturflöden i flera av Trafikverkets tunnlar.

Resultat från forskningen är redan hänsyntagen inom ramen för Trafikverkets olika styrdokument.

Forskningen som rapporteras är samfinansierad av BeFo, Formas och Trafikverket.

Referensgruppen som bistått projektet har utgjorts av Tommy Ellison, Thomas Dalmalm, Johan Funehag och Per Tengborg. Deras in-kind insatser har bidragit till projektets framgång men det är Anna Andréns, med handledning av Lars-Olof Dahlström och Erling Nordlund, arbete och finansiärernas möjliggörande av denna *långtidsinsats* har skapat en i det närmaste världsunik empiri och data.

Stockholm

Patrik Vidstrand

SUMMARY

Water in the surrounding rock mass flows into the tunnel via naturally occurring joints and via cracks caused by the blasting used to excavate the tunnel. The most common method in Sweden to reduce or prevent leakage problems are first and foremost the use of grouting. However, experience shows that despite extensive pre grouting and supplementary post-grouting, it is difficult to seal the rock mass so that drips and moisture are completely eliminated. Although the water itself causes degradation of the tunnel, the degradation process increases dramatically when the water is exposed to freezing temperatures. Water expands during freezing and due to water migration, which occurs in rock in a similar way as in soil, the ice causes frost shattering of the interface between rock and shotcrete and also to the shotcrete and the rock itself. This can damage the main load-bearing system. The ice formation itself is a maintenance problem, as the tunnels must be kept clear of icicles, ice pillars and ice layers in the tracks or on the roads. One of the main tasks in this research project has been to identify which problems cause the most maintenance work and where and when these problems occur in the tunnel.

During the field observations, many problems with water and ice were discovered, all of which contribute to increased maintenance. Many ice problems are directly linked to frost insulated drain mats. Leakage and ice formations occur at the edge of the drains, in mat splices and when brackets for cable racks, handrails or other installations puncture a drain and it has not been properly sealed. In drains covered with shotcrete, frost shattering and cracking in the shotcrete can be a problem. Frost cycles in the tunnel cause the water to freeze and thaw alternately, allowing more water to reach the freezing area due to water migration, resulting in frost shattering of the rock and the shotcrete. If not anchored with bolts, the reinforcing effect and the stability of shotcrete in a tunnel is dependent on the adhesion to the rock surface. It is, therefore, important to take all available measures to ensure good adhesion. Poor adhesion in itself is not a degradation problem, but a void can form in the interface between rock and shotcrete as a result of poor adhesion. If this void is filled with water that cannot drain away, ice pressure can occur in the layer between rock and shotcrete. The ice pressure can cause cracking and degradation of the shotcrete if the pressure exceeds the tensile strength of the adjacent material. In some of the reported fall-outs of rock and shotcrete, an ice layer was discovered between the rock surface and the edges of the remaining shotcrete layer. Therefore, frost shattering is a likely cause of the fall-outs. Many frost cycles combined with water leakage can cause frost shattering. The field measurements conducted as a part of this study have shown that most frost cycles do not occur closest to the tunnel entrances, but instead about 100 to 200 m into the longer tunnels. The results from the laboratory tests performed as part of this study showed that the adhesive strength between rock and shotcrete decreased significantly when the test panels were subjected to freeze-thaw cycles. Furthermore, more of the micro seismic events (AE - acoustic emission monitoring) occurred in the test panels that had access to water during freezing. Therefore, maintenance personnel and inspectors should pay particular attention to water leakage in sections that have an

increased number of frost cycles, to avoid future problems with frost shattering of rock or shotcrete.

In the longer tunnels studied in this work, a greater number of ice formations occurred in the inner parts of the tunnel, than close to the entrances. The rock mass emits heat, which heats up the cold outside air that enters the tunnel. Due to the heat transfer from the rock mass, leakage points located further along the tunnels can remain unfrozen. A leak that is closer to the tunnel entrances in the longer tunnels or a leak in a shorter tunnel are exposed to higher freezing rates. The entire rock mass freezes and the leak 'freezes dry', that is, ice forms in the water-bearing fracture, preventing further water leakage.

Where and when ice problems occur along a tunnel depends on many factors. Besides the obvious water leakage, the length of frost penetration into the tunnel is the main reason for where and when ice problems occur. The predominant cause of frost penetration in most of the tunnels is the thermally induced airflow. In the longer tunnels, the inclination of the tunnel affects frost penetration the most. The field observations showed that there was a difference in where and when leakage points appear during the year and also in terms of variation in the amount of leakage water. There was also a variation over different years. The conclusions of the field observations are that it is difficult to estimate where the insulated drain mats should be located along a tunnel. Based on experience from this survey, the location of the drains should be determined only after several inspections and especially after a winter period, when the main problems with ice formation occur. Previous perception regarding ice problems have been that ice formation only occurs at the tunnel entrances and in the outer parts of the tunnel. A proposed measure has, therefore, been to cover the first 300 m from each entrance with frost insulated drains to try to completely eliminate the ice problems. However, this is not an effective solution to the problem. The insulation not only prevents the cold from reaching the leakage point, but it also prevents the rock mass from emitting heat that warms up the cold outside air entering the tunnel. Thus, the frost can penetrate further into the tunnel and the problems with ice formation are only moved further into the tunnel. As the amount and location of the frost insulation affects frost penetration, the dimensioning of insulation must, therefore, be carried out in several iterations, where each new distribution of insulation along the tunnel is calculated separately.

For the tunnels studied, the following has emerged. The central and southern parts of Sweden have shorter cooling periods and the tunnels are exposed to many temperature fluctuations around 0°C during the winter. The frost does not have time to penetrate as far here as in the tunnels in the northern parts of Sweden. Therefore, more ice problems arise around the entrances of the tunnels in the southern parts of Sweden than for those in the northern parts. For northern parts of Sweden, the problem of growing ice formations in sections near the tunnel entrance usually occurs only during the autumn and spring, but not in winter. The field observations showed that the problems with ice growth and temperature fluctuations around 0°C occur further along the longer tunnels in the northern parts of Sweden. This is because the temperature of the tunnel air is higher due to heat transfer from the rock mass. For shorter tunnels that adopt the same temperatures as the outside air, ice formations can occur along the entire length of the tunnel in the sections that have leakage problems. The Swedish Transport Administration's regulations are currently being updated and the observations and measurements carried out in this work are now being used to propose and to evaluate new requirements regarding frost penetration in tunnels.

Keywords: Tunnel, frost penetration, ice formation, freeze-thaw test, frost shattering, temperature measurement, maintenance, degradation of rock and shotcrete, cold climate.

SAMMANFATTNING

Vatten i den omgivande bergmassan rinner in i tunneln via naturligt förekommande sprickor och via sprickor orsakade av själva sprängningen av tunneln. Den vanligaste metoden i Sverige för att minska eller förebygga läckageproblem är först och främst injektering. Erfarenheter visar dock att trots omfattande förinjektering och kompletterande efterinjektering, är det svårt att täta bergmassan så att dropp och fukt helt elimineras. Även om vattnet i sig orsakar nedbrytning av tunneln, ökar nedbrytningsprocessen dramatiskt när vattnet utsätts för minusgrader. Vattnet expanderar vid frysning och på grund av vattenvandring, som sker i berg på liknande sätt som i jord, kan isen orsaka frostsprängning i skiktet mellan sprutbetong och berg, men även i själva sprutbetongen och berget. Detta kan skada det bärande huvudsystemet. Själva isbildningen är ett underhållsproblem i sig, eftersom tunnlarna måste hållas fria från istappar, ispelare och islager i spår eller på vägar. En av uppgifterna i forskningsprojektet har varit att ta reda på vilka problem som orsakar mest underhållsarbete och var och när dessa problem uppstår i tunneln.

Vid fältobservationerna observerades många problem med vatten och is, som alla bidrar till ett ökat underhåll. Många isproblem är direkt kopplade till de frostisolerade dränmattorna. Läckage och isbildning uppstår vid dränkanterna, i skarvar mellan mattor och när fästen för kabelräcken, ledstänger eller andra installationer punkterar dränen som sedan inte har blivit ordentligt tätad. I dräner täckta med sprutbetong kan frostsprängning och sprickbildning i sprutbetongen vara ett problem. Frostcykler i tunneln gör att vattnet fryser och tinar om vartannat, vilket möjliggör vattentransport till frysområdet genom vattenvandring med frostsprängning av berg och sprutbetong som följd. Om sprutbetongen inte är bultförankrad är förstärkningseffekten och stabiliteten hos sprutbetongen i en tunnel helt beroende av vidhäftningen mot bergytan. Det är därför viktigt att vidta alla tillgängliga åtgärder för att säkerställa god vidhäftning. Dålig vidhäftning i sig är inte något nedbrytningsproblem. Om ett hålrum i skiktet mellan berget och sprutbetongen fylls med vatten som inte kan dränera undan, kan ett istryck byggas upp. Istrycket kan orsaka vidhäftningsbrott i kontakten mellan sprutbetong och berg, samt sprickbildning och nedbrytning av sprutbetongen och berget om trycket överstiger draghållfastheten hos det intilliggande materialet. Vid några av de rapporterade nedfallen av berg och sprutbetong upptäcktes ett islager mellan bergytan och kanterna på det kvarvarande sprutbetongskiktet. På grund av detta är frostsprängning är en trolig orsak till nedfallen. Många frostcykler i kombination med vattenläckage kan orsaka frostsprängning. Utförda fältmätningar har visat att de flesta frostcykler inte sker närmast tunnelmynningarna, utan istället på cirka 100 till 200 m in längs de längre tunnlarna som studerats inom ramen för detta doktorsarbete. Resultaten från utförda laboratorieförsök, visade att vidhäftningshållfastheten mellan berg och sprutbetong minskade betydligt när testpanelerna utsattes för frys-tiningscykler. Dessutom var de registrerade mikroseismiska händelserna (AE – mätning med akustisk emission) fler i de testpaneler som hade tillgång till vatten under frysning än de som saknade tillgång till vatten. Därför bör underhållspersonal och inspektörer vara särskilt uppmärksamma på vattenläckage i

sektioner som har ett ökat antal frostcykler, för att undvika framtida problem med frostsprängning av berg eller sprutbetong.

I de längre tunnlarna som har studerats, bildades ett större antal isformationer i de inre delarna av tunneln, jämfört med området kring mynningarna. Bergmassan avger värme som värmer upp den kalla uteluften som tränger in i tunneln. På grund av värmeöverföringen från bergmassan kan läckage som finns längre in i tunnlarna förblir ofrusna. Ett droppläckage som är närmare tunnelmynningarna i de längre tunnlarna eller droppläckage i de kortare tunnlarna utsätts för högre fryshastighet. Hela bergmassan fryser och läckaget ”fryser torrt”, det vill säga det bildas is i den vattenförande sprickan vilket förhindrar ytterligare vattenläckage.

Var och när isproblem uppstår längs en tunnel beror på många saker. Förutom det uppenbara vattenläckaget är längden på frostinträngning in längs tunneln den främsta orsaken till var och när isproblem uppstår. Den dominerande orsaken till frostinträngning i de flesta tunnlarna är det termiskt inducerade luftflödet. I de längre tunnlarna är det lutningen på tunneln som påverkar frostinträngningen allra mest. Fältobservationerna visade att det fanns en skillnad i var och när läckageställen uppstår under året och även en variation i mängden läckagevatten. Det fanns också en variation över olika år. Slutsatserna av fältobservationerna är att det är svårt att uppskatta var de isolerade dränmattorna ska placeras längs en tunnel. Utifrån erfarenheter från denna undersökning bör dränernas placering bestämmas först efter flera inspektioner och särskilt efter en vinterperiod, då de verkliga problemen med isbildning uppstår. Tidigare uppfattning kring isproblem har varit att isbildning endast sker vid tunnelmynningarna och i de yttre delarna av tunneln. Ett åtgärdsförslag har därför varit att klä in de första 300 m från vardera mynningen med frostisolerande dräner för att helt försöka eliminera problemen med isbildning. Det är inte en effektiv lösning på problemet. Isoleringen förhindrar inte bara kylan från att nå vattenläckaget, utan den hindrar även bergvärmen att komma ut i tunneln och värma upp den kalla uteluften. Därmed kan frosten tränga in längre och problemen med isbildning flyttas bara längre in längs tunneln. Då mängden och placeringen av frostisoleringen påverkar frostinträngningen, måste dimensioneringen av isolering utföras i flera iterationer, där varje ny fördelning av isolering längs tunneln beräknas separat.

För de tunnlar som har studerats i detta arbete har följande framkommit. De mellersta och södra delarna av Sverige har kortare frostperioder och tunnlarna utsätts för många temperaturväxlingar kring 0°C under vintern. Frosten hinner inte tränga in lika långt här, som i tunnlarna i de norra delarna av Sverige. Därför uppstår fler isproblem kring tunnlarnas mynningar i de södra delarna av Sverige, än för tunnlarna i de norra delarna. I de norra delarna av Sverige uppstår problemet med växande isformationer i sektioner nära tunnelmynningarna vanligtvis bara under hösten och våren, men inte under vintern. Fältobservationerna visade att problemen med istillväxt och temperaturväxlingar kring 0°C uppstår längre in i de längre tunnlarna i norra Sverige, eftersom tunnelluftens temperatur är högre på grund av värmetransport från bergmassan. För kortare tunnlar, som antar samma temperaturer som uteluften, kan isformationer uppstå längs hela tunnelns längd i de sektioner som har läckageproblem. Trafikverkets regelverk håller på att uppdateras och de observationer och framförallt mätningar utförda i detta arbete används nu för att föreslå och att utvärdera nya kravställningar kring köldinträngning i tunnlar.

Nyckelord: Tunnel, köldinträngning, isbildning, frystester, frostsprängning, temperaturmätning, underhåll, nedbrytning av berg och sprutbetong, kallt klimat.

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1. INTRODUCTION

1.1 Background

Ice formation in tunnels is a major problem that must be addressed frequently to ensure the continuation of train and road traffic, as well as the safety of the Swedish Transport Administration's tunnels. Cold outside air penetrating the tunnels during the winter causes water leaking into the tunnel to freeze and form ice. Icicles, ice pillars and ice layers can damage the tunnel construction and its installations such as handrails, cables, overhead contact lines and drainage systems. In railway tunnels, icicles can grow so long that they short-circuit the overhead contact line and ice formations can grow so large that they encroach on to the gauge clearance and operational space of the tunnel (Figure 1.1). Roads and tracks might be covered by ice because leaking water from the roof and walls freezes when it meets the cold track and road surface which, if the tunnels have not been inspected and ice removed, could lead to slipping and derailment with serious consequences. When the water freezes in the rock mass and its fracture network surrounding the tunnel or freezes in the interface between rock and the reinforcing shotcrete, frost shattering of the materials can cause degradation of rock and shotcrete. The material might lose its load-bearing capacity and might fall down on areas of the road or tracks. To maintain safety and prevent traffic disruptions, many tunnels require frequent and extensive maintenance. Removal of ice and loose rock and shotcrete is both costly and risky work (Figure 1.2). To reduce the development of ice formations and develop measures for efficient maintenance in the tunnels, improved knowledge is required about frost penetration, the effects of ice pressure on the main load-bearing system and where in the tunnels most ice problems occur.

a) b)

Figure 1.1 a) Icicle in the Rönninge tunnel (Photo: Infranord, 2010).
b) Ice pillar in the Glödberget tunnel (Andrén, 2008).

a) b) c)

Figure 1.2 a) and b) Removal of ice pillar in the Glödberget tunnel (Andrén, 2008).
c) Removal of icicles in tunnel roofs above the overhead contact line using long insulating plastic rods in the Rönninge tunnel (Andrén, 2008).

1.2 Problem description

In the early 2000s, there was an increase in reported incidents of rock and shotcrete fall-outs in Swedish railway tunnels. To mention a few, rock falls were reported in the Bergträsk, Aspen and Kålgård tunnels and shotcrete fall-outs were reported in the Gårda, Nuolja (Figure 1.3) and Bergträsk tunnels (see chapter 5.1). Inspections of these tunnels showed that frost action was one of the major reasons for movement (displacement and rotation) of rock blocks, which was indicated by exposed fracture surfaces covered by thin layers of ice. Shotcrete usually falls out as sheets, and the previously existing interfaces between shotcrete and rock are often covered with ice. This implies that water had accumulated in the interface between rock and shotcrete (Andrén, 2006 and Andrén, 2009).

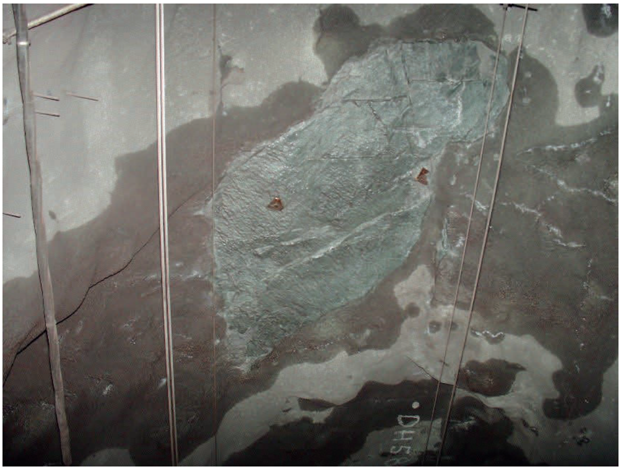


Figure 1.3. Shotcrete fall-out from 2003 in the roof of the Nuolja tunnel (Andrén, 2008).

The cause of rock and shotcrete fall-outs is not clear. One scenario is that the material undergoes degradation due to weathering processes such as frost shattering resulting in fall-outs, while another is that the shotcrete falls down due to poor adhesion between the rock and shotcrete. The fall-outs often occur in tunnel sections where problems with the leakage of water exist. Therefore, a likely scenario is that the water is subsequently freezing and expanding in joints or cracks near the tunnel contour, or that freezing water is slowly propagating in the interface between rock and shotcrete. This process can produce a pressure, which can cause pieces of rock to break loose from the tunnel walls or roof, as well as causing the shotcrete to crack. Cracking will then lower the load-bearing capacity of the shotcrete and can, in the worst-case scenarios, cause fall-outs.

To determine where along the tunnel efforts must be made to prevent ice formation, the frost penetration and temperature conditions of tunnels must be investigated. Therefore, long-term field measurements have been conducted in two Swedish railway tunnels. The measurements involve monitoring the air and rock temperatures, air pressure and air velocity. The results have been used to propose and to evaluate current and suggested future requirements regarding frost index in the Swedish Transport Administration's regulations (TRVINFRA-00233). Even though the problems regarding frost penetration, water leakage and ice formation were well recognised, the extent of the problems were not known in the early 2000s.

1.3 Aim and purpose

The purpose of this work is to gather information about problems with water leakage and its effect on a tunnel when it is subjected to freezing temperatures. To improve the understanding of the factors and processes that control the growth of ice, the development of ice pressure and frost shattering of rock and shotcrete. The work also aims to increase the understanding of temperature flows in a tunnel, where and when problems occur in a tunnel and how the problems can be detected and avoided.

1.4 Approach

The approach to seeking greater knowledge and understanding about ice problems and to achieve the objective has been through:

- Literature review.
- Field observations through inspections of water and ice problems.
- Field measurements of frost penetration in tunnels, including, among other things, the temperatures and air velocity in tunnels.
- Laboratory studies of freeze-thaw tests on shotcrete-rock panels.

1.5 Scope and limitations

Degradation of rock material is caused by different weathering processes and weathering is the decomposition of geological materials through mechanical or chemical processes. The remit of this work is limited in order to focus solely on mechanical weathering as a result of frost shattering and ice pressure. The focus is on the problem of degradation of the interface between rock and shotcrete. Only fractured hard rocks are considered, i.e., not sedimentary rocks.

In the sections on frost penetration, this report focuses mostly on railway tunnels because the project was first initiated by the Swedish National Rail Administration, and they have since continued to study natural causes that affect temperature flows in tunnels. Many road tunnels have mechanical ventilation to create a good air environment in the tunnel. This creates an airflow that can contribute to increasing frost penetration.

To explain where along a railway a specific section or measuring station is located, the term 'chainage km 20+100' is used. The term means that the measurement along the track length is 20 kilometres and 100 metres from a specified zero point. For example, the zero point for the Åsa tunnel is in Gothenburg and for the Glödberget tunnel, the zero point lies in Stockholm. When the term 'drain' or 'drain mat' is used in the text, it refers to a frost insulated drain mat.

2. WATER AND ICE PROBLEMS IN ROCK TUNNELS

2.1 Problems

When leaking water from discontinuities reaches the rock surface and is cooled by the tunnel air, ice is formed (Figure 1.1). Ice formations on the floor, roof or walls threaten the safety and functionality of the tunnels. Ice can also develop in joints or cracks and exerts a pressure on the joint or crack surface (P_{ice}), which leads to frost shattering of rock and shotcrete (Figure 2.1). Degradation of the material might result in a decreased load bearing capacity of the rock and the rock support, like shotcrete or concrete lining. This can lead to fall-outs of rock and shotcrete.

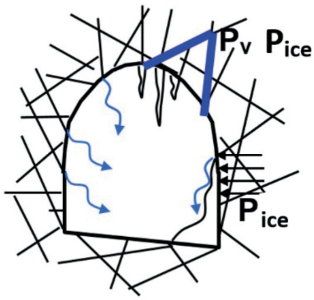


Figure 2.1. Ice loads (P_{ice}) arising when leakage occurs in the frost zone (Andrén, 2004).

There are many factors that determine whether frost action, ice formations or frost shattering of the rock mass, the shotcrete or the shotcrete-rock interface will appear in tunnels. A tunnel exposed to negative temperatures usually has no problems in sections where the rock material is intact and of good quality. Problems occur in sections with bad rock conditions and water leakage. The factors that govern ice formation are for example:

- The mechanical properties of the rock mass and the access to water (groundwater level, precipitation).
- Measures used in tunnels to prevent the inflow of water.
- Frost penetration and temperature conditions in the region where the tunnel is located.
- Ice formation and factors affecting freezing.
- Frost action and access to water during freezing.

2.2 Rock mass

2.2.1 Properties of the rock mass

Igneous and metamorphic rocks are most common in Sweden (Loberg 1993). They are often dense and water occurrence is concentrated in joints and fissure systems (Fairhurst et al., 1993). Micro cracks occur between or through the mineral particles, but the porosity and hydraulic conductivity are low (Gustafson, 1986). When a tunnel is excavated, the characteristics of the rock mass closest to the tunnel might change (Pusch, 1989). The excavation process leads to changes in the stress field in the rock mass and the geometry of the aperture between the joint surfaces can change due to an increase or decrease in the normal stress across the joint (Hakami, 1988). The excavation method is a factor that affects the rock mass behavior. When excavating by drill and blast technique, natural fractures might widen, and new cracks developed that will increase leakage and distribute it along the tunnel.

2.2.2 Access of water in the rock mass surrounding the tunnel

As much as 75% of the water leakage is thought to originate from only a few larger joints, while the remaining 25% of the leakage originates from a large number of small joints (Vägverket, 1994). Leakage of water in all unlined rock tunnels occurs as moist surfaces, drips or flowing water. The water enters the tunnel through a network of natural fractures and is also distributed via cracks caused by the blasting used to excavate the tunnel. Although the water itself causes degradation of the tunnel, the degradation process increases dramatically when the water is exposed to freezing temperatures. The leakage into a tunnel is affected by rock mass properties, topography and the location of the tunnel in relation to the groundwater level, the amount of precipitation during the year, ground frost and how the water is stored in the rock. The leakage is also affected by how the tunnel cuts through the fracture network and other discontinuities that facilitate water to flow towards the tunnel the flow paths of the water.

The leakage into the tunnel can be influenced by the frost action in rock because it can change the permeability of the joint filling material in the rock mass. When clay freezes, a restructuring of the clay particles occurs (Figure 2.2). Freeze consolidation causes settlements and an increase in the permeability of the soil (Chamberlain and Gow, 1978). This can cause problems in newly excavated tunnels when the clay is initially exposed to the negative temperatures of the cold air in the tunnel. A joint that appeared to be impermeable at the time the tunnel was excavated can start to leak after one freezing period due to the restructuring of the clay particles. Other joints can stop leaking as a result of natural clogging by debris or the precipitation of calcium oxide and by precipitations containing iron (Statens vegvesen, 2004).

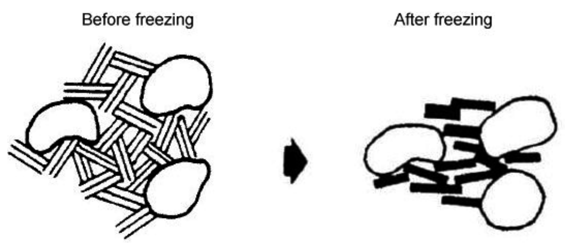


Figure 2.2 Restructuring of clay particles when freezing (after Chamberlain and Gow, 1978 – from Johansson, 2005).

2.2.3 Temperatures of leakage water

The rock mass has a large heat content and the leakage water, which adopts the same temperature as the rock mass, continuously supplies heat to the rock surface around the leakage point. The temperature of the bedrock in Sweden is the same as the temperature of the groundwater presented by the Geological Survey of Sweden, SGU, in Figure 2.3. The heat content of the leakage water keeps the leakage paths open and prevents it from freezing so quickly. The leakage point will continue to leak until the cooling from the tunnel air exceeds the amount of heat from the leaking water. A smaller leakage thus does not add enough heat and, therefore, freezes much faster, so-called ‘freeze dry’.

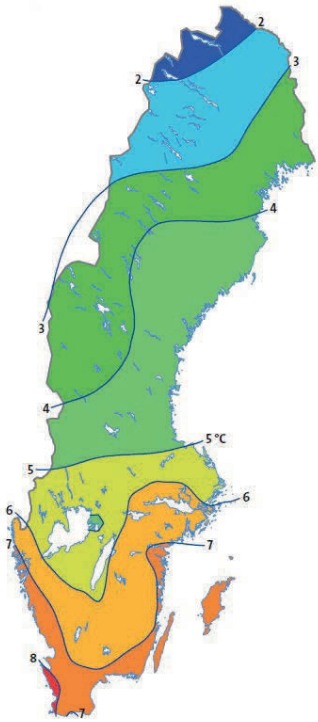


Figure 2.3 The median value of the groundwater temperature in Sweden for the period 1975–1995 (Erlström et al., 2016).

2.2.4 Measures used to reduce or prevent the inflow of water

The most common method used in Sweden to reduce or prevent problems with ice formations in tunnels is to prevent water from leaking into the tunnel using grouting. Grouting normally successfully meets the requirements of the Land and Environmental Court regarding ground water control and the requirement of not lowering the level of the groundwater; on some occasion's impermeable lining or infiltration might be required. Impermeable tunnel construction is a much more expensive solution compared to grouting but, on the other hand, any problems with ice formation can be completely eliminated. Experience shows that, despite extensive pre-grouting and supplementary post-grouting, it is difficult to seal the rock mass so that drips and moisture are completely eliminated. If grouting is not sufficient, the water must be diverted from the tunnel in some other way. These include diversion of water from the tunnel using lining, insulated drains or using impermeable constructions to prevent water from reaching the tunnel.

2.3 Frost penetration in tunnels

Frost penetration in a tunnel occurs when the tunnel air is set in motion and cooling of the tunnel air takes place due to the cold outside air penetrating the tunnel. The tunnel is exposed to a certain amount of cooling 'frost index' according on the tunnel's geographical location in Sweden (see chapter 2.3.2). How far into the tunnel the frost penetration occurs is affected by, among other things, the length and inclination of the tunnel, wind direction and by the traffic through the tunnel (see chapter 2.3.4).

2.3.1 The concept of the frost index

The frost index refers to the sum of all negative degrees in the daily mean temperature. The summation takes place from summer to summer and thus provides a measure of how cold the winter has been. See the explanation by Knutsson (1981) in Figure 2.4. The unit of frost index is negative degree days.

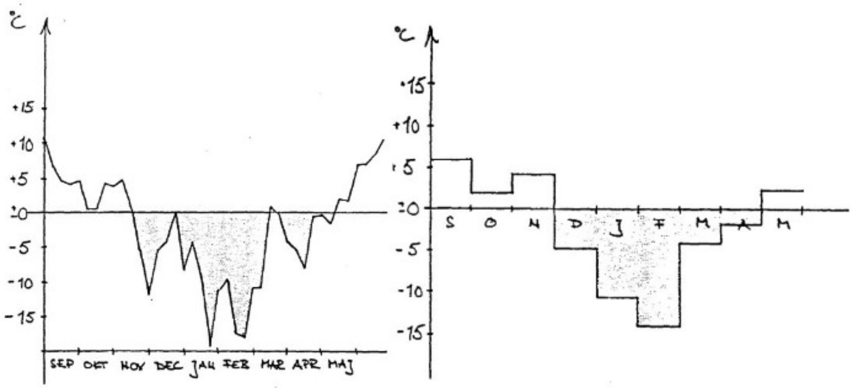
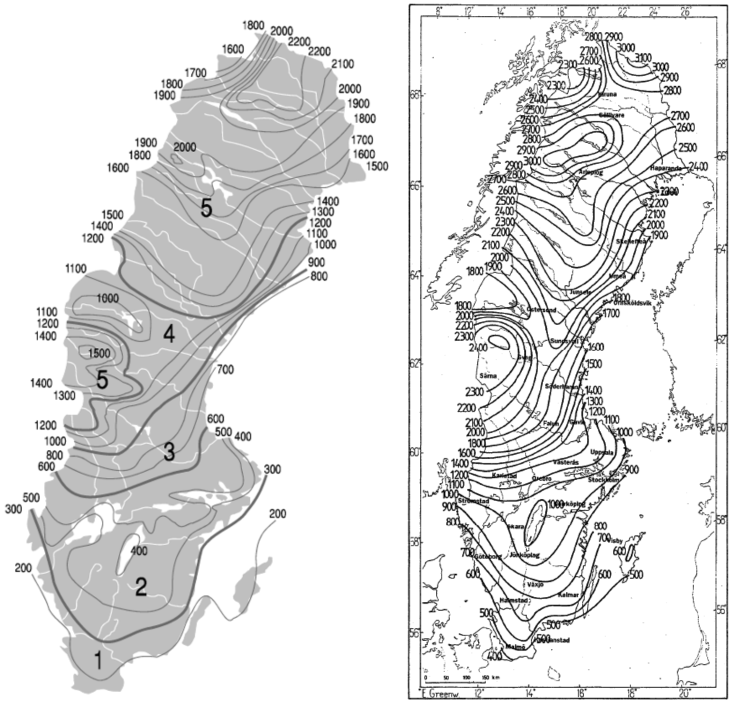


Figure 2.4 Frost index explained by Knutsson (1981).

2.3.2 Current and future requirements of the frost index

The Swedish Transport Administration's requirements and regulations (TRVINFRA-00233) provide frost index maps covering the whole of Sweden calculated by the Swedish

Meteorological and Hydrological Institute (SMHI). The current frost index is shown in Figure 2.5 and shows both mean annual frost index and frost index with 50 years return period for the outside air.



a) b)

Figure 2.5 Current requirements of the frost index in TRVINFRA-00233 (2021) for the years 1961/1962-1988/1989 (negative degree days).
a) Climate zones and mean annual frost index.
b) Frost index with 50 years return period.

Recently, SMHI updated maps of frost index for a new reference period spanning the years 1990/1991-2019/2020 (Asp, 2021). The updated maps and the suggested future division of climate zones due to changes in the world climate are shown in Figure 2.6 (Asp, 2022).

a) b)

Figure 2.6 Climate zones and frost index (negative degree days) for the years 1990/1991-2019/2020 (Asp, 2022).
a) Mean annual frost index.
b) Frost index with 50 years return period.

2.3.3 Reduction of requirements of the frost index inside a tunnel

The Swedish Transport Administration's requirements and regulations (TRVINFRA-00233) use the frost index calculated on the outside air temperature for different climate zones. But because of the heat transfer from the rock mass, which causes heating of the tunnel air, the requirements for the frost index inside a tunnel is lowered in relation to the requirements for the frost index of the outside air. The frost index inside the tunnels is used to assess where frost insulation should be located along a tunnel and how thick the insulation should be to ensure that water does not freeze. It is also used to calculate compelling forces due to the temperature gradient in, for example, the concrete construction, between the temperature in the rock mass and the temperature in the tunnel air.

The maps of frost index (Figure 2.5) are used to calculate the requirements for the frost index at specific sections along the tunnel. Simplified, the calculated frost index with 50 years return period is used in the outer parts of the tunnel (approximately 500 m in from each entrance) and the calculated mean annual frost index in the inner parts for tunnels that are over 1000 m long (Figure 2.7). In Table 2.1, the current calculated frost index inside a tunnel is shown for each climate zone.

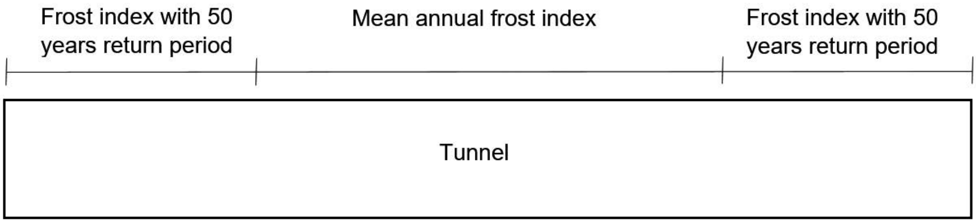


Figure 2.7 Current requirements for the frost index at different sections inside a tunnel.

Table 2.1 Calculated current requirements for the frost index inside a tunnel for different climate zones.

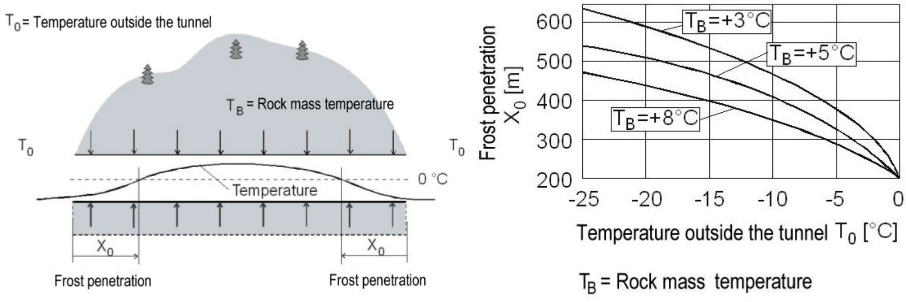
Climate zone	1	2	3	4	5
Frost index with 50 years return period	450	675	900	960	1350
Mean annual frost index	180	360	540	600	900

Due to climate changes (Figure 2.5 and Figure 2.6), the requirements for the frost index inside a tunnel also have to change. In order to propose new requirements for the frost index, division of sections inside a tunnel, and to find out if these values are relevant, the field measurements carried out in this work have been used for the evaluation (see section 4.3).

2.3.4 Previous performed laboratory model test

On behalf of the Swedish National Rail Administration, a laboratory model test was performed to identify which parts of a tunnel are not exposed to freezing temperatures (Sandberg et al., 2002). The model test concluded that the frost penetration in a tunnel occurs when the tunnel air is set in motion by: (i) thermal produced airflow, (ii) a train passing through the tunnel and (iii) wind pressure. In a majority of the tunnels, the predominant cause of frost penetration is the thermally induced airflow. Even though the air velocity is not necessarily high, it has a major impact on the tunnel temperature since it is continuous and fairly constant. Airflow due to train traffic was found to have little impact on frost penetration.

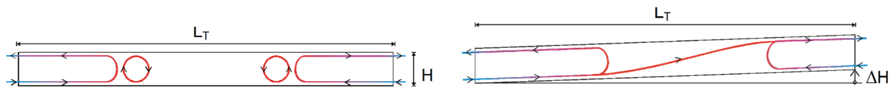
The results of the model test are presented as temperature diagrams for tunnels with different inclinations. Figure 2.8a shows the variation in temperature along a tunnel, where frost penetration is the distance from the tunnel entrance to the section where the temperature rises above 0°C. The frost penetration distance X_0 depends on the air temperature outside the tunnel T_0 and the rock mass temperature T_B. Examples are shown in Figure 2.8b.



a) b)

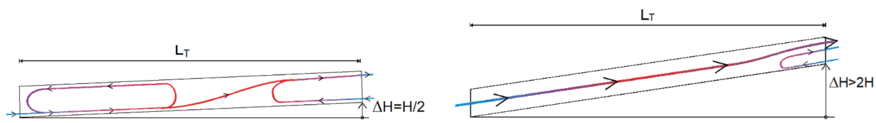
Figure 2.8 Frost penetration (figures modified from Sandberg et al., 2002).
a) Variations in temperature along a tunnel.
b) Frost penetration at the lower entrance of an inclined tunnel

Depending on the inclination of the tunnel, different airflow patterns occur in the tunnel where L_T is the length of the tunnel, H is the height of the tunnel and ΔH is the height difference between tunnel entrances (Figure 2.9 and Figure 2.10). The situation in Figure 2.10b applies to the Glödberget tunnel, which has an inclination of 12 ‰ (see chapter 4.2.7). The conclusion of the tests is that the inclination of the tunnel has a big influence on frost penetration. For example, frost penetration occurs further in from the lower tunnel entrance than from the upper entrance (Sandberg et al., (2002).



a) b)

Figure 2.9 a) Class I Case A ΔH = 0 Two convection loops with no contact with each other.
b) Class I Case B ΔH > 0 Net flow through the tunnel (Sandberg et al., 2002).



a) b)

Figure 2.10 a) Class II Case C ΔH = H/2 No air flows out of the tunnel at the lower entrance.
b) Class III Case D ΔH >2H The air flows in one direction in most of the tunnel. Cold air wedge at the upper entrance (Sandberg et al., 2002).

2.4 Ice formation and factors affecting freezing

2.4.1 Frost action

Frost weathering refers to the combination of mechanical and chemical processes which cause the in-situ breakdown of rock in cold-climate conditions. Among the mechanical weathering processes in rock, frost action is one of the dominant factors in cold regions (French, 1996). Frost action is most destructive in regions with frequent freezing and thawing, where partial thawing during the day adds new water into a joint. When the new water freezes during the night, more ice is formed, and the expansion causes the joint to widen even more. This is called frost wedging (Plummer and McGeary, 1996). In Sweden, frost wedging or frost shattering is often described as the most destructive process for rock weathering (Svensson, 2004).

2.4.2 Access to water and water migration

For a long time, the 9% volumetric expansion of water was thought to be the primary cause of frost shattering. An alternative mechanism was first presented by Everett (1961). He suggested that capillary suction caused water migration towards the freezing front. Then, the ice pressure led to the shattering of the rock. Experimental work by Walder and Hallet (1985) has shown that unfrozen water tends to migrate towards the frozen centre in rock as well as in soil (Figure 2.11). Water migration in frozen porous rock was observed in laboratory tests that showed that water migration could be responsible for frost shattering (Fukuda and Matsuoka, 1982 and Fukuda 1983). Laboratory tests of the influence of access to water during freezing led to a hypothesis that a combination of the two processes, volumetric expansion and water migration, controlled frost shattering (Matsuoka, 1990a), which was also suggested by Tharp (1987).

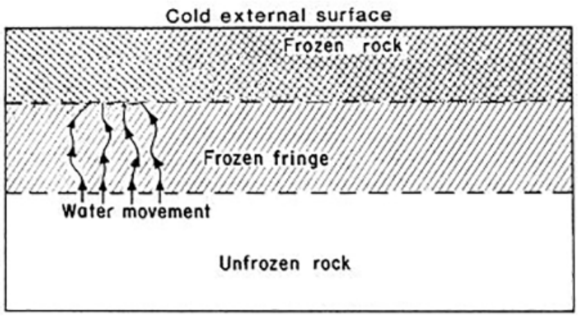


Figure 2.11 Frozen fringe – the zone between the frozen and the unfrozen layers (modified from Walder and Hallet, 1985).

The growth of ice lenses is the main reason behind frost heaving of soil. In rock, the water can migrate in a similar manner inside a joint. The water migrates into the water film at the interface between the ice and rock allowing expansion of the ice layer, which exerts pressure on the rock surfaces through the water film. This can cause frost shattering (Tharp, 1987). The freezing rate (decrease in temperature per unit of time, °C/h) has an influence on water accessibility. If the freezing rate is rapid enough, it can minimise the water uptake, thus preventing frost damage (Matsuoka, 2001a). In contrast, long-term, slow freezing which allows water migration can result in frost damage (Matsuoka, 2001a) because the longer duration of constant low temperature gives the mechanism of water migration more time to effectively increase ice pressure (Fridh, 2005).

Adsorbed water has a lower energy level than free water, and the adsorbed water requires lower temperatures to freeze. When the temperature decreases and all free water has been frozen, water with lower energy levels starts to freeze. The part with unfrozen water is reduced (Figure 2.12), causing the water film that separates the ice from the solid particles to become thinner. As the temperature continues to decrease, more of the adsorbed water freezes and the energy level in the unfrozen water decreases. In a volume of soil or rock, there will be sections of different energy levels in the unfrozen water due to the temperature variation. Water always strives to achieve the lowest energy possible, and this causes unfrozen water to migrate from warmer to colder zones because the energy level is lower there (Knutsson, 1999).

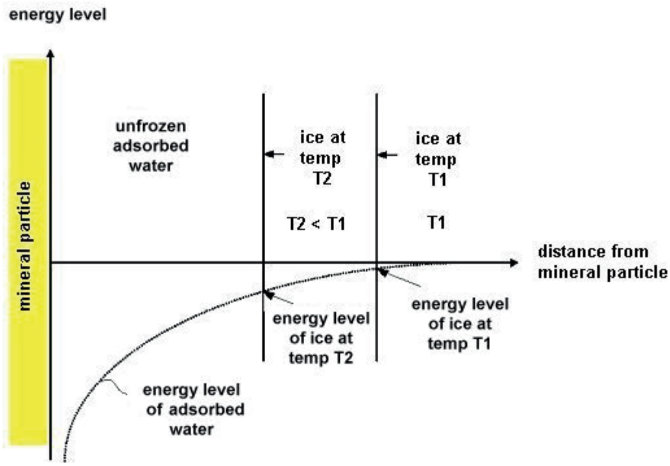


Figure 2.12 Energy level of water in proportion to the distance from the mineral particle (modified after Knutsson, 1981).

Experimental work has shown that a considerable amount of water remains unfrozen at subfreezing temperatures not only in soil, but also in rock, and that unfrozen water tends to migrate towards the freezing centre in rock as well as in soil (Walder and Hallet, 1985). According to Tharp (1987) the water migration creates an expansion of the ice layer, which can produce a pressure at the joint surfaces. Matsuoka (1990a) carried out freeze-thaw experiments and showed that water migration plays an important role in the frost shattering of rock. In the tests, the samples were exposed to both an open system (access to water during the freezing period) and a closed system (no access to water during the freezing period). The water migration in the open system led to an increase in ice volume, which caused major damage to the rock. In the closed system, the resultant damage was relatively small because only the pre-existing water became ice.

2.4.3 Saturation

To understand the mechanisms of rock breakdown, the influence of water saturation needs to be investigated. During freezing, water in a porous medium such as rock and concrete tends either to form ice or migrate, leading to redistribution of pore water. McGreevy and Whalley (1985) found that with intact rock more frost damage occurred at cracked zones compared to damage in the intact material. This occurred due to the concentration of moisture in the joints in proportion to the moisture content of the intact material.

In a saturated rock, there will always be a breakage if the water freezes in a confined space. If the pressure of the ice exceeds the tensile strength of the adjacent material, the material will be damaged and, together with other factors, the degree of damage is dependent on the degree of the saturation of the rock. A partially saturated rock can resist breakage despite its low strength because the expansion of the ice and the distribution of pore water can occur in pores that were initially filled with air. A fully saturated rock, however, yields to frost action regardless of its strength because it does not have any free space, which is needed to allow for the expansion. For shotcrete, one of the main destructive mechanisms is hydraulic pressure. The pressure occurs when water becomes confined due to rapid freezing so, in this case, rapid freezing is more harmful than slow freezing. The ice lens grows larger when the freezing rate is slow (Fridh, 2005).

Frost damage can occur in initially unsaturated rocks when slow freezing causes water migration from the surrounding rock or an external moisture source. However, when a rock undergoes rapid freezing, frost damage can occur only when the degree of saturation is high (>80%) or if the water can migrate (Matsuoka, 2001b). If the freezing rate is rapid enough, it can minimise the water uptake, thus preventing frost damage. In contrast, long-term slow freezing which allows water migration can result in frost damage (Matsuoka, 2001a).

2.4.4 Volumetric expansion of ice

The conventional perception has been that frost shattering is the result of the 9% volumetric expansion, which occurs during the water-ice phase transition. When freezing from 0°C down to -22°C, the total volumetric expansion of ice is 13.5%. When water transforms into ice, phase transition depends on the stiffness of the adjacent material. Thus, the stiffer the adjacent material, the higher the ice pressure (e.g., Krus and Sundquist, 1996). If the tensile strength of the adjacent material is lower than the ice pressure, the material breaks and cracks will appear. Hard intact rock has a tensile strength of approximately 10 MPa (e.g., Matsuoka, 1990b) and shotcrete about 4 MPa (Brandshaug, 2004).

Theoretically, if the surrounding material is rigidly confined, the pressure at the freezing point increases almost linearly from zero at 0°C to a maximum of 207 MPa at -22°C, which is the ice pressure melting point (Tharp, 1987). At temperatures below this, the pressure decreases because the ice begins to contract (French, 1996). A number of factors affect the maximum pressure. Firstly, the water or ice must be contained within a closed system for high pressures to develop. This usually means conditions of extremely rapid freezing from the surface and downwards, which seals the pores and joints in the rock.

Secondly, air bubbles in the ice and pore spaces within the rock reduce pressures considerably. Thirdly, and probably the most important of all, the rock itself is not strong enough to withstand such extreme pressures, especially since it is a tensile force rather than a compressive force. As a result, the actual pressure developed by the freezing of water in rocks is much less than the theoretical maximum (French, 1996).

2.5 Adhesion

Poor adhesion can occur between rock and shotcrete, causing the shotcrete to fall out. However, it is not clear whether the reported fall-outs (see chapter 5.1) result from poor adhesion due to quality problems during the process of applying the shotcrete, as an effect of degradation or as a combination of these two factors. The problems arising from poor adhesion between rock and shotcrete might be due to the following:

- Rock type and mineral composition.
- Excess leakage from the rock during shotcreting.
- Low adhesive strength due to poor rock conditions.
- Uneven rock contours – which make it difficult to achieve good contact with the rock surface.

If not anchored with bolts, the reinforcing effect and the stability of shotcrete in a tunnel is entirely dependent on the adhesion to the rock surface when it is applied with normal thickness and not acting as a supporting arch. It is, therefore, important to take all available measures to ensure good adhesion. This is especially the case in areas with complex water conditions. For example, with relatively open joints and fissures, the shotcrete might cause a stability problem itself. It is important to obtain good adhesion between the shotcrete and the rock. Otherwise, when exposed to frost, ice pressure might develop in the interface between them, thus causing the shotcrete to crack. Consequently, load-bearing capacity is lowered, and fall-outs of shotcrete fragments might occur (Selmer-Olsen and Broch, 1976). One of these measures is to thoroughly clean the rock surface prior to shotcreting. A study by Malmgren et al. (2005) showed that adhesion between rock and shotcrete is one of the most important properties that determines its supporting effect, and that adhesion strength mainly depends on treatment (scaling and cleaning), roughness of the rock surface, mineral composition of the rock and the shotcreting technique used. One objective of the study was to investigate the influence of surface treatments (scaling and cleaning) on the adhesion strength of shotcrete. To do so, several pull-out tests were performed on over-cored samples on a rock wall covered with sprayed concrete. The study showed that when the rock surface was prepared with the normal treatment before shotcreting (flushing using water at a high nozzle pressure of 0.7 MPa), most of the failure surfaces were located within the rock (rock to rock failure). When the rock surface was prepared with water jet-scaling (at a pressure of 22 MPa), a greater proportion of the failures were located at the interfaces between the shotcrete and the rock (rock to shotcrete failure). Malmgren (2001) showed that when the rock surface was cleaned by water-jet scaling instead of using a normal treatment, the adhesive strength increased from 0.21 MPa to 0.61 MPa.

3. FIELD OBSERVATIONS OF PROBLEMS RELATING TO WATER AND ICE

3.1 Background

In order to collect information on problems caused by ice formation, field observations were conducted (Andrén, 2008) in five Swedish railway tunnels between autumn 2004 and summer 2005. These tunnels were the Nuolja tunnel, the Laduberg tunnel and the Glödberget tunnel in the north of Sweden, while in the Stockholm area observations were made in the Rönninge tunnels, which consist of three shorter tunnels close to each other, and in the Kvedesta tunnels, consisting of two shorter tunnels (Figure 3.1). These tunnels were inspected on four different occasions in order to determine the seasonal impact of the problems related to freezing and thawing throughout the year. The first occasion was in the autumn while water was still leaking into the tunnels. The second occasion was at the beginning of the freezing period, when the leakage points began to freeze and ice formations were formed. The third occasion was during the winter, when the tunnels had been frozen for a while, in order to tell whether any leaks were active and to examine how the ice formations had developed. The fourth occasion was in the spring, when the tunnels had begun to thaw, and the leaks were active again. In the Glödberget tunnel, the inspections were carried out in March during three consecutive years with the intention of recording the variations from year to year (Andrén, 2008 and Andrén et al. 2023).

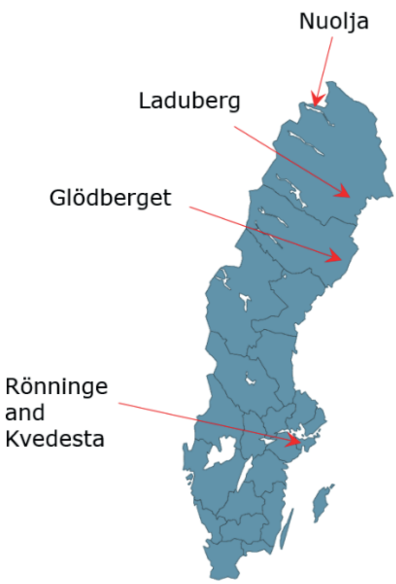


Figure 3.1 Location of selected tunnels.

3.2 Field observations

Inspections of the tunnels revealed many problems caused by water and ice at freezing temperatures, all of which contributed to increased maintenance. The observations have shown that water can continue to leak for a long time if the freezing rate is slow. The most obvious problems are ice in the form of icicles, ice layers and ice pillars (Figure 3.2). Ice layers can spread out over the tunnel floor and on the rails, which can cause derailment. Ice pillars on the tunnel walls can grow so large that they intrude on the clearance gauge. Another problem in railway tunnels is that icicles can grow so long that they reach the overhead contact line, which can cause a short-circuit (Swedish Transport Administration, 2012). They are also a hazard because they can fall down and injure personnel working in the tunnel and cause damage to installations or trains. The problem of ice is of greater concern when it occurs in the fracture network close to the tunnel contour or in the interface between rock and shotcrete, since it accelerates the degradation process of the load-bearing structure and jeopardises stability due to fall-outs of both shotcrete and rock. Many problems are directly linked to the frost insulated drains. Leakage and ice formations occur at the edge of the drains, in mat splices and when brackets for cable racks, handrails or other installations go straight through and puncture the drains which have not been properly sealed. In drains covered with shotcrete, frost shattering and cracking of the shotcrete can be a problem.

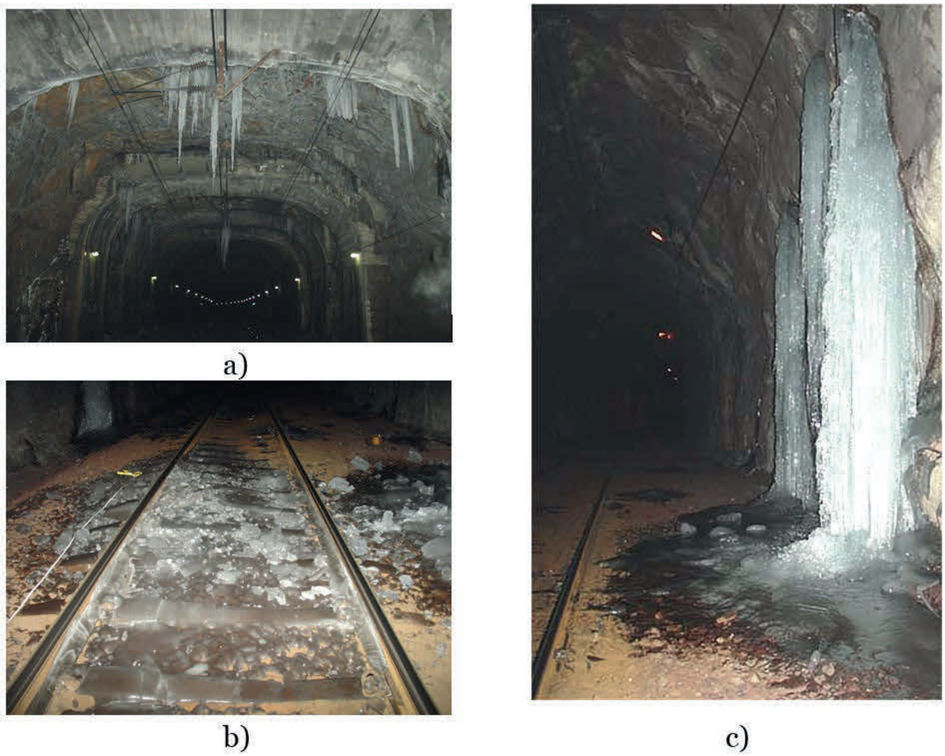


Figure 3.2 Typical problems with ice formations that might develop in unlined tunnels (Andrén, 2008):
a) Icicles in the tunnel roof.
b) Ice layer spread out over the tunnel floor.
c) Ice pillars on the tunnel wall.

The field observations reveal that there is a difference as to where and when leakage points appear during the year, and also in terms of variations in the amount of leakage water. This is exemplified in Figure 3.3a to d, which shows the results from the Glödberget tunnel (1680 m long from chainage km 816+160 to km 817+840). Comparing the red and green ellipses in Figure 3.3a and d, the number of drip observations had increased significantly between the first and the fourth inspection. It is also difficult to foresee where ice problems will occur. For example, in a section where there were just a few leakage points in October (black ellipse in Figure 3.3a), a large number of ice observations could have developed by the inspections in December and March (black ellipse in Figure 3.3b and c). The conclusion of the field observations is that it is difficult to estimate where the insulated drains should best be located along the tunnel. Based on experience gained from this investigation, the determination of location for drains should be carried out after several inspections and especially after a winter period, when the main problems with ice development occur.

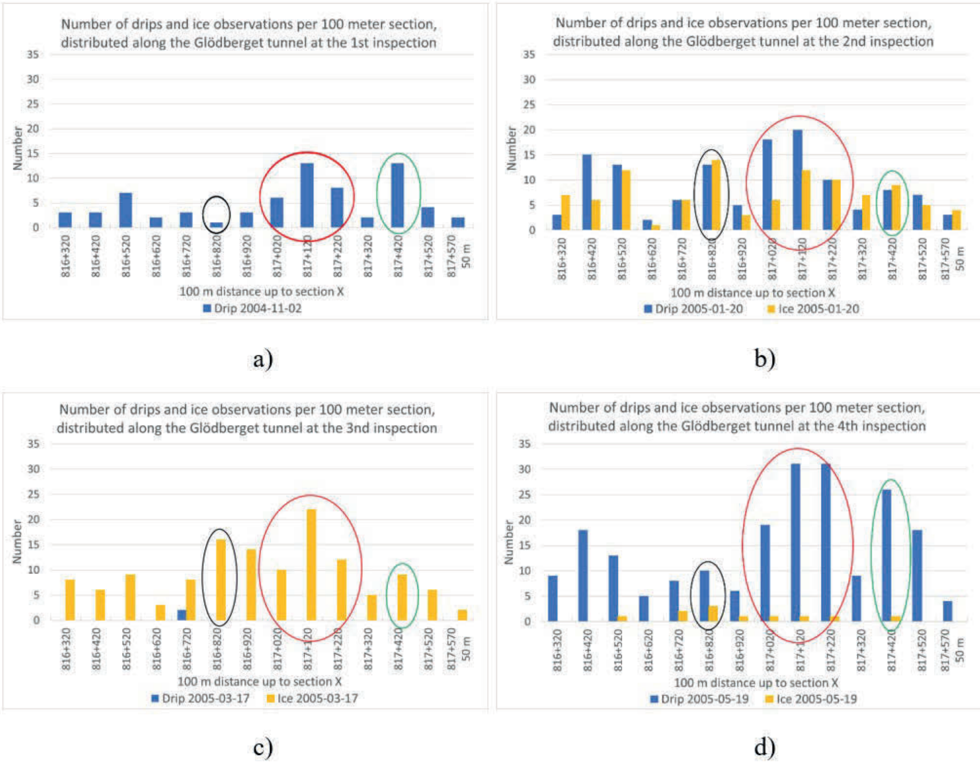


Figure 3.3 Number of drips and ice observations per 100 m section for the Glödberget tunnel, 2004/2005 (Andrén et al., 2023).

These field observations have also shown that ice formations appear along the entire tunnel, even in tunnels that are over 1000 m long. In the Glödberget tunnel, an even larger number of ice formations occur in the inner sections of the tunnel than in those around the tunnel entrances (compare the black and red ellipses in Figure 3.3c to the sections near the entrances).

The duration of and alteration in the freezing periods have a major effect on the number and location of leakage points and the development of ice formations in a tunnel. If a freezing period is of long duration, some of the leakage points become frozen. The water at the rock surface freezes, ice formations are created, and the leakage points are plugged – they ‘freeze dry’. If the leak is subjected instead to short periods of freezing and thawing, the joint will never become frozen and water will continue to leak, resulting in growing ice formations. This phenomenon is most common in the central and southern parts of Sweden, where the temperature often fluctuates around 0°C during the winter. In the north of Sweden, the climate is colder, and the leakage points close to the tunnel entrance almost always become frozen. The problem of growing ice formations in these outer sections appears only in the autumn and spring and not during the winter. But the problem can occur further along the tunnels, where the tunnel air temperature is higher due to heat transfer from the rock mass.

3.3 Photo documentation

To allow a comparison between the different observation occasions in the different tunnels, some selected sections were photographed at all four inspections. To take one example, at chainage km 816+345 in the Glödberget tunnel (185 m from the south entrance), there was a leakage point at the edge of a covered drain mat. The drain is shown at the right side of the photo (Figure 3.4) and cracks in the shotcrete can be seen clearly along the outer edge of the drain. During the first inspection in November, the shotcrete around the leakage point was wet and the handrail was broken, which led to this section being flagged as a potential maintenance problem. When the second inspection was conducted in January, a large ice pillar had developed beside the edge of the drain and the handrail was covered with ice. When comparing the first and the second inspection, the photos show that the shotcrete was much moister during the second inspection. During the third inspection in March, the large ice pillar had been removed from the tunnel, leakage had stopped and there was no longer any moisture on the tunnel wall. During the fourth inspection in May, the leak was active again, the shotcrete was moist and the ice pillar was slowly melting (Andrén, 2008 and Andrén et al. 2023).

Figure 3.4 Differences between the four inspections in the Glödberget tunnel at chainage km 816+345, 185 m from the south entrance (Andrén, 2008).

To see how the occurrence of ice formation varies over different years, further follow-up inspections of the Glödberget tunnel were conducted in March 2005, 2006 and 2007. These inspections showed that an annual variation in the moisture and quantity of ice in tunnels can occur. Figure 3.5 shows the difference in size of ice formation at a particular section during the three annual inspections (505 m from the south entrance). The photos also show the difference in moisture conditions in the tunnel wall. During the 2007 inspection, the shotcrete was much moister than in the two previous years, which can partly be explained by the fact that the temperature had fluctuated around 0°C for about a week before the inspection (Figure 3.6). This might have caused warmer outside air to penetrate the tunnel, thawing the rock mass nearest the tunnel wall and causing the leak to become active again (Andrén, 2008 and Andrén et al., 2023).

Figure 3.5 Comparison at chainage km 816+665 (505 m from the south entrance) in the Glödberget tunnel in March 2005, 2006 and 2007 (Andrén, 2008).

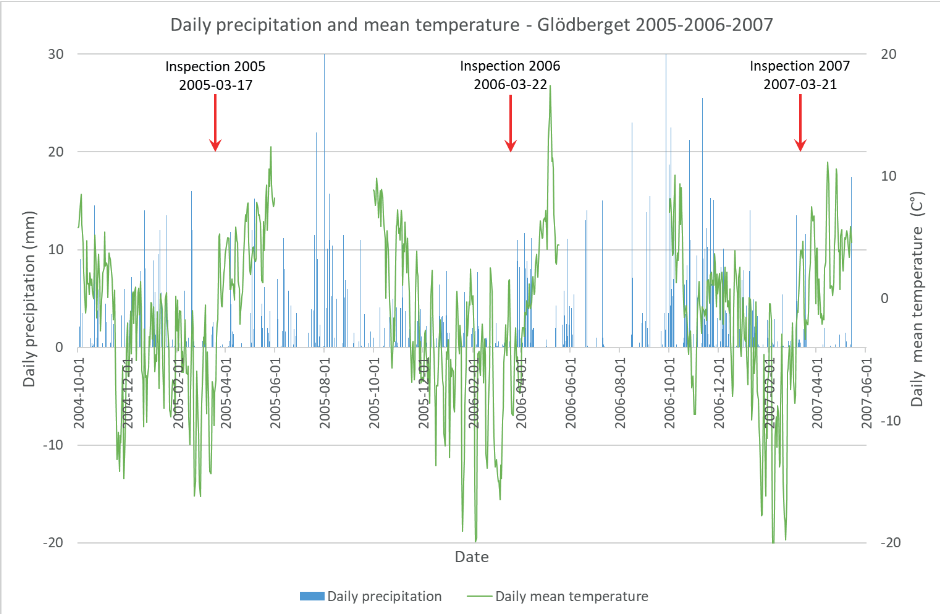


Figure 3.6 Daily mean value for precipitation and temperature for the Glödberget tunnel (Andrén et al., 2023).

3.4 Problems with insulated drain mats

In the spring of 2011, a survey of existing water and frost insulation was carried out in the Skogsby and Margreteberg tunnels, located on the west coast in southern Sweden (Tyréns, 2011). The survey revealed many problems with drains and some of them are shown in the figures below, together with other observations from several railway tunnels. Figure 3.7 shows the locations of the tunnels mentioned in this chapter.

Figure 3.7 Location of tunnels.

Some typical problems that occur with the type of frost insulated drain mats that are not covered with shotcrete are listed below:

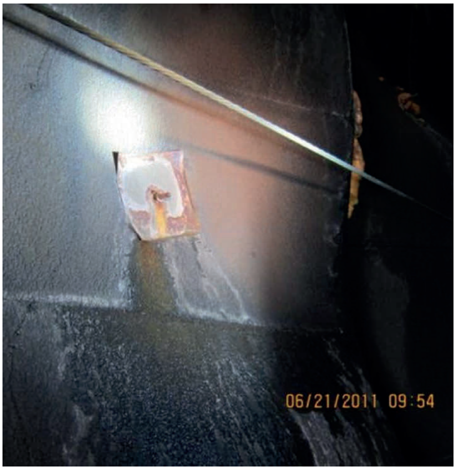
- Drain mats are not sealed against the tunnel contour, which leads to frost penetration behind the drains (Figure 3.8).
- Brackets for attachments such as contact wires, handrails and bolts are inserted straight through and puncture the drains, which have not been properly sealed (Figure 3.9a and b).
- Leakage from poorly sealed or welded splices in drain mats (Figure 3.10).
- Leakage above drain mats that are not installed high enough up along the tunnel wall.
- Leakage along the side of drain mats (Figure 3.12).
- Drains blocked by debris, causing leakage at joints.
- Undersized drains, which can freeze and cause blockages, causing leakage at joints.
- Holes in drain mats.
- Loose bolts.
- Corroded bolt washers (Figure 3.9a).

Leakage next to drains can occur due to unsatisfactory seals at the edge of the drain, or where it is difficult to seal the area properly due to the tunnel contour being very uneven (Figure 3.8a). With an uneven tunnel contour, it is more difficult to keep the leakage water inside the drains and the water tends to leak alongside the edge of the drain (Figure 3.8b). If drains are poorly sealed, frost can penetrate behind the drains and cause ice formations, which result in clogging and frost shattering.

a) b)

Figure 3.8 a) Drain mat not sealed against the tunnel contour, Margreteberg (Tyréns, 2011).
b) Ice pillar at the edge of a drain, Laduberg (Andrén, 2008).

Leakage and ice occur not only at the side of drains, but also occur in drain mat splices and when, for example, brackets for handrails, cable racks and other installations pass through the drain material and are not sealed properly. Ice formation leads not only to frost shattering but also to an extra load on the installation itself, which can cause material breakage (Figure 3.9). The reason why the brackets are not sealed could be that the maintenance workers who carry out the installation do not know that a drain is installed behind the shotcrete, or do not know that a leak can cause problems. It is important that the Swedish Transport Administration provides the maintenance workers with correct and updated documentation about where drains are located in order to avoid unnecessary errors during installation. For example, supplying updated drawings of where drains are installed along the tunnel section. That simplifies the selection of suitable sections for installations, so that sections with drains can be avoid altogether or that required sealing of the puncture point can be made properly.



a) b)

Figure 3.9 a) Leakage around rusty bolt and bolt washer, Skogsby tunnel (Tyréns, 2011).
b) Water leakage through drains with ice formation as a result, Laduberg (Andrén, 2008).

Figure 3.10 Leaking welded splices, Margreteberg (Tyréns, 2011).

Additional problems with drains occur, for example, when the drains are patched and repaired in an incorrect way (Figure 3.11). The patched drain does not keep cold away from the leak along the rock surface and ice formation can be expected during the next cold period.

Figure 3.11 Patched and repaired drain in the Bergträsk tunnel (Photo: Erik Stål, 2011).

In many tunnels, large ice pillars form along the tunnel walls every winter season. The ice pillars can encroach on the gauge clearance and must, therefore, be constantly monitored and taken down when required. During the field observations (Andrén, 2008), it was noted that many ice pillars arose from leaks that lay next to drains. If the water from the rock surface cannot drain away down to the tunnel floor in a frost-free way, unwanted ice formation can occur behind or at the edge of drains. The reason is not clear, but if the drain is clogged by debris, chemical or biological deposits or ice, then the leakage water is forced to take a different path. The leakage point might also have moved because the water bearing fracture is sealed by natural causes.

During an inventory of drains maintained by the Swedish Railway Administration that are covered with shotcrete, it was found that cracking was common, and 65% of the open cracks that were recorded had a width of 0.3 mm or more. That means that the fibers in the shotcrete are exposed to the risk of corrosion. However, it is difficult to assess whether the cracks in the shotcrete have arisen due to frost shattering or whether they are shrinkage cracks (Boman, 2005). The photographs in Figure 3.12 show drain mats in the Bergträsk tunnel that are covered with fibre-reinforced shotcrete. Ice formation has occurred behind the drains due to lack of drainage and this has caused the shotcrete to crack due to the increased ice pressure.

Figure 3.12 Cracked shotcrete over drain mat in the Bergträsk tunnel (Photo: Stabilt, 2020).

Ice layers on ballast surface and on tracks pose a risk of derailment. Ice layers occur partly because leakage from the tunnel roof drips down and freezes on the rails or in the ballast and partly because leakage in the walls is not drained in a correct way (Figure 3.13). Water leaking from the walls freezes on contact with the cooler ballast. A problem that has been observed is that the drains do not extend all the way down to the tunnel floor but end above the ballast surface. Leakage water flows out on top of the ballast and forms ice layers. This problem could be avoided if the drains are installed so that they extend beneath the ballast bed, down to a frost-free depth on the tunnel floor. A successful example of how to control ice layers has been carried out in the Laduberg tunnel. There, a heating cable was laid along the tunnel wall that kept the ballast from freezing so that the leakage water could flow down and reach the frost-free tunnel floor and drain away (Andrén, 2008).

Figure 3.13 Ice layer in the Glödberget tunnel (Andrén, 2008).

During the field observations (Andrén, 2008 and Andrén et al., 2023), many icicles were found in the centre of the roof because some drains extended from one tunnel wall up to the middle of the tunnel roof. If the roof is so flat that there is no inclination down along the drain at the wall, or if the edge of the drain is not properly sealed, leakage water can cause a drip in the centre of the roof, which can lead to an icicle formation directly above the overhead contact line (Figure 3.14a). Furthermore, ice layers can form in the middle of the track which can cause a risk of derailment (Figure 3.14b). If the drain is instead extended beyond the centre of the roof, drips directly on the contact line can be avoided. Unfortunately, the problem is only moved a bit further out to the side and, if the roof is flat, there is also a risk that water will accumulate in the centre of the roof and can cause ice pressure on the drain. To prevent dripping within the track area and reduce the risk of ice layers, the drains should, therefore, be extended further out to the side and preferably all the way down to the opposite wall and down to the tunnel floor.

a) b)

Figure 3.14 a) Icicle in the roof of the Rönninge tunnel (Andrén, 2008).
b) Ice layer on the track at the Glödberget tunnel (Andrén, 2008).

3.5 Ice pillar in the Glödberget tunnel

In April 2008, an ice pillar detached from the left tunnel wall in the Glödberget tunnel chainage km 816+345 when a northbound passenger train passed by. The pillar of ice hit the train and bounced several times between the train and the tunnel wall. Three carriages and the locomotive were damaged. The locomotive had only sheet metal damage but, in the sleeping cars, window frames had been deformed and the glass panes were broken (Figure 3.15 and Figure 3.16). Fortunately, the window damage occurred in the corridor of the carriage and not inside the sleeping compartments themselves. To avoid similar problems in the future, large ice pillars should always be cleared away, even if they appear to be stable (Nilsson, 2008).

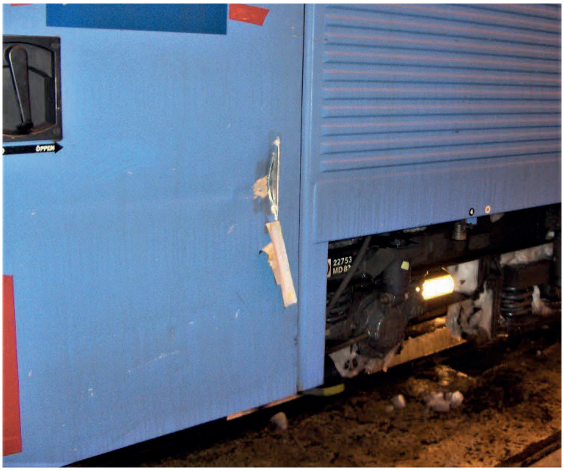


Figure 3.15 Sheet metal damage (Photo: Veolia transport).

Figure 3.16 Deformed window frames (Photo: Veolia transport).

4. FROST PENETRATION IN ROCK TUNNELS

A typical water and frost-protection system in tunnels in Sweden consists of insulating sealing membranes (for example, insulated drain mats), which fulfill two purposes. The first is to prevent the cold tunnel air from reaching a leakage point and causing water to freeze. The second is to divert the water from the traffic space down to the tunnel floor to be channeled out of the tunnel in a frost-free manner. The Swedish Transport Administration conducts ongoing work to develop programmes and techniques to reduce and streamline maintenance in the tunnels. As part of that work, studies have been conducted to find the expected temperature conditions along a tunnel. For example, long-term field measurements of temperatures in railway tunnels (Andrén, 2008-2016, Andrén and Dahlström, 2011, Andrén et al., 2020b and Andrén et al., 2022) have been carried out for more than 10 years. The purpose of the long-term field measurements was to provide a basis for increased understanding of temperature flow and frost penetration in tunnels and to evaluate requirements regarding frost index in the Swedish Transport Administration's current regulations (TRVINFRA-00233) and to propose new updated requirements. The long-term field measurements were also used to evaluate the validity of the results from a previously performed laboratory model test by comparing the laboratory model test results with the actual measured temperature conditions.

4.1 Experiences from field observations

The field observations conducted by Andrén (Andrén, 2008 and Andrén et al., 2023) have shown that frost penetration and ice formation occur throughout the length of the tunnel, even in the tunnels that are longer than 1000 m. The perception has previously been that ice problems only occur at the entrances and in the outer parts of the tunnels. One proposed measure has been to cover the first 300 m from each entrance with frost insulated drains in order to avoid the problem of ice formations. However, this is not an effective solution to the problem, as the insulation does not only prevent the cold from reaching the leakage point, it also prevents heat from the rock mass passing into the tunnel and warming up the cold air entering it from outside. This means that freezing temperatures can reach further into the tunnel and the problems with ice formations also occur in the inner parts of the tunnel (Andrén, 2008 and Andrén et al., 2023).

During the inspections of the longer tunnels, observations showed that an even larger number of ice formations occur in the inner parts of the tunnel compared to the areas around the entrances (Andrén, 2008). One reason is that the leaks near the entrances freeze faster. The leaks that are located further into the tunnel are not exposed to the same cooling as the leaks near the entrances. This, in combination with the leakage water conveying heat to the leakage point, allows more time for ice to form in the inner parts of the tunnel compared to that near the entrances. The southern parts of Sweden have shorter cooling periods and the tunnels are more exposed to temperature changes around zero. The frost does not have time to penetrate into the tunnel in the same way as in the northern parts of Sweden. Therefore, more ice problems arise around the entrances of these tunnels, while the tunnels in northern Sweden instead have more ice problems in their inner sections.

4.2 Field measurements of frost penetration

4.2.1 Field test configuration

A monitoring system was installed in the Åsa tunnel, south of Gothenburg, in April 2006, and in the Glödberget tunnel, south of Umeå, in February 2007. They measure the tunnel air, rock surface and rock mass temperatures, as well as air pressure and wind velocity along the tunnel. In the Glödberget tunnel, the temperature was also measured in the ballast bed, behind an insulated drain mat and in the adjacent service tunnel, which partially runs parallel to the track tunnel. More information about the monitoring system and results can be found in Andrén, (2018-2016) and Andrén et al., (2020b).

4.2.2 Results of temperature measurements

The field measurements show that freezing temperatures penetrate further into the tunnels than previously assumed. Although the Glödberget tunnel is 1680 m long, frost penetrates along the whole tunnel length even at an outside temperature of a few degrees below zero. Figure 4.1 shows the air temperature at the measuring stations along the Glödberget tunnel for five consecutive days in February 2017. The 21 m higher southern entrance is on the left side of the diagram, and the lower northern entrance is on the right side. The temperature displayed at both ends of the diagram is the temperature measured at the climate station outside the southern entrance. The frost penetrates further along the tunnel from the northern entrance than from the southern entrance. The tunnel air, heated by the rock mass, moves by convection (the chimney effect) towards the southern tunnel entrance, resulting in higher temperatures in this section.

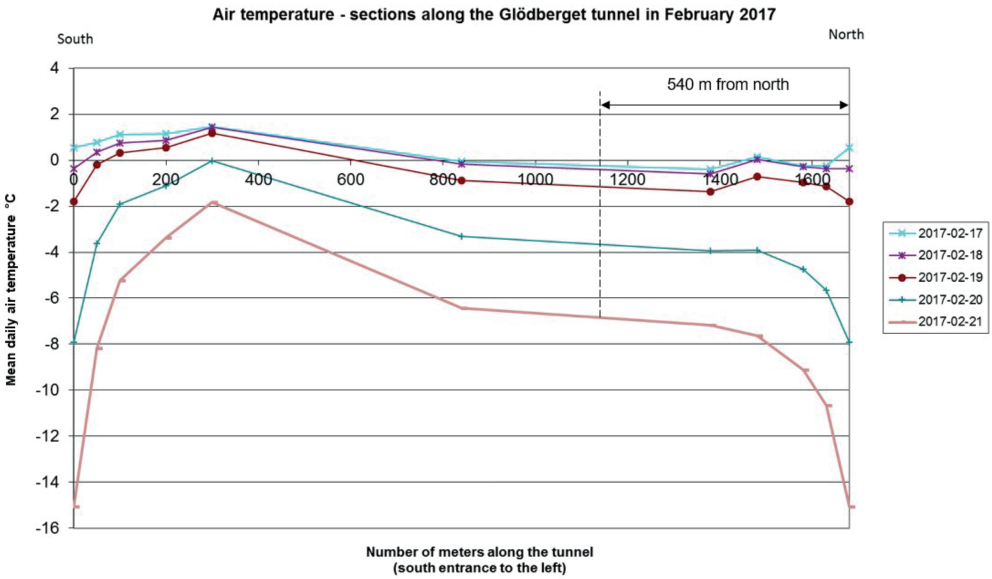


Figure 4.1 Air temperature in the Glödberget tunnel for five consecutive days in February 2017 (Andrén et al., 2022).

Figure 4.2 shows the air temperature at the measuring stations in the Åsa tunnel for seven consecutive days in January 2010. The left side of the diagram represents the northern entrance with a higher elevation than the southern entrance, which is represented by the right side of the diagram. The temperature displayed at both ends of the diagram is the temperature measured at the climate station outside the northern entrance. In the Åsa tunnel, the frost penetrates further into the tunnel from the lower south entrance and the measurements show that the tunnel air temperature is higher in the northern parts of the tunnel.

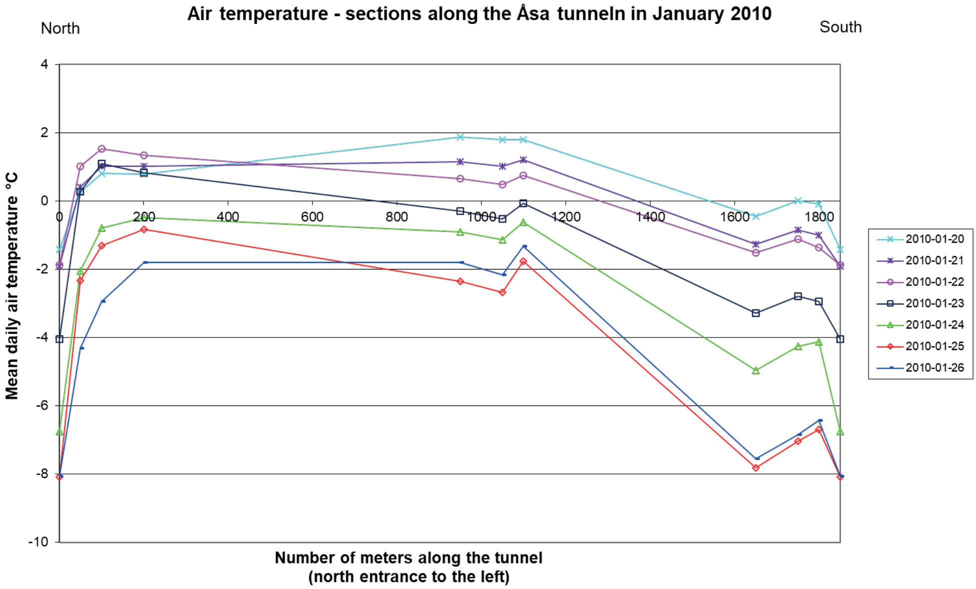


Figure 4.2 Air temperature in the Åsa tunnel for seven consecutive days in January 2010 (Andrén et al., 2020b).

4.2.3 Train passages

Airflow due to train traffic has some impact on frost penetration. The results from the field measurements of what happens during train passages (Figure 4.3) showed that the air velocity (green curve) and the temperature (cyan, blue, magenta and purple curves) return to initial values relatively quickly after a train passage. More information about measurement, explanations of different directions of trains etc. can be found in Andrén (2018-2016), Andrén et al., (2020b) and Andrén et al., (2022). The Glödberget tunnel has two-way traffic with a low intensity. In one-way tunnels with a higher traffic intensity, the train passage affects the frost penetration and increases the length of negative temperatures along a tunnel (Wikström and Sahlin, 2019).

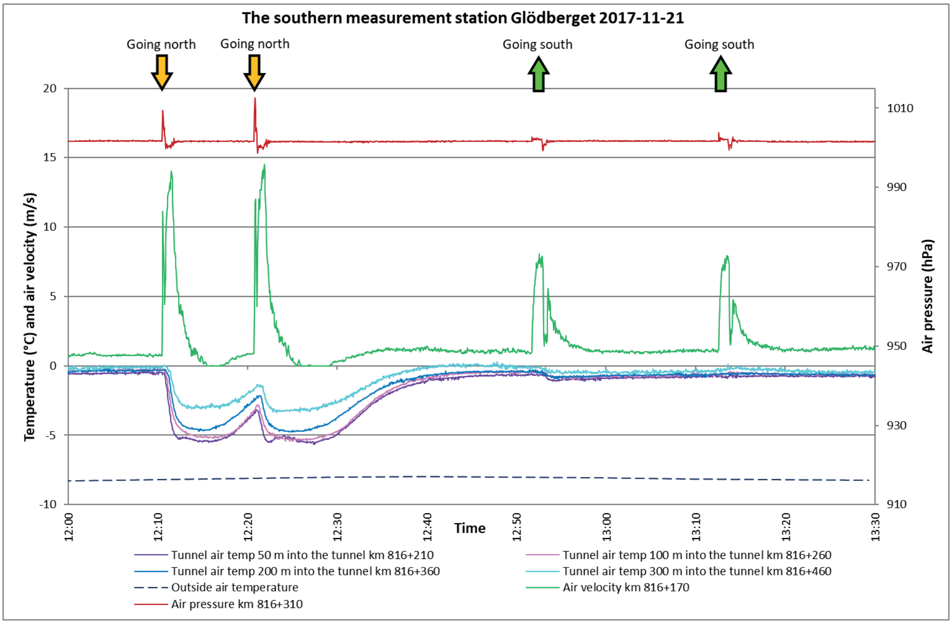


Figure 4.3 Four train passages through the Glödberget tunnel, the southern measurement station (Andrén et al., 2022).

4.2.4 Train passages

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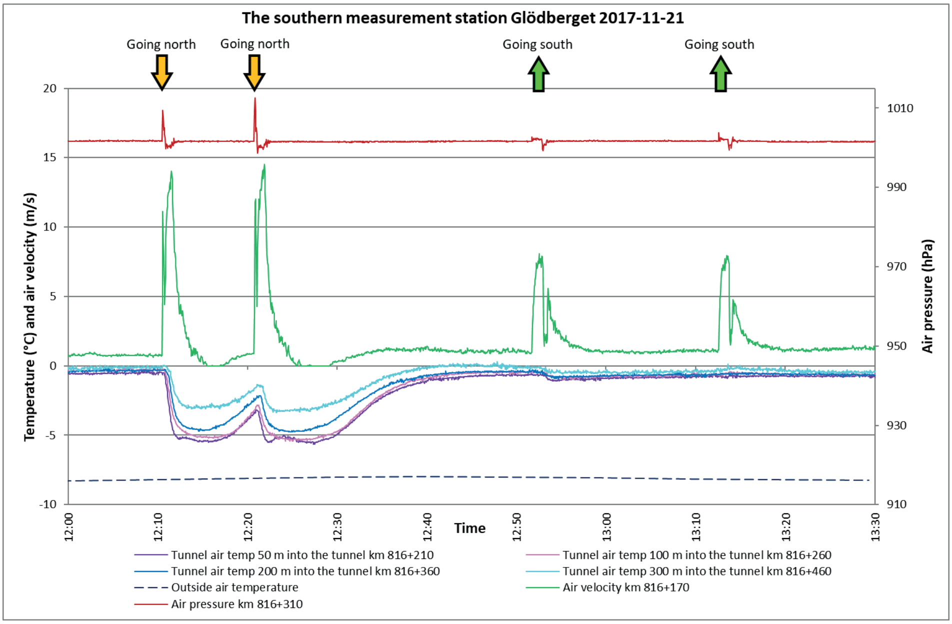


Figure 4.4 Four train passages through the Glödberget tunnel, the southern measurement station (Andrén et al., 2022).

4.2.5 Confined airflow

If the airflow is confined, the air is heated by heat exchange from the rock mass and the tunnel air adopts the same temperature as the surrounding rock mass. This usually corresponds to the annual mean temperature applicable to the region where the tunnel is located (2-3°C in Figure 4.5). In the Glödberget tunnel, measurements have been carried out in the adjacent service tunnel (red line in Figure 4.6, about 2-3°C). This service tunnel has closed doors, both towards the track tunnel and towards the outside air, so the airflow is confined as opposed to the airflow in the track tunnel. Measurement in the adjacent service tunnel shows how great an influence the airflow in the track tunnel has on the frost penetration.

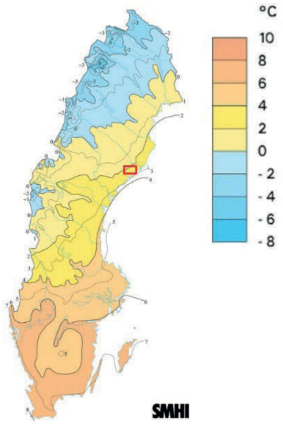


Figure 4.5 The annual mean temperature in Sweden – the location of the Glödberget tunnel is marked with a red rectangle (SMHI).

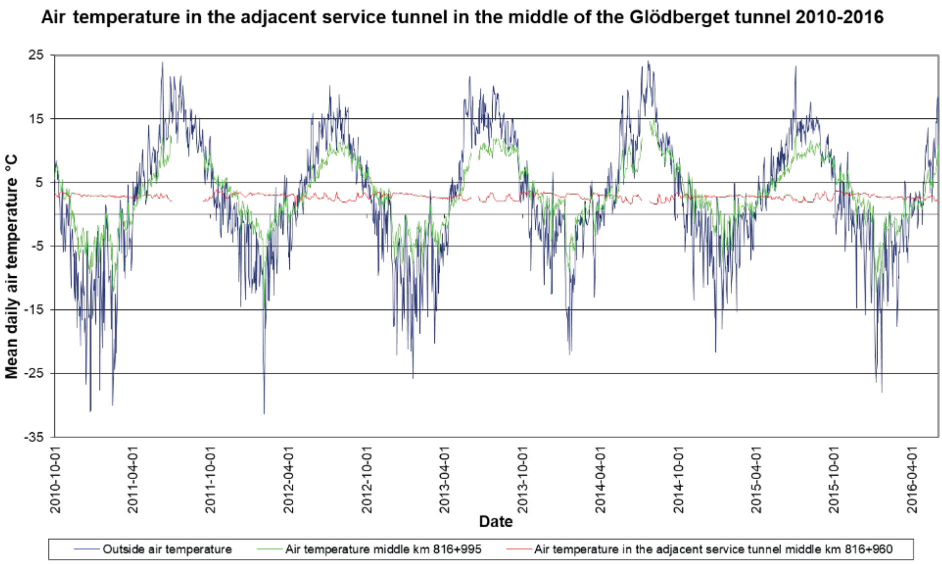


Figure 4.6 Temperature in the adjacent service tunnel (red curve), in comparison to outside temperature (blue) and middle section tunnel air temperature (green), Glödberget 2010-2016.

Behind a drain mat, the air is also confined. During the field measurements, one of the temperature gauges was placed behind an insulated drain mat in the middle of the Glödberget tunnel. The purpose of the measurement was to monitor temperature differences between the tunnel air and the air behind a drain mat, which would be heated by the rock mass, in order to determine the effect of the insulation and verify the design. In Figure 4.7, the temperature behind the drain (red line) is compared to the outside air temperature (blue line) and the tunnel air temperature (green line) in the same section as the drain mat. The measurements show that the insulated drain is able to even out the temperature changes occurring in the tunnel air right outside the drain. The winter period 2010/2011 was longer than 2009/2010 but the temperature behind the drain drops slowly below zero degrees at the end of both winter periods. If the temperature is below zero degrees behind the drain, the water from the rock mass cannot be drained properly and can cause the shotcrete on the drain mat to crack due to the increased ice pressure.

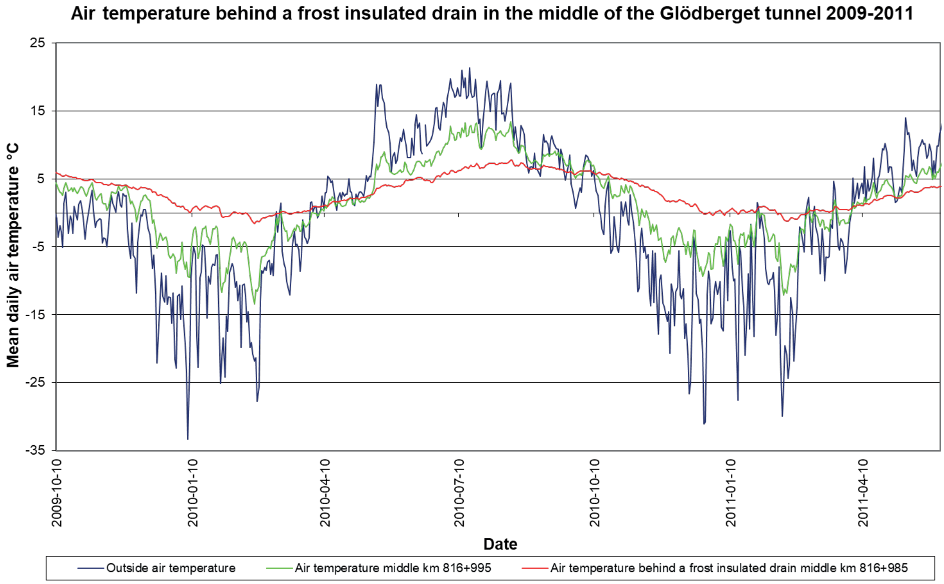


Figure 4.7 Temperature behind a frost insulated drain mat, Glödberget 2009-2011 (Andrén et al., 2022).

4.2.6 Frost cycles

The purpose of using insulated drain mats is to prevent the cold from reaching the leakage point and thus prevent ice formations. They also reduce the number of frost cycles. The temperature data from the field measurements have been processed to show the number of frost cycles that occur at the various measuring stations along the tunnels. The expression ‘one frost cycle’ is the same as the expression ‘freeze-thaw cycle’. It refers to when the temperature drops below zero degrees and then rises above zero again.

Figure 4.8 and Figure 4.9 show the total number of frost cycles for all measured seasons for each measuring station in the tunnels. The values at both ends of the diagrams refer to the temperature changes of the outside air. In both the Glödberget tunnel and the Åsa tunnel, the number of frost cycles at the measuring station 50 m in from the tunnel entrance are significantly lowered in relation to frost cycles outside the tunnel. There is an increase in the number of frost cycles at 100 m and 200 m along the Glödberget tunnel in relation to the measurement at 50 m. After 300 m along the Glödberget tunnel, there is again a reduction in the number of frost cycles (Figure 4.8). For the Åsa tunnel, there is a further reduction in the number of frost cycles 100 m in from the entrance, but the number increases at the measuring station located 200 m in from the southern tunnel entrance (Figure 4.9).

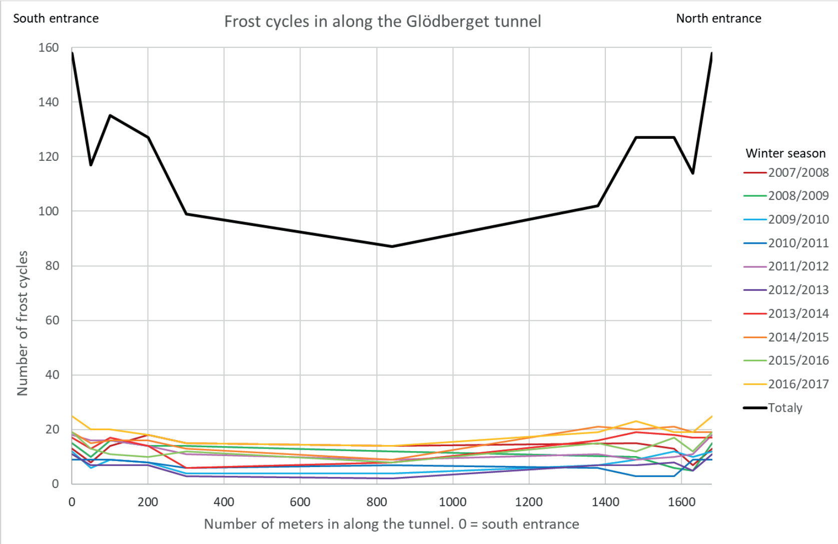


Figure 4.8 Number of frost cycles along the Glödberget tunnel.

For both tunnels the measurements indicate that more frost cycles occur a bit further into the tunnels and not directly at the entrances or at the first measuring station at 50 m in from the entrance. In these sections, with an increased number of frost cycles, water leakage should receive additional attention from the maintenance workers or inspectors to avoid future problems with frost shattering of rock or shotcrete. The results from the laboratory tests performed by Andrén (2009) showed that there was a clear reduction of adhesive strength between rock and shotcrete when the test panels were subjected to freeze-thaw cycles, and also that more AE events occurred in a panel when it has access to water during freezing. Therefore, particular attention must be given to leakages in sections with many frost cycles.

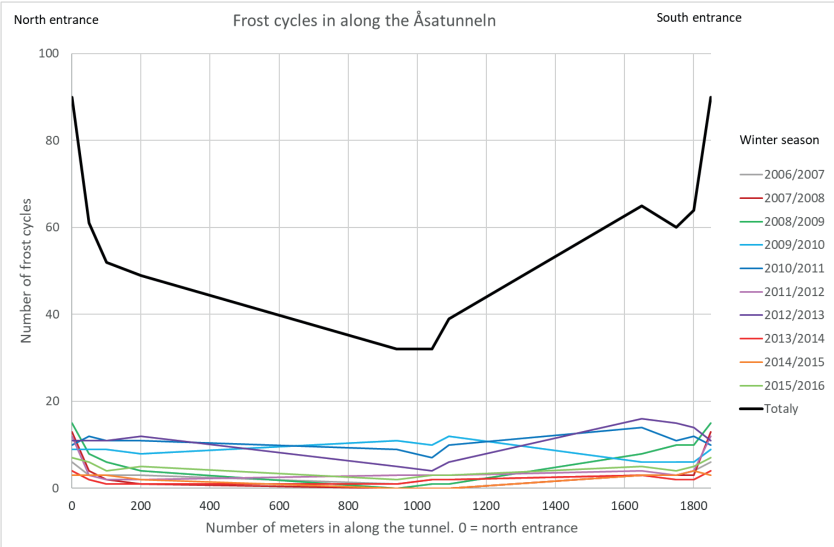
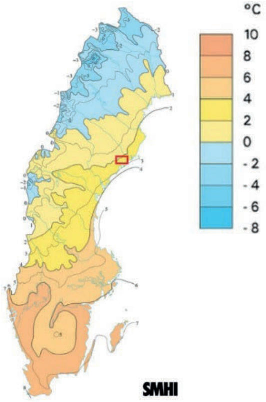
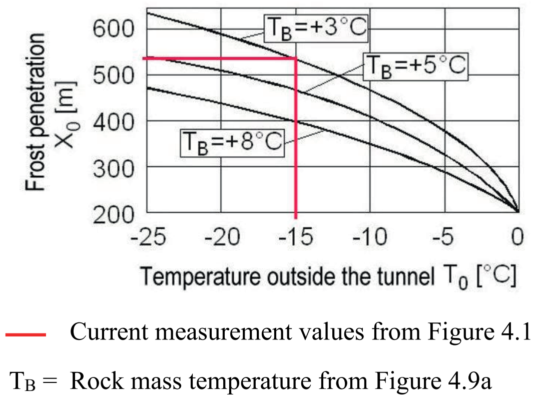


Figure 4.9 Number of frost cycles along the Åsa tunnel.

4.2.7 Comparison with the model test

A comparison of the results from the measurements in the Glödberget tunnel and those obtained in the model tests (see chapter 2.3.4), can be carried out by inserting the temperature curves from Figure 4.1 into the diagram of Sandberg et al. (2002). With an outside temperature of T_0 = -15°C and a rock mass temperature of T_B = +3°C (which is the same as the annual mean temperature value for the region where the Glödberget tunnel is located, see Figure 4.10a), the red lines in Figure 4.10b show that, according to the model test, maximum frost penetration should be found at approximately 540 m from the lower tunnel entrance at an outside temperature of -15°C. But measurements show that the temperatures are sub-zero in the entire tunnel (see dotted line in Figure 4.1).





a) b)

Figure 4.10 a) The annual mean temperature in Sweden – the location of the Glödberget tunnel is marked with a red rectangle (modified from SMHI). b) Frost penetration from the lowest tunnel entrance in the Glödberget tunnel compared to the model test (Andrén et al., 2022, diagram modified from Sandberg et al., 2002).

The charts from the model test seem to overestimate the temperature in the tunnels and the model is not directly relevant for insulated or partially insulated tunnels. The frost penetrates much further into the tunnel. To evaluate the frost penetration, consideration must be given to how much of the walls and roof are covered with insulation and how the insulation is distributed along the tunnel (Andrén and Dahlström, 2011, Andrén et al., 2020b and Andrén et al., 2022).

4.3 Frost index in tunnels

The Swedish Transport Administration's suggestion is not only to change the division of the climate zones (as suggested in section 2.3.2), but also how the frost index is distributed in the sections of the tunnel to better suit the reality. This study was used to propose and evaluate the new approach. Figure 4.11 shows suggestions for the new division of sections along the tunnel. Section 1, 0-100 m from each tunnel entrance, has the same frost index as outside air with 50 years return period. Section 2, 100-600 m from each tunnel entrance, has reduced frost index requirements. Finally, Section 3, which is the tunnel section that lies at a greater distance than 600 m from each tunnel entrance, has further reduced requirements for the frost index. Table 4.1 shows the suggestions for the calculated future requirements for the frost index inside a tunnel for each climate zone.

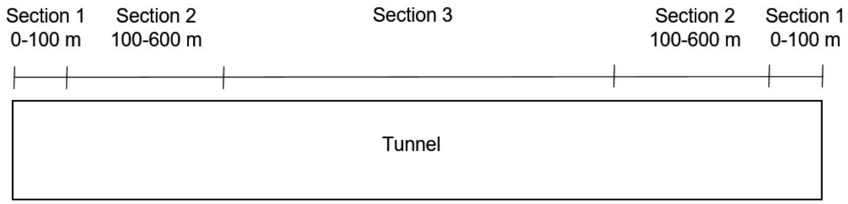


Figure 4.11 Future division of tunnel sections for different frost indexes inside a tunnel.

Table 4.1 Calculated future requirements for the frost index inside a tunnel for different climate zones.

Climate zone	1	2	3	4	5
Frost index for section 1	400	720	1200	1850	2400
Frost index for section 2	290	510	860	1330	1690
Frost index for section 3	130	270	480	810	970

To verify that the suggestions for updated requirements for the frost index are relevant in the tunnels, long-term measurements in the Glödberget tunnel and the Åsa tunnel are used (Andrén 2008-2016 and Andrén et al., 2020b). Another measurement of tunnel air temperatures has also been used in the evaluation. That is a shorter tunnel in the Stockholm area, the Björnkulla tunnel, single track and 239 m long. Measurements were taken in collaboration with Bergab in a survey conducted in 2014 (Bergab, 2014). The tunnels are marked on the map in Figure 4.12a. For further information about the surveys' instrumentation, measurements, results etc. the following reports are recommended; Andrén, 2008-2016, Andrén et al., 2020b, Andrén et al., 2022 and Bergab, 2014.

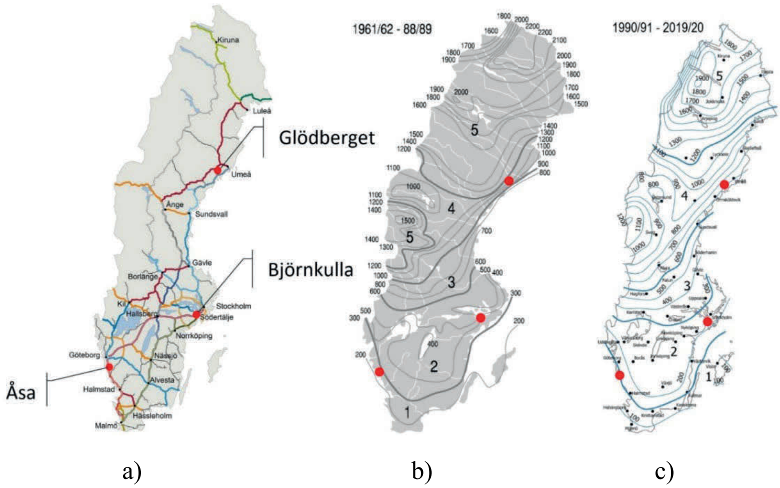


Figure 4.12 Location of the tunnels used in the evaluation of frost index:
a) Location and names.
b) Current climate zones (TRVINFRA-00233, 2021).
c) Future climate zones (Asp, 2022).

As an example, the daily mean air temperatures both outside and inside the Glödberget tunnel are shown in Figure 4.13. The dark blue curve represents the outside temperature. The pink curve is the temperature at the south measuring station located 300 m in from the south tunnel entrance and the cyan curve is the temperature at the north measuring station located 300 m in from the north tunnel entrance. Finally, the green curve represents the temperature in the middle of the tunnel, 840 m from each entrance. Temperatures from each measuring station are used to calculate the frost index along the tunnel, according to Figure 2.4. Figure 4.14 shows how the frost index varies at each measuring station along the tunnel over different winter seasons. The number 0 at the x-axis (at the left hand side of the diagram Figure 4.14) corresponds to the southern entrance of the Glödberget tunnel, and the numbers on the x-axis are the number of metres into the tunnel from that entrance.

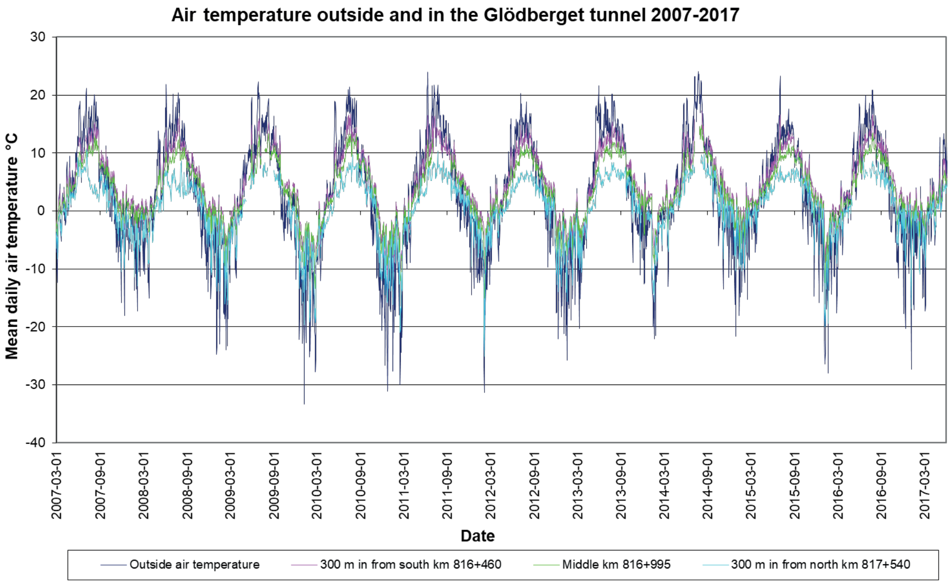


Figure 4.13 Daily mean air temperatures outside and in the Glödberget tunnel 2006-2017.

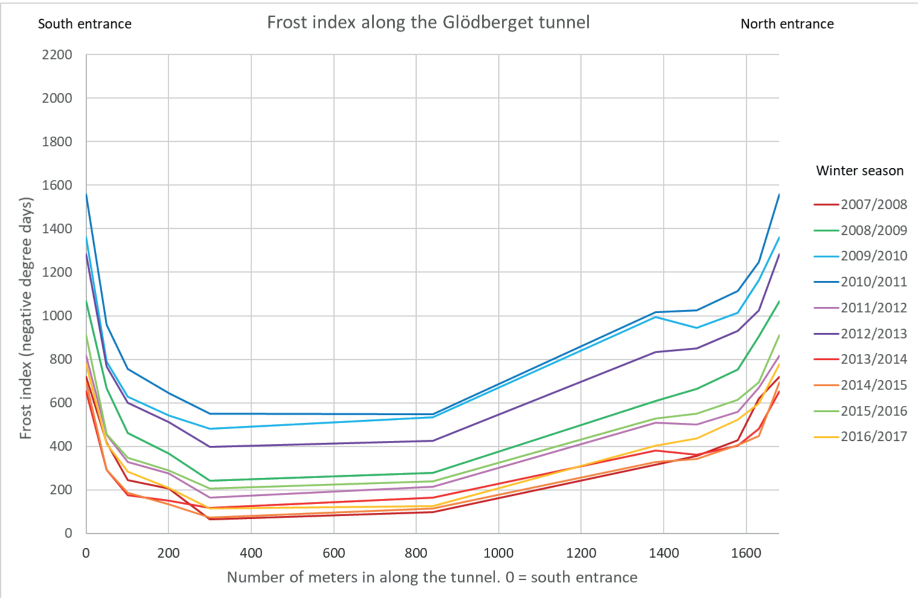


Figure 4.14 Frost index variations in the Glödberget tunnel for different winter seasons.

In the same way, calculations of the frost index have been made for all tunnels included in this study. Figure 4.15, Figure 4.16 and Figure 4.17 show the frost index for different winter season. The current and suggested future requirements according to suggested new climate zones (Figure 4.12c) and suggestions for the new division of sections along the tunnel (Figure 4.11 and Table 4.1) are inserted in the charts. The solid black curve refers to current requirements while the dashed black curve refers to the suggested future requirements.

For the southern-most tunnel in this study, the Åsa tunnel (Figure 4.15), which is located in climate zone 1, the current requirements for the frost index at the outermost 500 m sections of the tunnel is 450 negative degree days, while the inner part is 180 negative degree days according to climate zone 1 in **Fel! Hittar inte referenskälla.**. The measurements show that the current requirements are high in comparison with the calculated frost index for the relevant measurement period. The suggested future requirements of the frost index is lower (climate zone 1 in Table 4.1) and appears to agree better with actual measured values.

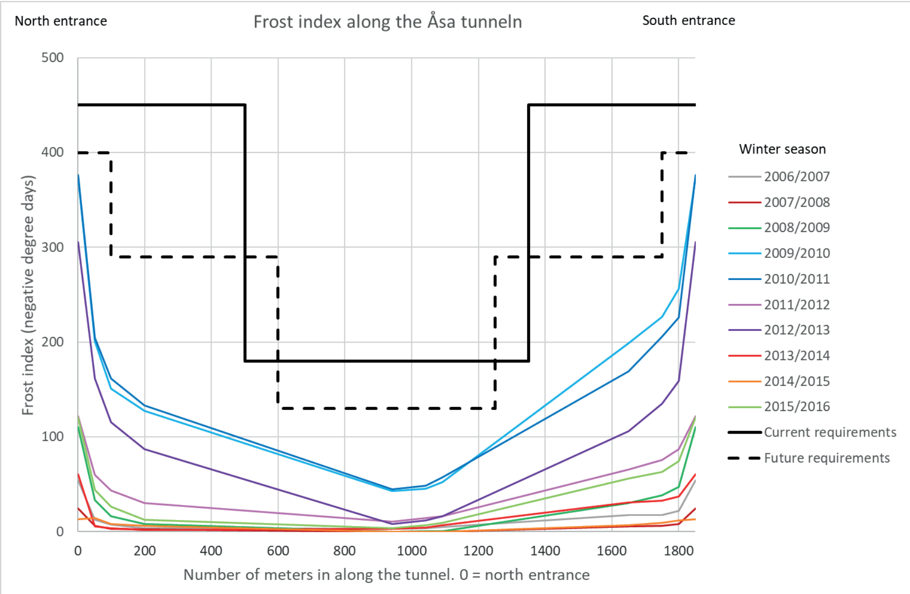


Figure 4.15 Frost index variations in the Åsa tunnel for different winter seasons.

The Björnkulla tunnel (Figure 4.16) is located in climate zone 2. It is a short tunnel (length < 1000 m) and, therefore, the current requirement for the frost index is 675 negative degree days throughout the whole tunnel according to climate zone 2 in **Fel! Hittar inte referenskälla.**. The suggested future requirement for the frost index is higher in the outermost sections and lower in the inner section of the tunnel according to climate zone 2 in Table 4.1.

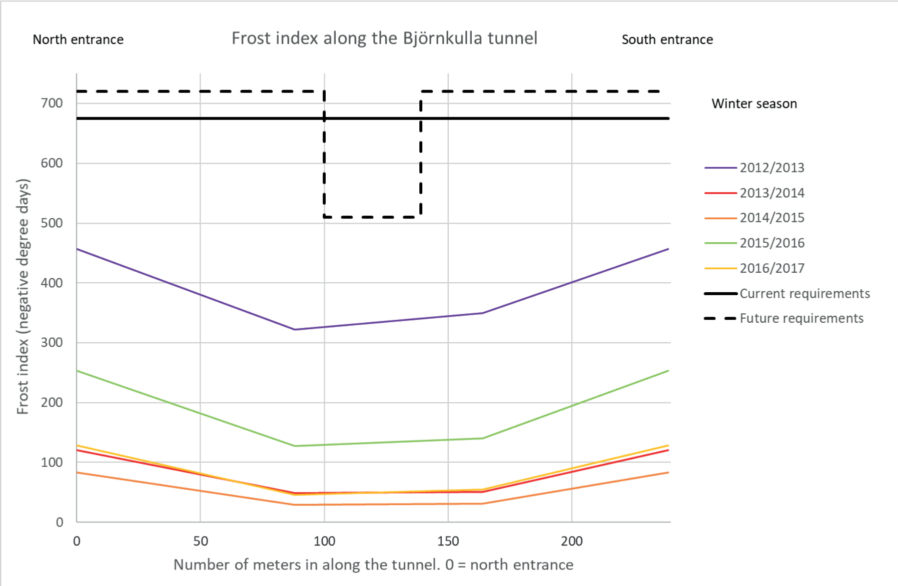


Figure 4.16 Frost index variations in the Björnkulla tunnel for different winter seasons.

The Glödberget tunnel is located in climate zone 4. According to climate zone 4 in **Fel! Hittar inte referenskälla.**, the current requirements for the frost index at the outermost 500 m sections of the tunnel is 960 negative degree days, while the inner part is 600 negative degree days. The current requirements are too low in the outermost sections of the tunnel and also in the lower and, therefore, colder northern parts of the tunnel (Figure 4.17). The suggested future requirements for the frost index according to climate zone 4 in Table 4.1 fit better with the actual measurements. It is clear that the inclination has a major impact on the temperature distribution along the tunnel and frost penetration occurs at a greater distance from the lower tunnel entrance than from the upper entrance. The Swedish Transport Administration must consider the inclination of a tunnel when determining the final change in the future requirements. The suggestion is that a special investigation should be carried out for tunnels longer than 2000 m and for tunnels with high inclination.

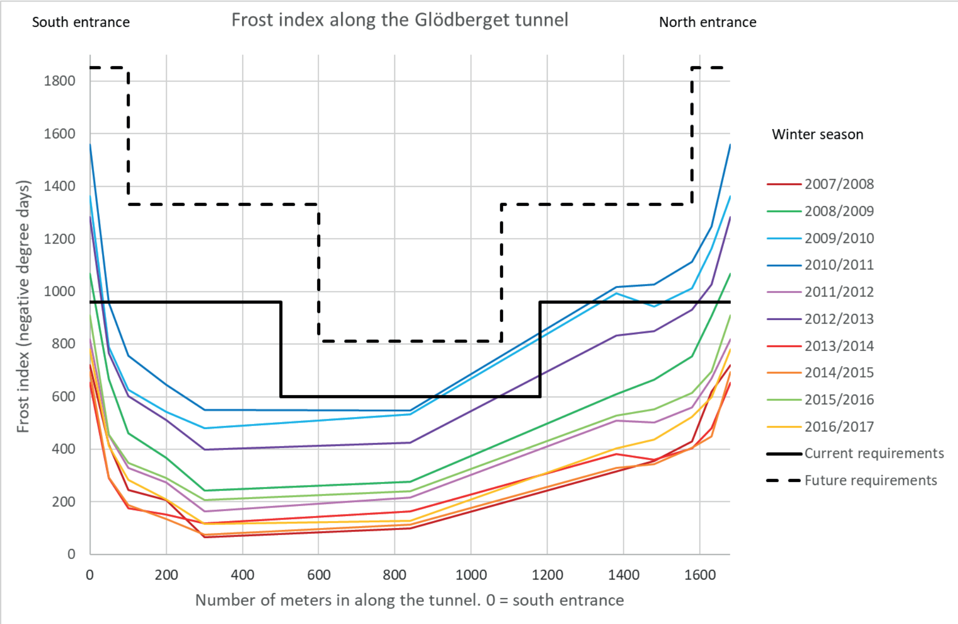


Figure 4.17 Frost index variations in the Glödberget tunnel for different winter seasons.

5. ROCK AND SHOTCRETE DEGRADATION

Degradation of rock and shotcrete can occur due to the weathering processes of the material or to poor adhesion between the materials. Poor adhesion on its own does not pose a degradation problem but voids can form as a result of the poor adhesion in the interface between rock and shotcrete. If this void is filled with water, it can lead to the development of ice pressure at freezing temperatures. Furthermore, the ice exerts pressure at the interface causing cracking and degradation of the shotcrete, if the ice pressure exceeds the tensile strength of the adjacent material.

In order to control the problems that can be caused by ice and frost shattering, inspections of the tunnels are carried out. The main inspection of tunnels is carried out at least every six years and is registered in the BaTMan management system (TRVINFRA-00215). The purpose of the main inspections is to detect and assess deficiencies that might affect the tunnel structures' function or safety within a ten-year period. The purpose is also to detect deficiencies which, if they are not remedied within the time period, can lead to increased management costs. In addition to the main inspection, safety inspections must be performed twice a year in a tunnel (TDOK 2014:0240). Several of the reported fall-outs have occurred despite inspections of the tunnels being carried out as prescribed in the Swedish Transport Administration's regulations. This might indicate that ice problems are more complicated than previously assumed and furthermore that the regulations might need to be adjusted.

5.1 Case studies of fall-outs

During the early 2000s, the Swedish Railway Administration noticed an increase in reported fall-outs of rock and shotcrete in the railway tunnels. Although inspections were being carried out as prescribed in their regulations, fall-outs of rock continued to occur in the tunnels. For example, a number of fall-outs of rock were reported in the Bergträsk, Aspen and Kålgård tunnels and shotcrete fall-outs were reported in the Gårda, Nuolja and Bergträsk tunnels (Figure 5.1).

Figure 5.1 Tunnels with reported fall-outs of rock and shotcrete in the early 2000s (Andrén et al., 2020a).

5.1.1 Rock fall-outs

In November 2005, two fall-outs of blocks from the tunnel wall occurred in the Bergträsk tunnel (Figure 5.1). The blocks were about 1 m in size. The rock surface above the fall-outs was fractured, and this section was reinforced with rock bolts. The latest scaling of the tunnel was carried out in 2002 (Banverket BRN, 2005). The cause of the fall-outs was not clear, but since the ground freezing period had started, frost action might have been one of the reasons for the movement of the blocks.

In December 2003, a train driver reported a fall-out in the Aspen tunnel (Figure 5.1). A rock block (1×0.5m) had fallen from the roof. Upon inspection of the tunnel roof, it was noted that the rock surface consisted of open oxidised joints. The cause of the fall-out was presumed to be vibrations from the train traffic. Incidentally, this fall-out also happened during the winter period and so frost action might have been one of the reasons for the fall-out (Bergab, 2003b).

In January 2006, a fall-out of six small rock blocks (size about 0.2 to 0.4 m) were reported in the Herrljunga tunnel (Figure 5.1). The blocks had disintegrated joint surfaces and some of the joint surfaces were also covered by thin layers of ice. The fall-outs was presumed to be caused by frost shattering (SwedPower, 2006).

5.1.2 Shotcrete fall-outs

Shotcrete usually falls out as sheets and is sometimes covered with ice on the interface side. There is also often ice cover on the exposed rock surface. This implies that water has accumulated in the interface between rock and shotcrete. According to the reports summarised below, the fall-outs had occurred despite recent inspections being performed. At the time, the inspections reported that the shotcrete showed no indication of faults. The question is whether the shotcrete could deteriorate so significantly that it could fall out in just a year or two, or whether some defects were missed during the inspection.

The Gårda tunnel (Figure 5.1) was built in the late 1960s and a complementary station was built in the beginning of 1990. In January 2003, a fall-out of shotcrete and a thin sheet of rock with an area of 1 m^2 occurred in the tunnel. An additional 2-3 m^2 of loose material was removed when scrapping the damaged area. Upon inspecting the whole tunnel, more areas with reduced surface stability were detected. The inspectors found that the shotcrete had degraded and that it is was a continuing and accelerating process (Bergab, 2003a).

The Nuolja tunnel (Figure 5.1) was built in 1990 and in January 2003 a fall-out of shotcrete with an area of 2 m^2 covered parts of the rail. The overhead wire was slightly damaged. In 1995, there was another fall-out of 1 m^2 of shotcrete in the same area. The fall-out in 2003 had an ice layer on the interface side and in the tunnel roof a layer of ice was noted on the interface between rock and shotcrete. The tunnel was scaled in July 2001 and, according to that report, the tunnel was in a good condition at the time and the shotcrete was intact throughout the whole tunnel (Banverket BRN, 2003a).

The Bergträsk tunnel (Figure 5.1) was built in 1982 and a fall-out of shotcrete with an area of 1-2 m^2 was detected during a routine check in September 2003. The tunnel was inspected in the spring of 2002 and scaling was carried out during the same year. The section where the fall-out occurred had several spots of water leakage and the fall-out was caused by frost shattering (Banverket BRN, 2003b).

5.2 Freeze-thaw tests on shotcrete-rock panels

Laboratory studies consisting of freeze-thaw tests on shotcrete-rock panels were conducted (Andrén, 2009 and Andrén et al., 2020a) to investigate how water migration affects the growth of ice and ice pressure in the shotcrete-rock interface and how small areas of poor adhesion affect the degradation of the interface between rock and shotcrete. A small area of poor adhesion around a rock joint opening can cause a void in the shotcrete-rock interface. Ice pressure can develop in that void during freezing if there is access to water. This can cause adhesion failure and shotcrete degradation.

5.2.1 Preparations for the freeze-thaw tests

The tests were performed on saturated shotcrete-rock panels both with and without access to water during freezing as a means of determining the difference in degradation under varying water conditions. The test panels were made of Kuru granite with a dimension of 80×800×800 mm. Boreholes with a diameter of 5 mm to simulate water-bearing fractures were drilled through the rock panels to enable the supply of water to the shotcrete-rock interface. Six borehole entries on the rock surface at the shotcrete-rock interface were prepared to decrease the adhesion and two boreholes were left unprepared as reference samples with good adhesion (Figure 5.2). Two different materials were selected to simulate poor adhesion around the borehole. They were geotextile (Typar 3377) and a white wax crayon. After preparation, the panels were covered with shotcrete and placed in a water reservoir for at least two weeks to ensure their water saturated condition before the freeze-thaw test started.

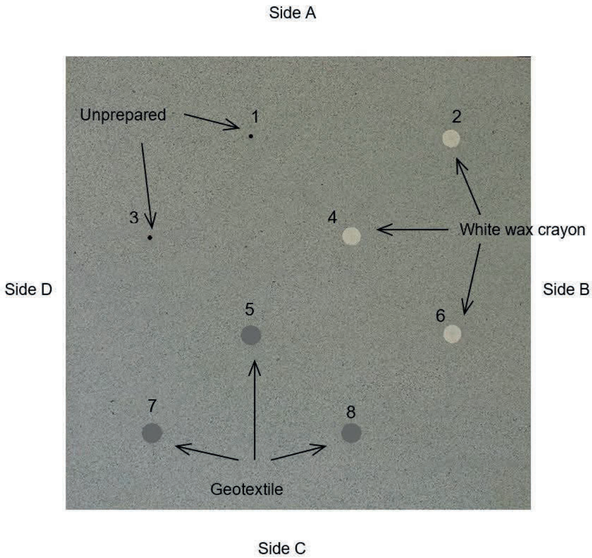


Figure 5.2 Preparation of the test panels (Andrén et al., 2020a).

5.2.2 Experimental arrangement

The freeze-thaw tests were performed in a cooling chamber at a constant temperature of +4°C in the MCE laboratory at the Luleå University of Technology. The test panels were put in a box of cellular plastic insulation and cooling took place from the shotcrete side of the panel to simulate a tunnel situation. The cooling system consists of a cryostat (water with 20-30% ethanol) that circulates in copper pipes at the bottom of the box at a temperature around -15°C. To even out the temperatures across the test panel, a steel plate was placed on top of the pipes, and a layer of sand was then placed on the plate to level the test panel in the box (Figure 5.3).

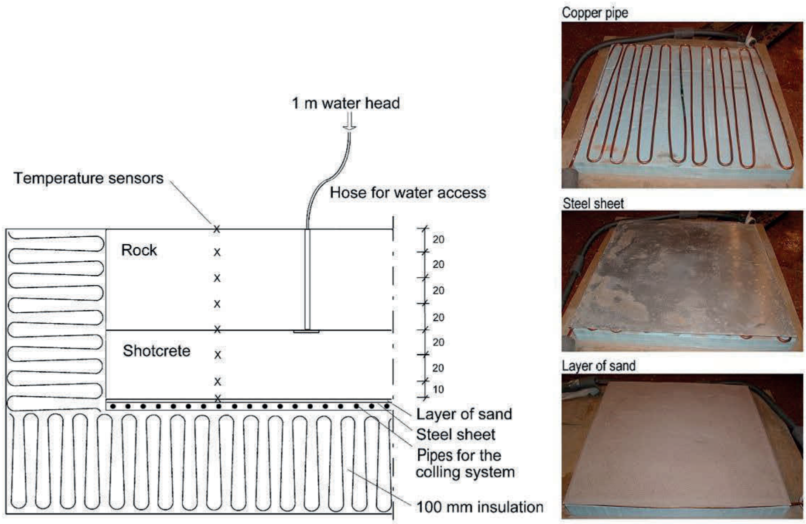


Figure 5.3 Arrangement of the freeze-thaw test experiment (Andrén et al., 2020a).

To ensure identical freezing and thawing cycles for all the test panels, the cooling system was controlled by a temperature relay that started or stopped the cryostat circulation at a pre-set temperature based on the temperature sensors placed at the shotcrete-rock interface (Figure 5.3). The shotcrete-rock interface in the panels was subjected to 20 freeze-thaw cycles. This is not a standard method. The number of freeze-thaw cycles have been selected as a result of the field measurements of tunnel air temperatures taken in the Glödberget tunnel. During a single winter season, the temperature fluctuated around the zero mark about 20 times (Andrén, 2008-2016 and Andrén et al., 2020b). Hence, in the laboratory tests, the temperature at the interface was made to oscillate around 0°C 20 times in order to cause potential water in the interface to freeze and subsequently thaw and allow more water to reach the interface area through water migration. A water access hose was connected to a bucket filled with water about 1 m above the shotcrete-rock interface to generate a water pressure with one-metre water head. The water head around the periphery of a grouted tunnel varies but a one-metre water head was selected as a reasonable value for the experiment. Acoustic emission monitoring (AE) was performed to follow the failure process during the tests. The system consisted of eight sensors and eight preamplifiers. More information about the experimental set-up, measurements and the AE system can be found in Mainali et al., (2015) and Andrén, (2009).

5.2.3 Results of the freeze-thaw tests

To evaluate if degradation occurred due to the freeze-thaw cycles, acoustic emission (AE) monitoring and tensile strength tests were performed. AE monitoring is a non-destructive method and can be used continuously during the freezing test without influencing the results. The direct tensile strength test is a destructive test, which is used to determine the adhesive strength between shotcrete and rock before and after the freeze-thaw tests.

In total, four panels were tested (panel numbers 4, 5, 6 and 7) and three of them were subjected to the freeze-thaw tests in different water conditions. Test panel number 6 was a reference panel and was not subjected to freezing and thawing. Test panel number 5 and number 7 were subjected to freeze-thaw cycles, and they were saturated with access to water during freezing. The last test panel, number 4, was subjected to freeze-thaw cycles and it was water saturated but without access to water during freezing. When referring to boreholes and test samples the following name is used X:Y, where X is the number of the panel and Y stands for the number of the boreholes it relates to.

Acoustic emission measurements

The results of the laboratory tests showed that the number of AE events increased considerably in a panel when it had access to water during freezing. In the following figures illustrating AE events, every dot indicates a recorded event that triggered more than four sensors. The colour of the dot represents the number of sensors that were triggered during that specific event (Figure 5.4).

Panel number 7 had access to water during freezing and Figure 5.4a and the chart in Figure 5.5 shows the total number of AE events (1603) for the 20 cycles. There was a concentration of events around boreholes 7:7, 7:5 and 7:3 and in the area between boreholes 7:8, 7:6 and 7:4. Figure 5.5 shows many events during the first six cycles, which decrease drastically during the following cycles.

The test on panel number 4 differed from the other panels. It was water saturated but it had no access to water during freezing. This panel had far fewer AE events than the other panels – only 129 events compared to over 1600. Figure 5.4b shows the location of all the AE events for panel number 4. There was no obvious concentration of events around any borehole, which was expected, since this panel had no access to water through the boreholes. Figure 5.6 shows the number of AE events for each cycle. In the first four cycles, a few AE events occurred while, during the rest of the test, the AE activity was almost negligible.

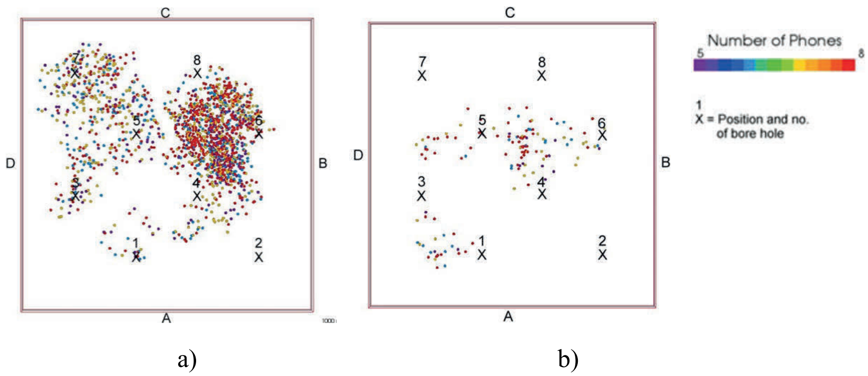


Figure 5.4 a) Location of AE events for panel number 7 (Andrén et al., 2020a).
b) Location of AE events for panel number 4 (Andrén et al., 2020a).

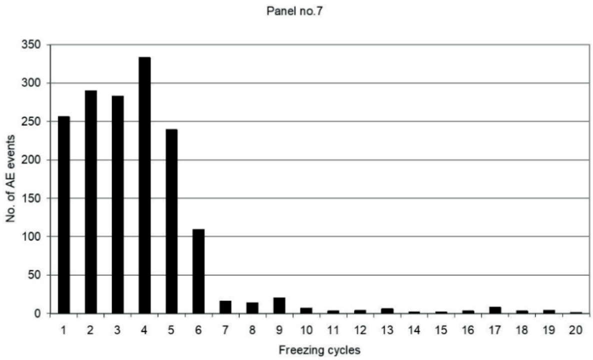


Figure 5.5 Number of AE events for each freezing cycle for panel number 7 with access to water during freezing (Andrén et al., 2020a).

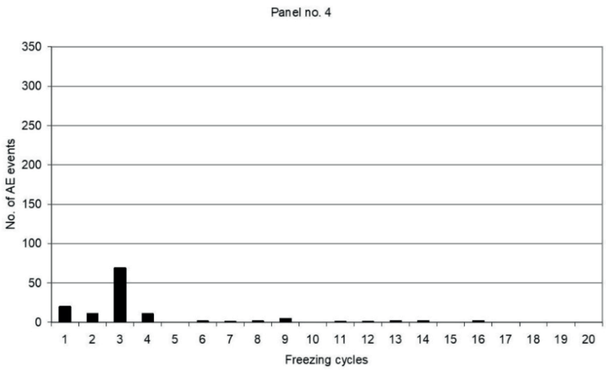


Figure 5.6 Number of AE events for each freezing cycle for panel number 4 without access to water during freezing (Andrén et al., 2020a).

Adhesive strength test

After the test panels had been exposed to the freeze-thaw tests, eight cores with a diameter of 94 mm were extracted from each shotcrete-rock panel (Figure 5.7). The cores were drilled centrically by over-coring the 5 mm boreholes. Uniaxial tensile tests were then used to determine the adhesive strength of the shotcrete-rock interface.

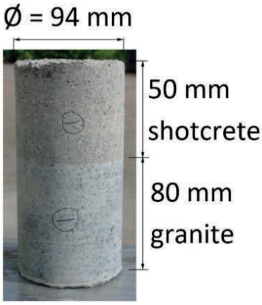


Figure 5.7 Test sample of shotcrete-rock core (Andrén et al., 2020a).

The results of the tensile tests for all panels and their preparation are shown in Table 5.1. The results of the tensile tests did not reveal whether the preparation with poor adhesion was of major significance.

Table 5.1 Results of tensile tests for all panels and their preparation (Andrén et al., 2020a).

Sample number	**Preparation**	**Adhesive strength (MPa)**			
		Panel no. 6 reference panel	**Panel no. 5 access to water**	**Panel no. 7 access to water**	**Panel no. 4 no access to water**
1	Unprepared	0.58	0.35	0.51	0.23
3	Unprepared	1.31	0.54	0.37	0.00[1]
2	Wax crayon	0.44	0.00	2.72[2]	0.40
4	Wax crayon	0.45	0.23	0.23	0.28
6	Wax crayon	0.26	0.00	0.44	0.74
5	Geotextile	0.21	0.31	0.22	0.30
7	Geotextile	1.09	0.68	0.24	0.40
8	Geotextile	0.83	0.70	0.50	0.54

[1] Sample subjected to accidental movement.

[2] Breakage in the shotcrete. Sample excluded from further evaluations.

The results from the laboratory tests showed that the adhesive strength between rock and shotcrete decreases after the test panels are subjected to freeze-thaw cycles. However, there is no great difference in adhesive strength among the panels that had access to water or not during freezing. The deterioration of the adhesive strength of the test samples was about 50% when subjected to freeze-thaw tests compared to the reference panel (Table 5.2).

Table 5.2 Mean values of adhesive strength and deterioration compared to the reference panel number 6 (Andrén et al., 2020a).

No. of panel	**Access to water**	**Adhesive strength (MPa)**	**Deterioration of adhesive strength (%)**
Reference no. 6	-	0.68	-
Nos. 5 and 7	Yes	0.36	47
No. 4	No	0.37	45

6. DISCUSSION

6.1 Water and frost

During this work and especially the field observations in the Swedish railway tunnels (Andrén, 2008 and Andrén et al., 2023), many problems relating to water and ice were discovered, all of which contribute to increased maintenance. The main problem is not the water itself, but problems arise when the leakage water is exposed to freezing temperatures. The observations have shown that water can continue to leak for a long time if the freezing rate is slow. If a tunnel is subjected to many frost cycles, problems with ice occur due to the fact that it enables water migration, which can enlarge the ice formations. Many problems with ice are directly linked to the frost insulated drains. Leakage and ice formation occurs at the edge of the drains, in mat splices and when brackets for cable racks, handrails or other installations puncture a drain and it has not been properly sealed. In drains covered with shotcrete, frost shattering and cracking of the shotcrete can be a problem.

Frost cycles in tunnels cause freezing and subsequently thawing of the available water in the rock and shotcrete. This allow more water to reach the area through water migration, with frost shattering of the material as a result. If the shotcrete is not anchored with bolts, the reinforcing effect and the stability of shotcrete in a tunnel is entirely dependent on the adhesion to the rock. It is, therefore, important to take all available measures to ensure good adhesion. One of these measures is to thoroughly clean the rock surface prior to shotcreting. Poor adhesion on its own does not pose a degradation problem. However, voids can form as a result of the poor adhesion in the interface between rock and shotcrete. If this void is filled with water, it can lead to the development of ice pressure at freezing temperatures. Furthermore, if the ice pressure exceeds the tensile strength of the adjacent material, the ice exerts pressure at the interface causing cracking and degradation of the shotcrete. The scatter in the results of the laboratory freeze-thaw tests indicates that further investigations need to be done in order to establish reliable theories relating to how small areas of poor adhesion affect the degradation of the interface between rock and shotcrete. Indeed, the adhesion strength tests performed in this study were too coarse for its purpose. However, these results indicate that access to water affects ice growth and ice pressure in the shotcrete-rock interface when it is exposed to freezing temperatures, which contributes to material deterioration. It would have been interesting to perform freeze-thaw tests on a completely dry panel. This was discussed at an early stage in the project, but the idea was rejected because conditions in a tunnel situation are never completely dry. However, it would have been a good idea to test a dry panel in order to better understand the problem of water migration. Consideration of the obvious difference in the number of AE events between the two different water conditions makes it clear that some activity is occurring when the panel has access to free water during freezing.

6.2 Where do problems with ice arise along a tunnel

In the longer tunnels, a greater number of ice formations occurred in the inner parts of the tunnel compared with the areas around the entrances. Leaks that are closer to the tunnel entrances are exposed to a higher freezing rate. The entire rock mass freezes and the leakage ‘freezes dry’, i.e., ice forms in the water-bearing joint, consequently the leakage paths freeze and prevent further water leakage. The leaks in the inner parts of the tunnel are not exposed to the same freezing temperatures as those near the entrances because the rock mass emits heat that warms up the tunnel air. Therefore, the rock mass can remain unfrozen. Frost penetration in a tunnel occurs when the tunnel air is set in motion. The predominant cause of frost penetration in most of the tunnels is the thermally induced airflow and, in the longer tunnels, it is the inclination of the tunnel that affects frost penetration the most. Frost penetrates at a greater distance from the lower tunnel entrance than from the upper entrance because the warm air, heated by the rock mass, moves due to the chimney effect towards the higher parts of the tunnel. In shorter tunnels that can adopt the same temperatures as the outside air, frost penetration often occurs along the entire length of the tunnel. Therefore, problems with ice might occur at all leakage points throughout the length of the tunnel. The amount of the leakage water is of great importance to the size of the ice formation. The rock mass has a large heat content and the leakage water, which adopts the same temperature as the rock mass, continuously supplies heat to the rock surface around the leak. The leakage paths stay open and do not freeze as easily. The leakage point will consequently continue to leak until the cooling from the tunnel air exceeds the amount of heat from the leaking water. A smaller leak, thus, does not add enough heat and, therefore, freezes much faster.

6.3 When water and ice problems occur during the year

The field observations (Andrén, 2008 and Andrén et al., 2023) showed that the location and the time when the leaks are active vary over the year. The amount of leakage water also vary over time. Another observation was that sections with similar leakage during the autumn, show different behaviour during winter. In some sections ice formations are formed while in other sections the surface is dry, with no ice formations. In another section, there was only moisture on the wall at the inspection in the autumn while a large amount of ice had formed in that particular section during winter. The amount of leakage water depends on the contact point with the surrounding aquifer. If the joint has contact with the groundwater, it can continue to carry water to the leakage point. If the joint instead is above the groundwater surface, it is affected by the amount of precipitation during the year, ground frost and how the water is stored in the rock. The number of ice observations noted during the inspections also depends on what the temperature was before and at the time of the inspection. If the temperature had been low for a long time before the inspection, some leaks might have ‘frozen dry’ while other leaks might have resulted in large ice formations. The location of the leak in relation to the tunnel entrance affects the temperature ratio and hence the ice formation.

6.4 Where and when water and ice problems occur in a tunnel at different locations in Sweden

The changes in the freezing periods and their duration have a major effect on the number and location of leakage points and ice formations in a tunnel. The central and southern parts of Sweden have shorter cooling periods and the tunnels are exposed to many temperature fluctuations around 0°C during the winter. Frost does not penetrate into the tunnels in the same way as in the northern parts of Sweden. Therefore, more ice problems arise around the entrances of the tunnels in the southern parts of Sweden than for those in the northern parts. For northern parts of Sweden, the problem of growing ice formations in sections near the tunnel entrance usually only appears during the autumn and spring and not during the winter. The field observations (Andrén, 2008 and Andrén et al., 2023) and the field measurements (Andrén 2008-2016 and Andrén et al., 2020b) showed that the problems with ice growth and temperature fluctuations around 0°C occur further in along the longer tunnels in the northern parts of Sweden because the tunnel air temperature is higher due to heat transfer from the rock mass. For shorter tunnels that adopt the same temperatures as the outside air, the number of ice formations are evenly distributed over the entire length of the tunnel and correspond to the number of drip observations within the same section.

This study have been used to propose and to evaluate the new approach for the future requirements regarding frost index in the Swedish Transport Administration’s regulations. Because of the heat transfer from the rock mass, the requirements for the frost index inside a tunnel is lowered in relation to the requirements for the frost index of the outside air. The proposed changes relate partly to a new division of climate zones in Sweden, partly to the division of sections with different frost index requirements along the tunnel, depending on the length of the tunnel. For the south of Sweden, the measurements show that the current requirements are high in comparison with the calculated frost index for the relevant measurement period. The suggested future requirements of the frost index is lower and appears to agree better with actual measured values. In the north of Sweden, the current requirements are too low in the outermost sections of the tunnel. The suggested future requirements for the frost index fit better with the actual measurements. It is clear that the inclination has a major impact on the temperature distribution along the tunnel and frost penetration occurs at a greater distance from the lower tunnel entrance than from the upper entrance. The Swedish Transport Administration must consider the inclination of a tunnel when determining the final change in the future requirements. The suggestion is that a special investigation should be carried out for tunnels longer than 2000 m and for tunnels with high inclination.

6.5 Drain location in a tunnel

This study have shown that there is a variation in where and when water and ice problems occur. Since many leaks seem to occur next to the drains, questions such as: ‘Is the drain clogged? Has the flow path of the leak changed? Has frost shattering at the edge of the drain caused the flow paths to open up at the side of the drain?' are asked. Where there are no problems with leakage next to drains, instead questions such as: 'Has the leakage stopped? Has the path of the leak changed? Does the drain function as it should?' can be asked. Leakage points might move because the previous leakage path has been sealed in a natural way. For example, in the Laduberg tunnel, in some sections the drains were disassembled and no new drains were installed, and the rock surfaces were still dry after several years. That indicates that the leakage paths have changed or that they might have been sealed naturally. Therefore, the placement of drains is difficult to determine. In some projects, drains are installed based on one observation during a single inspection. The conclusions of the field observations are that it is difficult to estimate where the insulated drains should be located along a tunnel. Based on experience gained from this investigation, the determination of location for drains should be carried out after several inspections and especially after a winter period, when the main problems with ice formations occur.

Previous perception regarding problems with ice have been that ice formation only occurs at the tunnel entrances and in the outer parts of the tunnel. Therefore, one solution has been to install insulated drains along the entire tunnel area over a distance of 300 m from each tunnel entrance in an effort to completely eliminate the problem of ice formation. However, this is not an effective solution to the problem, as the insulation does not only prevent the cold from reaching the leakage point, it also prevents the rock mass from emitting heat that warms up the cold tunnel air. With many insulating drains, frost can occur further into the tunnel and the problems with ice formation also develop in the inner parts of the tunnel (Andrén, 2009). The frost index in a tunnel mainly depends on the degree of insulation. The frost index increases as insulation prevents the heat from the surrounding rock from warming up the tunnel air. Dimensioning of the insulation must, therefore, be carried out in several iterations, where each new insulation distribution is separately calculated (Wikström and Sahlin, 2019).

7. CONCLUSIONS

The conclusions of this work are:

- Water leakage and ice problems in Swedish tunnels are mainly controlled by the access of water and the occurrence of freezing temperatures.
- The access of water is controlled by water bearing fracture network and the hydraulic conductivity of the unfrozen rock mass and the effect of the formation of ice in the joints and cracks.
- Heat from the rock mass is transported by the water to the location of the leakage point.
    - If the leak is large, the heat content of the water keeps the rock joint unfrozen despite the freezing tunnel air temperatures and the water continues to flow and the ice formation grows larger.
    - If the leak consists of small drips, the water does not add enough heat and the flow path can ’freeze dry’ when the cooler air from the tunnel exceeds the heat content from the leakage water.
- Temperature changes and the duration of freezing periods have a major effect on the number and location of leakage spots and the ice formations in a tunnel.
    - Long freezing periods: the leakage points freeze and ice forms in the water-bearing fracture, preventing further water leakage; it ‘freezes dry’.
    - Short and frequent freezing and thawing periods: the water-bearing fracture will never become completely frozen and water will continue to leak, resulting in growing ice formations or increased frost shattering.
    - Many frost cycles can lead to frost shattering of rock and shotcrete and ice formations, if the interface between rock and shotcrete has access to water during freezing.
- Frost penetration along the tunnel.
    - Earlier the general opinion was that ice formations occurred only at the tunnel entrances and the parts of the tunnel closest to the tunnel entrances. This study has shown that the frost penetrates further into the tunnels than previously assumed.
    - The inclination and the difference in the outside and the tunnel air temperature is crucial for the length of frost penetration. The frost penetrates a greater distance from the lower tunnel entrance than from the upper entrance because the warm air, heated by the rock mass, moves due to the chimney effect towards the higher parts of the tunnel.
    - To benefit from the heat from the rock mass, a tunnel can be built with a high point in the middle of the tunnel, instead of a constant inclination. Then the heated air rises towards the high point and stays inside the tunnel.
    - The air velocity in the middle of the longer tunnels increases during the winter periods. This indicates increased airflow throughout the entire length of the tunnel during the winter periods, resulting in increased frost penetration along the tunnel.

    - Measurement in the adjacent service tunnel at Glödberget shows how great an influence the airflow in the track tunnel has on the frost penetration. With closed doors at each service tunnel entrance, the airflow is confined. The air is heated by heat exchange between rock and air and the tunnel air adopts the same temperature as the surrounding rock mass throughout the year. This temperature usually coincides with the annual mean temperature of the region where the tunnel is located.
    - Passing trains create very high air velocities in the tunnel that cause the tunnel air to move. The air velocity reduces quickly after the passage and the conclusion is that train passages have no greater impact on the total frost penetration in tunnels with low traffic intensity. However, in one-way tunnels with a higher traffic intensity, the train passage can increases the length of negative temperatures along the tunnels.
    - The use of frost insulated drain mats along the tunnel, prevent the rock mass from emitting heat to the tunnel air, therefore, the frost can penetrate further into the tunnel and the problems with ice formations also occur in the inner parts of the tunnel.
- The Swedish Transport Administration's requirements of the frost index: The frost index calculated from the performed field measurements in the tunnels, show that:
    - For the tunnels located in the southern part of Sweden, the current frost index requirements are higher than the calculated frost index. The current requirements should be adjusted to lower design values.
    - For the tunnels located in the northern parts of Sweden, the current frost index requirements should be increased, especially for the outer parts of the tunnel where the current requirements are too low.
    - The distribution of the frost index and the division of sections along the tunnel should be changed to better suit the reality, with higher frost index in the outer parts of the tunnel, which then decreases in steps along the tunnel depending on the total length of the tunnel.
    - It is clear that the inclination has a major impact on the temperature distribution along the tunnel and frost penetration occurs at a greater distance from the lower tunnel entrance than from the upper entrance. Therefore, the inclination of the tunnel should also be taken into account when changing the current requirements.
- Occurrence and development of ice formations depends on the length of the tunnel and its location in Sweden.
    - Short tunnels.
        - Can adopt the same temperature as the outside air and ice formations can occur along the entire tunnel length.
        - Depending on the heat transfer from the rock mass, leakages might 'freeze dry' or continue to leak, with ice formations as a result.
    - Long tunnels in the northern parts of Sweden.

        - Have longer periods of freezing temperatures. The sections close to the tunnel entrances often become frozen, while the inner parts are warmer due to heat transfer from the rock mass.
        - Growing ice formations in the sections close to the tunnel entrances usually occur only in the autumn and spring and not during the winter because they ’freeze dry’.
        - Ice growth and temperature fluctuations around 0°C occur further into the tunnel, because the tunnel air temperature is higher due to heat transfer from the rock mass. Hence, more ice is formed from leaks in the inner parts of the tunnel than from the leaks near the entrances.
    - Long tunnels in the central and southern parts of Sweden.
        - Have shorter periods of freezing temperatures than in the northern parts of Sweden and the tunnels are exposed to many temperature fluctuations around 0°C during the winter.
        - Frost does not penetrate into the tunnels in the same way as in the northern parts of Sweden.
        - More ice problems arise near the entrances of the tunnels than for the tunnels in the northern parts of Sweden.
- Degradation of shotcrete:
    - According to the laboratory tests, there was a clear reduction of adhesive strength for the test panels when subjected to freeze-thaw tests. These results indicate that access to water affects the shotcrete-rock interface when it is exposed to freezing temperatures. This contributes to material deterioration.
    - The results indicated that most activity occurred during the first cycles, since the number of AE events was greater in the first part of the test. The number of AE events was much greater for the panels that had access to water during freezing, than for the panel without access to water.
    - The direct tensile strength tests that were performed, were too coarse for its purpose. It is clear that a reduction in adhesive strength occurs in the saturated samples subjected to freezing. But the methods used, AE monitoring and direct tensile tests, did not lead to the same conclusion according to surface treatment (wax crayon and geotextile). The AE monitoring indicated that fracturing took place around the boreholes with a surface treatment, but the direct tensile tests showed no significant difference in the results in adhesive strength between the tests samples with or without surface treatment.
    - If there is good adhesion between rock and shotcrete, the degradation due to frost shattering at the interface should not be a problem. But maintenance reports reveal that areas of poor shotcrete adhesion can appear and propagate rather quickly, in areas that have access to water during freezing, i.e. areas with leakage problems. Therefore, it is recommended that the time period between the inspections, according to

the current requirements, should be modified to enable detection of problem areas.

- Frost insulated drain mats:
    - Prevent frost cycles. Frost insulated drain mats reduce the number of frost cycles that the material behind the drain is exposed to.
    - The edges of the drain mats must be properly sealed to prevent the cold air from reaching the leakage point.
    - To prevent leakage from walls forming ice layers on the tunnel floor, drain mats should be installed so that they extend all the way to the frost-free tunnel floor. This can be combined with heating cables in the ballast bed.
    - To prevent icicles in the roof or ice layers at the road or tracks, drain mats should be installed from floor to floor.
    - If the drains are clogged by debris, chemical or biological deposits or ice, or the water bearing fracture is sealed by natural causes, the leakage water can take a different path and therefore the leakage can occur at the edge of the drains.
    - The best location for drains should be decided after several inspections have been carried out and especially after a winter period, which is when the main problems with ice formations occur.
    - It is important that maintenance staff have the correct and updated documentation about where drains are located in a tunnel to avoid unnecessary damage to the drain during installation of, for example, brackets for handrails. If a puncture of the drain cannot be avoided, the drain must be properly sealed once the work is completed.

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ACKNOWLEDGEMENT

Thanks to The Swedish Transport Administration, Swedish Research Council Formas and the Rock Engineering Research Foundation BeFo for supporting this study. I would also like to thank the people in the reference group: Lars-Olof Dahlström and Erling Nordlund/Luleå University of Technology, Tommy Ellison/Besab, Johan Funehag/ Luleå University of Technology-Tyréns, Thomas Dalmalm/The Swedish Transport Administration and Per Tengborg and Patrik Vidstrand/ the Rock Engineering Research Foundation BeFo.

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Visiting address: Storgatan 19, Stockholm
ISSN 1104-1773