# Winter Road Maintenance as a Threat to Our Built Heritage

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## ABSTRACT

Winter Road Maintenance (WRM) is necessary to maintain the daily rhythm of society during the winter season; however, the chemicals used create a harsh environment for historic monuments through the salinization of urban soils. The damage caused to monuments occurs both inside and out. The negative effects of sodium chloride are known yet, it is widely used due to its cost effectiveness, efficiency, and availability. Soluble salt contributes to stone decay through the confined crystallization of salts within the pore structure of the material causing the stone to break down. Salt can infiltrate structures through capillary rise in the subsurface soils, rising damp, and splash from vehicles. Dry winter weather does not preclude the risk of damage. Residual salts become crystallized and are dispersed by vehicles and humans, allowing them to become airborne. Masonry is not the only historic building material vulnerable to salt degradation. Historic infrastructure, such as lamp posts, boundary markings, and bridges, is also susceptible to salt degradation. This endangers our built heritage and compromises the historic record of past construction techniques. This study examines how salts and the soil/structure interactions affect historic monuments and explores methods that can be used to mitigate the resulting damage, thus preserving our built heritage for future generations.

*Keywords: Winter Road Maintenance, Built Heritage, Monuments, Salt Deterioration, Capillary Rise, Soil/Structure Interactions*

## INTRODUCTION

Icing on roads and bridges due to winter weather events presents a unique challenge for transportation agencies. Icing on roadways is dangerous and costly. Icy road conditions decrease traffic flow, resulting in lost profits for businesses as well as lost wages for workers (DiLorenzo & Yu, 2025).

Winter Road Maintenance (WRM) operations are executed based on forecasting using data from Road Weather Information Stations (RWIS) and cameras, combined with the experience and judgement of transportation agency personnel. Decisions, such as when to apply anti-icing chemicals ahead of the anticipated winter event or de-icing chemicals during the winter event are made using this data. This can lead to an increase in overapplication, contributing to runoff of excess chemicals to the roadside environment (Dai et al., 2012). The most commonly used chemical is sodium chloride (NaCl). It is estimated that over 200 million metric tons of NaCl are used world-wide for WRM (Steigler et al., 2011). Damage from salts to infrastructure involve physical and chemical mechanisms resulting in corrosion, chemical reactions, and excessive damage from freeze/thaw cycles (Korhonen, 2002; Shi, et al., 2009). Although the damaging nature of salts is known, they continue to be widely used due to their cost-effectiveness, efficiency, and availability (Ratkevicius et al., 2014).

Degradation to the built heritage can be caused by a variety of conditions, with salt weathering through the crystallization of salts being the primary cause (Evans, 1970; Winkler, 1994, Price, 1996; Gomez-Heras & Fort, 2007, Steiger et al., 2010). The monument’s exposure to salts can be caused by natural sources, anthropogenic sources, or a combination of both.

# TRANSPORT OF DEICING SALTS TO THE ROADSIDE ENVIRONMENT

Salts applied to roads and walkways during a winter event will migrate away from the pavement surface and become part of the roadside environment. Salts can be spread away from the pavements in multiple ways including runoff, vehicle and pedestrian splash, and airborne spreading, resulting in a physicochemical alteration of the subgrade soils (Durickovic, 2019). The figure below illustrates common methods of salt migration into the roadside environment.

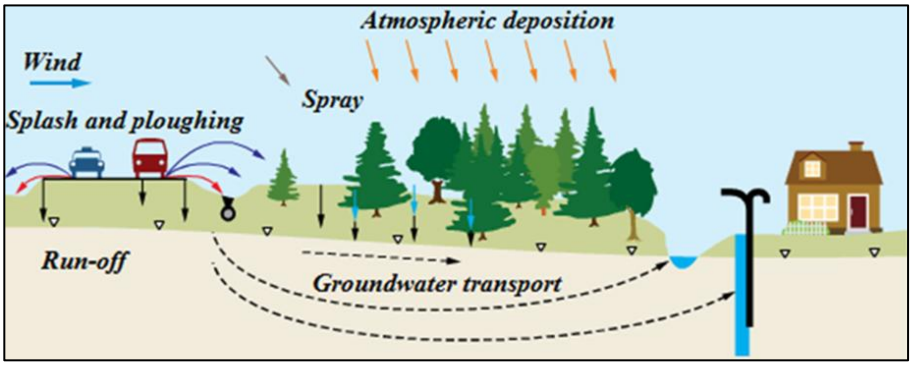


***Figure 1.*** *Salt migration in the environment (From Ratkevicius et al., 2014)*

Salts applied to pavements reach groundwater by infiltrating the adjacent soils. Once these salts have reached the subsurface, they can be retained in the subsoil or migrate further from the place of origin through the groundwater and then back to the surface via capillary rise.

## The Role of Capillary Rise in Subgrade Soils

Within the framework of soil mechanics, soil governs key hydrological processes through its permeability, porosity, and moisture retention characteristics. These characteristics control water infiltration, storage, and subsurface flow within a watershed. These mechanics regulate runoff, flow through the vadose zone and hypodermic layer, groundwater migrations and aquifer recharge. Capillary rise occurs when water migrates vertically from higher moisture regions of the subsurface to drier regions and is more pronounced in regions with a shallow water table that allows a continuous vertical rise of water not retained within the soil matrix Some of the most intrusive salts, such as sodium and chlorides, are a result of the ion exchange process within the solid and liquid phases of the soil (Afif-Khouri et al., 2025). Capillary rise plays a significant role in the vertical infiltration of these intrusive salts from the subgrade soils into historic structures, particularly those constructed of calcareous stones such as limestone and marble.

# MECHANISMS OF SALT DETERIORATION TO STRUCTURES

Stone and masonry have a porous structure, which makes these materials particularly vulnerable to weathering and deterioration as a result of salt exposure. The following section covers the mechanism by which salt causes damage to structures.

## Salt Crystallization and Pore Damage

Soluble salt is a main contributing factor to stone decay (Price & Doehne, 2011). The damage is caused through the crystallization of salt within the pore structure of the material. When the salt crystals expand, there is a decrease in the pore size; while pressure, in the form of tensile stress, is exerted on the solid matrix (Delgado et al, 2016; Steiger et al, 2010). The magnitude of the stresses can exceed the strength of the stone pore structure, thus causing the stone to break down. This increase in the pore stress is especially pronounced in structures with calcite, where the expansion of NaCl occurs at a rate five times that of the calcite (Price & Doehne, 2011).

It has been shown experimentally by Angeli et al. (2008), that weathered stone has a higher porosity after salt exposure. The study further showed that salt crystals in pores that are several microns in diameter can exert enough pressure to initiate and further perpetuate a crack. Pre-existing cracks were found to accelerate their propagation with continued salt exposure.

Transport can occur through porous material by convection (in the form of liquid) or diffusion (in the form of vapor). Salt infiltrates structures through rising damp and splash from vehicles and pedestrians. Infiltration through groundwater is another mechanism by which salt contributes to the weakening of the pore structure by transporting polluted runoff from roads treated with salt and from the mineral particles in the soil itself (Oguchi & Yu, 2021). Rising damp is caused by deicing salts present in the soil that then travel to the base or foundation of a structure via capillary rise (Steiger et al., 2010).

Deicing salts have been found to be a major contributor to chlorides accumulating at the ground level of masonry. Figure 2 shows the effects of de-icing salts on urban masonry. It can be observed from the figure below, that efflorescence from de-icing salts has accumulated on the stairs and impacted the masonry.

***Figure 2.*** *Accumulated efflorescence from dried deicing salts (From Steiger et al., 2010)*

Rising damp is caused by deicing salts present in the soil that then travel to the base or foundation of a structure via capillary rise (Steigler et al., 2010). Older structures are particularly vulnerable to this phenomenon due to insufficient insulation from ground moisture. During capillary rise, moisture travels from the subsurface soils to the foundation of base of the structure and then through the structure allowing the salt in the water to travel further from the base. The ultimate height of this capillary rise is given as the height where the evaporation rate is equal to the supply of moisture from below. Because the rate of evaporation will vary based on the amount of salt present and the porosity of the material, the deterioration of the material will vary significantly. Figure 3 below illustrates the effects of capillary rise on masonry. Here, the damage sustained to the wall from NaCl is over 2 meters above the ground level.

***Figure 3.*** *Salt weathering in upper portion of structure (From Charola et al., 2017)*

Dry winter weather does not prevent the risk of damage. Porous materials absorb moisture from the atmosphere; this moisture can mobilize and deposit salt into cracks and pores of the structure, becoming a major source of salt contamination. Remaining salts on pavements crystallize and these particles are dispersed by vehicles and pedestrians, allowing them to become airborne. A study of European air quality showed PM air levels contained enough NaCl for inland areas to be considered as sea salt air (Charola et al., 2017). Salt damage is not limited to the outside of monuments. Morabito 2013 found chloride deposits in the entrance of St. Mark's Basilica. The levels of chloride decreased further into the chapel, indicating the source of contamination was from outside the structure. The figure below illustrates the accumulation of residual deicing salts on the base of the structure during a dry winter period. These residual salts can be mobilized and then enter the pores of the structure through absorption (Charola et al. 2017).

***Figure 4.*** *Accumulated salts at the base of the structure (From Charola et al., 2017)*

The crystallization of salt is a complex process with phase changes that include, but are not limited to, variations in hydration and chemical reactions. Crystallization is governed by the response of the salts present in the pore structure to their surrounding climate conditions, such as freeze-thaw cycles. The freeze-thaw cycle is particularly damaging to porous materials, with repeated cycles causing progressively more damage. The application of salt during winter weather events lowers the eutectic point of water by disrupting the ice crystal structure, slowing or preventing the formation of ice on pavements during freezing weather. It has been shown in the literature that porous stone sustained more damage when exposed to repeated freeze-thaw cycling with the presence of salts, when compared to only pure water (Steigler et al., 2011; Arnold & Zehnder, 1991). Additionally, NaCl has been shown to cause the greatest deterioration to stone compared to other salts (Williams & Robinson, 1981, 2001).

## SALT DETERIORATION OF MONUMENTS

The negative effects of salts are widely known and have been for over two millennia when it was identified by Herodotus as a detriment to stone (Cardell et al., 2003; Price & Doehne, 2010; Zezza & Macri, 1995; Morabito et al., 2013; Charola et al., 2011). The deterioration of stone varies temporally and spatially, being dependent on the pore size distribution and the total specific porosity of the material. The modification of these are indicative of weathering (Cardell et al., 2003).

Cardell et al. (2003), studied the weathering of two calcareous types of stone used in monuments in the southwest of France. The monuments were located at varying distances from the coast in a typical Mediterranean marine environment. Structures were examined at the coast to 30 km away from the coast, illustrating the threat posed by airborne salt particles. They found that the decayed stone contained more soluble salts than fresh stone and that there was more damage observed in the upper half of the structure, indicating salt crystallization occurred while the salts were in a vapour phase.

Zehnder (2006) conducted a study on the effects of soluble salts on wall paintings in historic monuments. Case studies of the deterioration of wall paintings in several historic sites in Switzerland were presented. The study found that salt deterioration occurred seasonally and was related to levels of moisture, heat, and humidity, illustrating that the interior of a structure is not excluded from salt infiltration.

The 12th century temple of Ankor Wat, located in Cambodia, is part of the UNESCO World Cultural Heritage. The deterioration of the monument due to salt load has been extensively studied (Hosono et al., 2006; Siedel et al., 2008; Waragai & Hiki, 2019). The superficial degradation here is characterized by scaling and flaking. Siedel et al., 2008 found that structural damage to the stone occurred in areas that are not exposed to prolonged high surface temperatures. The higher surface temperatures allow the stone to dry, illustrating the requirement of moisture in any form for salt crystallization to occur and thus cause pore expansion and degradation of the material's structure.

***Figure 5.*** *Damage to a pillar (left). Example of scaling on the carvings and salt efflorescence, in boxed area (right). (From Siedel et al., 2008)*

These are just a few of the multitude of studies conducted illustrating the deleterious effects of salt on monuments. While they are not directly related to WRM, they show that salt has a direct effect on the structural integrity of monuments and is deemed a threat to their survival.

## WRM CHEMICALS AND THEIR EFFECTS ON MONUMENT INTEGRITY

Masonry is not the only historic building material vulnerable to salt degradation. A study conducted by Antonson et al. (2021) examined the damage caused by WRM salting to historic cast-iron milestones. The study found an increase in the degradation of the road-facing side of the milestone versus the side facing away from the road. Historic infrastructure such as lamp posts, boundary markings, and bridges is also susceptible to salt degradation. This not only endangers the built heritage and compromises the historical record of past iron-making techniques.

### *Historical Milestone Markers in Sweden*

Sweden began using milestones as a result of the 1649 Innkeeper Ordinance in an attempt to have a more accurate method of overseeing the payment of travel allowances to the government. Milestones were made of wood, stone, or cast iron and were positioned along the main roads. More than 7000 of these milestones have been preserved, with 288 of them being made of cast iron (Antonson et al., 2021). The milestones have been registered in the National Heritage Board's antiquities register and the Swedish Transport Administration's register of historical road remains.

To evaluate the damage of road salt to the cast iron milestones, Antonson et al. (2021) studied 37 of the remaining 288 milestones. These milestones date from between 1760 and 1770 with seven milestones located on farm roads that are not subject to WRM operations, the other 30 are located on main roads that are included in WRM operations. In 1994, the milestones were restored back to their original conditions, allowing for an accurate baseline for the study. The study considered the presence of road salt, the distance of the milestone from the roadway, and the face direction of the compass. The subset of milestones in the study was in a limited geographical area with comparable environmental conditions.

The milestones were photographed using high resolution photography in October 2019 and September 2020. The front (road-facing) and back (non-road facing) of the milestones were visually examined both in the field and using photographs. Results showed that milestones located along the roads that were subjected to WRM salting suffered greater damage compared to the milestones located on the roads that were not salted. Further, the front of the milestones along the treated roads suffered more damage compared to its back.

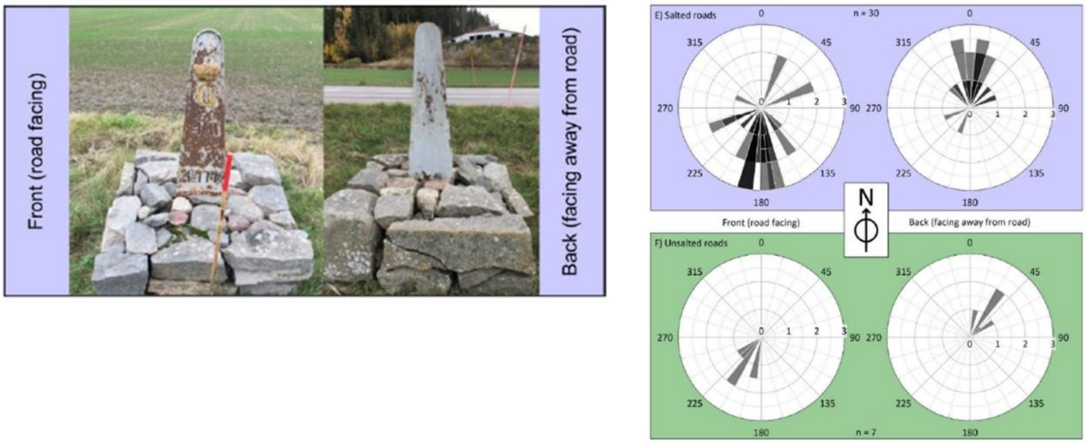


***Figure 6.*** *Photographs of the front and back of a milestone (left). Wind rose diagrams illustrating damage to the milestone in relation to orientation of the compass (right). (From Antonson et al., 2021)*

It can be observed from Figure 6 that there is substantially more damage inflicted upon the milestones that are located along treated roads versus the untreated roads. It should be noted that during the study, none of the milestones on the treated roads had more damage to the back versus the front; milestones on the untreated roads exhibited the same damage on the front and the back, showing that exposure to salts from WRM operations is the main cause of the damage to the milestone.

## CAN MONUMENT DAMAGE AS A RESULT OF WRM OPERATIONS BE MITIGATED?

In climates where ice and snow are a part of life, there is a need for WRM operations to keep daily life moving. WRM operations benefit the economic and social aspects of society. However, WRM negatively affects the natural and built environment through the application of chemicals before and during a winter event. Technology such as smart sensors and intelligent transportation systems can be exploited to help decrease the amount of salts used while helping to mitigate structural deterioration. Proactive, rather than reactive, strategies that focus on salt management, vegetative solutions, improved weather forecasting, and physical and engineered controls are a few methods that can also help to reduce the amount of runoff infiltrating the roadside environment.

Although the reduction of applied salts is beneficial, the challenge of managing the migration of salts into the roadside environment will continue to exist, particularly because soil can retain salts for months and years following the initial introduction (Nawroth et al., 2025). Conventional desalination methods, such as reverse osmosis among others, are largely cost prohibitive. Phytodesalination is a vegetative solution that is becoming a viable option as an economical and environmentally sensitive remediation method. Phytodesalination relies on the use of halophytes (vegetation that tolerates a high saline environment) to neutralize the contamination of soils by salts. Nawroth et al. (2025), conducted a two-year field study in Toronto, Canada using halophytes native to the area. The halophytes were planted along a road that received WRM salt treatment and included a control area. The study found that the halophytes successfully reduced the amount of chlorides in the soil, despite the short study timeline.

Physical and engineered controls for the reduction of runoff include check dams and berms along with permeable pavements systems and engineered infiltration. Permeable solutions for pavements include porous concrete, porous asphalt, permeable interlocking concrete pavers and many others. Permeable pavements have a higher percentage of air voids compared to impermeable pavements, allowing for the infiltration of water through its layers. Permeable pavements reduce the amount of runoff that is allowed to migrate into the roadside environment, thereby reducing the salt exposure. Permeable pavements not only reduce the amount of runoff but also reduce the amount of pollutants that reach the roadside soils through filtering the salt particles out of the water as it travels through the permeable layers of the pavement (Sousa et al., 2024). Permeable pavements have been found to reduce the total suspended solids in runoff by 80-90% (NPEDS, 2021), making permeable pavement systems a significant and practical tool in the reduction of salt infiltration into the roadside environment.

## DISCUSSION AND CONCLUSIONS

This study examines the mechanisms by which salts can compromise the structural health of our built heritage. It is clear that the effects from both natural and anthropogenic sources create a harsh and unforgiving environment where no historic building material is excluded from these assaults. The rate and extent of structural deterioration depend on a variety of factors from environmental to the physical characteristics of the material in question, making a standard solution to the problem difficult. WRM agencies can contribute to minimizing further damage through the application of technology that can reduce the amount of NaCl used, which can decrease the amount of run-off to the surrounding environment. Further studies on NaCl alternatives that are cost effective are needed to reduce society's reliance on a chemical that is widely known for its harsh effects. The use of a combination of natural remediation methods in the form of phytodesalination combined with engineered controls, such as permeable pavements, offers a viable and cost-effective method of decreasing the amount of salts that enters the roadside soils. This reduction can help to improve the soil structure interaction by reducing the amount of contaminants travelling to the structure base through capillary rise.

Although direct field case studies linking WRM operations to specific monument deterioration are limited, several lines of evidence support exposure to NaCl as a pathway of deterioration. Comprehensive reviews of salt weathering further note that NaCl frequently contaminates stone and masonry in urban environments, contributing to the crystallization cycles that drive deterioration. WRM operations remain a vital part of life in cold weather climates however, it needs to be balanced with finding a path of sustainability for the monuments that are a direct link to our built heritage. Monuments are a living and breathing connection to the past, it is society's responsibility to not only keep these monuments alive for future generations, but to keep them well and consider the impact our decisions today make on them for tomorrow.

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