THE FUTURE OF TRANSPORT

PUBLISHED PROJECT REPORT PPR1001

Effective Winter Service Treatments on Major Structures

M Evans, H Ye and E Wang

Report details

Report prepared for:	Transport Scotland		
Project/customer reference:			
Copyright:	© TRL Limited		
Report date:	1st December 2020		
Report status/version:	1.0		
Quality approval:			
Yorgos Voukas (Project Manager)		Evan Wang (Technical Reviewer)	

Disclaimer

This report has been produced by TRL Limited (TRL) under a contract with Transport Scotland. Any views expressed in this report are not necessarily those of Transport Scotland.

The information contained herein is the property of TRL Limited and does not necessarily reflect the views or policies of the customer for whom this report was prepared. Whilst every effort has been made to ensure that the matter presented in this report is relevant, accurate and up-to-date, TRL Limited cannot accept any liability for any error or omission, or reliance on part or all of the content in another context.

When purchased in hard copy, this publication is printed on paper that is FSC (Forest Stewardship Council) and TCF (Totally Chlorine Free) registered.

Table of Contents

Executive Summary

Transport Scotland requirements (as of 2020) currently stipulate the use of Potassium Acetate at certain identified locations of the network where structures are susceptible to corrosion. The requirements are that the potassium acetate product used must meet the Ministry of Defence Specification 68-118 (De-icing/Anti-Icing Fluid for Runways), an outdated document for liquid de-icers providing treatments on airport runways. Other specifications may be used with the written consent of Transport Scotland.

A review was undertaken to understand the basis of the current and any future specification for treatments on structures, applicable to Transport Scotland requirements but also to inform future guidance issued by the National Winter Service Research Group (NWSRG).

Controlling corrosion is one of the top threats to bridges. Salt and other de-icers can have a range of effects with corrosion to reinforcing steel bar (rebar) in concrete structures, effects on concrete itself, structural steel, and roadside structures. Acetates and formates are generally considered non- corrosive to highways materials, although there have been some reports of the corrosive effect of acetates and formates on galvanised steel as they react slowly with zinc (for example affecting crash barriers).

The review has identified a range of solid and liquid de-icers applied for bridge treatments and corrosion sensitive structures in the UK and worldwide, but special arrangements and non-corrosive de-icers are not always specified for winter service. The review has identified that treatments with sodium chloride brine and salt are used on many structures, including major suspension and cable stayed bridges, without significant adverse effect with reliance on protection techniques and construction to prevent corrosion. This will critically depend on the construction, protection measures and maintenance practices followed. Modern standards and protection measures have improved significantly, mitigating the risk of impacts from de-icing treatments, and key factors impacting the bridge susceptibility are identified in the review.

The current spread rates for 50% potassium acetate are providing effective treatments under the range of UK conditions. These de-icers can provide a complete solution for de-icing a structure i.e. a de-icing solution to cover the full range of conditions without reverting to salt or other solid de-icers.

For pre-cautionary treatments on damp surfaces or before frost, it is considered that the 50% potassium acetate products currently used offer a higher level of freezing point protection than required in UK conditions. In such conditions, treatments with Sodium chloride brine, lower concentration potassium acetate and formate (to 30% concentration) and calcium magnesium acetate (CMA) (to 25% concentration) can provide good performance on damp roads and frost across the range of temperatures experienced on UK bridges.

During more severe conditions of snow or lower temperatures, de-icers with higher effective temperatures may reach the limits of effectiveness. For example, operational feedback from the review has highlighted that in heavy snowfall compacted snow can form with the lower concentration liquid de-icers and sodium chloride brine. There will be wider scope for use of these de-icers where resources are in place for more frequent treatment and ploughing cycle

times i.e. 2 hours or less. Also where operators have capability to switch between different de-icers on a day by day basis e.g. reverting to salt or other de-icers in more severe conditions.

Based on comments from operators using potassium acetate, it is likely to offer advantages in terms of de-icing performance from greater longevity and eliminating the need for (or reduced top up rates) repeated de-icing and anti-icing treatments; however, detailed information is not currently available from the literature to quantify the spread rate reduction or effect on retreatment frequency.

Where alternatives to salt are used, the choice of any de-icer and application (spread rates, spreader performance etc.) should be made such that it provides equivalent or better performance to treatments with salt carried out in accordance with accepted treatment guidelines e.g. the NWSRG Practical Guide section 'Spread rates for precautionary salting'.

A comparison was made, based on the average winter severity number of treatments, between the real cost of treatments with salt and potassium acetate. Comparison was made based on a range of acetate performance benefit, from equivalent damage to salt to no damage cost. The analysis indicated that acetate starts to gain positive benefit if its reduction of damage cost can reach 50% of the salt damage cost. The use of potassium acetate requires a significant additional de-icer cost; however, this analysis may indicate that the overall resulting cost -benefit may be positive from the reduction in damage costs.

It should be noted that although cost-benefit analysis is a relatively straightforward tool for deciding whether to use a product, the cost rates are based on assumptions and are difficult to monetise.

1 Introduction

Transport Scotland requirements (as of September 2020) currently stipulate the use of Potassium Acetate at certain identified locations of the network where structures are susceptible to corrosion.

The requirements are that the Potassium Acetate product used must meet the Ministry of Defence Specification 68-118 (De-icing/Anti-Icing Fluid for Runways), an outdated document for liquid de-icers providing treatments on airport runways. Other specifications may be used with the written consent of Transport Scotland.

Transport Scotland has invited TRL to review these requirements and are seeking to understand the basis of the current and any future specification for treatments on such structures. The outputs from the work will be applicable to Transport Scotland requirements but also inform future guidance issued by the National Winter Service Research Group (NWSRG).

The study comprised a desktop literature review of research and operational practice including:

- Current UK and international operational practice and treatment guidelines, including
    - Types of products and any standards/specifications used for products
    - Spread rates and treatment guidelines
    - Feedback on operational performance and any issues identified
- Laboratory and field-testing reports tests of de-icer performance including freezing point, ice melting and corrosion performance for different compositions
- Impacts of de-icers on highway structures, including costs and benefits of different de-icers
- Review of weather conditions on selected bridges, to assess the operating conditions where treatments have been carried out, and any implication for the required performance of the treatment methods used.

Based on this information, the requirements were reviewed, and recommendations made regarding the specification for treatments on structures.

2 Review of research and operational practice

2.1 Types of product and specifications

The review has highlighted that while alternative de-icers to salt are used on some corrosion sensitive structures in the UK and worldwide, special arrangements and non-corrosive de-icers are not always specified for winter service on structures. Reliance is often on modern protection techniques and construction methods to guard against corrosion. (WRA, 2018). Further discussion of these construction issues is provided in Section 2.3.2

When alternative de-icers to salt are used on bridges, a range of de-icers have been reported across different countries including:

- Potassium acetate (KAc) – 50% concentration
- Calcium magnesium acetate (CMA)
- Calcium chloride ($CaCl_2$)
- CMAK - mixture of CMA and Potassium Acetate
- Magnesium chloride ($MgCl_2$)
- Potassium formate (KFm) – 50 and 30% concentration
- Agricultural by-products (ABPs)

The review has identified the use of fixed automatic spray treatment (FAST) systems in a number of countries including USA, Canada, New Zealand, Spain, Switzerland, England, Denmark, France, Netherlands and Hungary. De-icers used in such systems have include the above de-icers and also sodium chloride brine. Anti-icing treatments with FAST systems can reportedly be as low as low as 1g/m^2 for marginal conditions. (WRA (2018), Zhang et al (2007), WRA (2019)). Other non-chloride based de-icers available include glycol based products and succinate based de-icers.

Within the UK, Highways England requirements state that any use of an alternative anti-icing/de-icing material will be restricted to isolated, specific circumstances (e.g. structures susceptible to corrosion). It further states a range of alternative anti-icing/de-icing materials that may be considered for use on the network including Calcium Chloride, Acetates, Formates, Glycol and Urea.

Potassium acetate (50%) is used by Highways England Service Providers at a number of corrosion sensitive major bridges and tunnels on the Highways England network, however there are no particular standards or specifications or treatment guidelines used for the products common to all Service Providers.

There have been no reported issues with the de-icing performance of potassium acetate (50%) as used in the range of conditions in the UK.

Since the 1990's, CMA has been used in New Zealand on the highway network and some local roads because of the phasing out of dry salt over environmental concerns. CMA has been proven effective in preventing the formation of ice at road surface temperatures above -7°C. Best practice guidance from the New Zealand transport Agency (NZTA, 2012) is to use liquid

CMA (25% concentration) before frost and solid CMA for wetter roads and for snow and ice. The recommended application rate for liquid or solid CMA is between 7.5 and 30g/m² and in light frosty weather 7.5 g/m² has proven effective.

The guidance further states that CMA chemically ties up the first moisture melted as water of hydration resulting in very little runoff and keeps the snow 'dry' which prevents snow pack under vehicle action assisting in easy removal of the snow.

Potassium acetate and CMA have previously been used extensively for structures on the TfL network, before reverting back to salt in recent years.

Sodium chloride brine and pre-wetted salt have been used successfully on the Storebælt East Bridge in Denmark since 2004 with no corrosion issues (Finn Bormlund, Personal Communication). Brine or pre-wetted salt are used as a precautionary treatment before frost and snow, with 40ml/m² brine spread before snowfall. For reactive treatments on snow and ice treatments are made with pre-wetted salt. Brine spreading at 40ml/m² is specified as an option for treatments on white frost.

Prior to 2004, the bridge was treated using two non-corrosive de-icers, a 30% solution of potassium formate and a 25% CMA solution. In most conditions experience with these de-icers was good, with the 30% potassium formate effective at temperatures down to -10 °C. It was reported to be difficult to keep the lanes completely free from snow and ice in heavy snowfall and in areas the snow became compacted and difficult to remove with the liquid de-icers, requiring the use of sweepers in combination with the snow ploughs and the salt spreaders.

Corrosion inhibitors are chemical compounds in either liquid or solid form which, when added to an environment containing a metal, slow down the chemical reaction of corrosion. There are various mechanisms by which corrosion can be inhibited. In simple terms, these mechanisms either remove corrosive agents, such as chloride ions and oxygen, from the environment surrounding the metal or produce a protective layer on the metal surface to prevent corrosion. A review carried out by Booth et al, 2011 identified nine commercially available corrosion inhibitors for salt; these are currently used in the USA and Canada. There are several laboratory test methods available for assessing the effectiveness of inhibitors in reducing de-icer corrosivity. The general approach is to expose metal coupons of known weight and dimension to a corrosive environment, for example by immersing them in or spraying with a chloride solution, for a specific period of time and measuring the weight loss due to corrosion. The assets most likely to benefit from the use of inhibitors are spreaders. Walker et al (2010) suggested that the influence of a corrosion inhibitor becomes less the further the asset is from the spreading mechanism.

In the UK two additives, Safecote and Eco-Thaw, have been used in winter service. Laboratory tests have shown that Safecote can reduce corrosion. Field trials undertaken on behalf of the HA found that metal coupons mounted on spreaders which were spreading Safecote treated salt suffered less corrosion than those mounted on spreaders spreading dry salt. However, the results for coupons mounted on safety barriers alongside the roads treated by these spreaders did not show any major and consistent difference in corrosion for dry and treated salt.

Succinates are a recent deicing technology currently primarily for use at airports, due to the extremely low corrosivity compared to chlorides, acetates, and formates. Succinates are a non-corrosive option for all pavement and metal types, functioning as a corrosion inhibitor.

Table 1 show a summary of the types of products used on bridges in the UK and internationally.

Table 1: Summary of de-icer types used on major structures on Transport Scotland and Highways England network

Type	Location used	Additional information
Potassium acetate (KAc) – 65%	Amey – FB Unit (2018/19)	Spread rates as Appendix A2
Potassium acetate (KAc) – 50%	Amey – FB Unit (2019/20)	Spread rates as Table 7.2.K.3
Potassium acetate (KAc) – 50% **Specification 68-118**	BEAR- NW	Spread rates as Table 7.2.K.3 – See Appendix A1
Potassium acetate (KAc) – 50% **Specification 68-118**	BEAR- NE	Spread rates as Table 7.2.K.3
Potassium acetate (KAc) – 50% **to SAE AMS 1435C**	ScotlandTranServ -SW	Spread rates as Table 7.2.K.3
Potassium acetate (KAc) – 50%	Amey - SE	Spread rates as Table 7.2.K.3
Potassium acetate (KAc) – 50%	HE Area 9 – Meir Tunnel	Used as an anti-corrosion measure instead of salt. De-icer stored in 15,000 litre storage tank at depot. In winter 2015/16, 6,000 litres used on the tunnel. Treatment carried out for both bores and starts approximately 250 m before each bore with a 1 km treatment length. Spreading carried out using a combi spreader.

Type	Location used	Additional information
Potassium acetate (KAc) – 50%	HE Area 2 – Severn Crossings, Avonmouth Bridge M32 Eastville Viaduct	Bunded storage tanks with associated pumps, standby pumps and standby generators. Feedback that treatments are effective and, if conditions are favourable, retreatment is every 24 hrs (supplier states that this could be 48 hrs). Potassium Acetate general spread rate of 18g/m^2 (14ml/m^2), increased to 26g/m^2 for hard packed snow or ice. 80,000 litre storage tank capacity. Currently two treatment vehicles specifically designed for spreading Isomex (liquid only spreaders) with an additional vehicle with Isomex spreading capability (combi).
Potassium acetate (KAc) – 50%	HE Area 3 - Hindhead tunnel	The approaches to Hindhead Tunnel are treated with Potassium Acetate using combi spreaders. The Acetate spread pattern is calibrated to 20g/m^2 to a width of 3.5m, after that each lane is set to 7.0m (lane 2) and 10.5m (lane 3) using the information supplied by the HE calibration sheet. 10,000 litre storage tank capacity.

Type	Location used	Additional information
Potassium acetate (KAc) – 50% to SAE AMS 1435C	HE Area 4 - Roundhill and Southwick tunnels	
Potassium acetate (KAc) – 50%	Dartford River Crossing and tunnels	15g/m² to 30g/m²
Urea	Humber Bridge	
Urea	Tamar Bridge	
CMA (liquid and solid)	New Zealand Transport Agency	
Prior to 2004: Potassium formate (30 and 50%) and CMA (25% solution) **Since 2004: Sodium chloride (Brine and Pre-wetted salt)**	Storebælt East Bridge in Denmark	Various de-icing products have been in use since the opening in 1998: Treatments reverted to salt, because of cost and tests showing extended life of the galvanized objects on the bridge when using NaCl. Solid magnesium chloride ($MgCl_2$) pre-wetted with brine for road temperatures below -8°C and in case of compact snow or ice on the roadway. Spread 10 g/m² of MgCl2, and as the compact snow or ice can have a thickness which may result in refreezing of the roadway, also spread 20 g/m² prewetted NaCl both before and after the spreading of $MgCl_2$.

The current Transport Scotland requirements are that the Potassium Acetate must meet the Ministry of Defence Specification 68-118 (De-icing/Anti-Icing Fluid for Run Ways).

In addition to specification 68-118, the following standards and product approval schemes used by road operators, both in the UK and internationally, have been identified:

- SAE AMS 1435 (Liquid Runway Deicing/Anti-Icing Product)
- CEN/TS 16811-3 Other solid and liquid de-icing agents - Requirements and test methods
- Clear Roads Qualified Products List – various categories of de-icer covered including corrosion inhibited products

A summary of key requirements of these standards is shown in Table 2 and further details of the requirements from the Ministry of Defence Specification 68-118 are included in Appendix A.

Table 2: Summary of de-icer standard requirements

	68-118	AMS 1435	CEN/TS 16811-3	QPL
Freezing Point	Equivalent to 50% KAc	Equivalent to 50% KAc	Freezing curve must be supplied but no limits	N/A
Other de-icing tests	De-icing and holdover test	Ice melting (SHRP)	Ice melting	N/A
Corrosion	Selected metals and alloys	Selected metals and alloys	Steel and Aluminium - Classed as 1,2 or 3	NACE Standard TM0169-95 - Steel and Aluminium
Field testing	N/A	N/A	N/A	Field Data reviewed before approval

2.2 Spread rates and treatment guidelines

Potassium acetate spread rates used on the Transport Scotland and Highways England truck road network were reviewed and are summarised in Table 3. Also included are rates developed in the USA, Clear Roads (2015).

Peeling et al (2017) reviewed the types of alternative de-icer in use in the UK and worldwide, noting that alternative de-icers have been used as standalone treatments or in combination with sodium chloride (NaCl) treatments to lower the required spread rate of salt on the roads and therefore, reduce its harmful effects on infrastructure and the surrounding environment, in particular for temperatures below approximately -7°C.

The most detailed treatment guidelines and spread rate information applicable for the use of alternative de-icers to salt is available from the US. It is stated by Nixon and Devries (n.d.) that for a liquid spreading program to be successful, an agency must follow very specific policies and have knowledge of the current weather conditions including pavement temperature, dew points, wind speeds and general road conditions. Liquids are typically recommended for precautionary treatments when there is a lower risk of dilution from precipitation or melting snow and ice. When spreading as a liquid only treatment, anecdotal experience from the US has indicated that the hydroscopic characteristics of CaCl2 and MgCl2 can induce slipperiness under specific weather conditions and require careful consideration of application rates.

Key documents providing guidelines for winter maintenance in the US include the Federal Highway Administration (FHWA) 'Manual of Practice for an Effective Anti-icing Program' (US FHWA, 1996). The guidance is to spread liquids when temperatures are greater than -5°C; below this temperature, it is stated that liquids can be used at higher spread rates but the cost effectiveness will need to be assessed on a case by case basis.

Guidance in NCHRP 526 'Snow and Ice Control: Guidelines for materials and methods' by Blackburn et al. (2004) recommends that liquid-only precautionary treatments should not be used when temperatures fall below 20°F/ -6.7°C. Guidelines are provided for making treatment decisions based on the pavement temperature and dilution potential in the presence of precipitation.

Based on research, the use of $CaCl_2$, ABPs and $MgCl_2$ as liquids or for pre-wetting salt at cold temperatures can increase flexibility and resilience of treatment options and potentially reduce the amount of salt spread over time. However, detailed information is not currently available from the literature to quantify the spread rate reduction or effect on retreatment frequency resulting from the use of alternative de-icers.

NOTES FOR POTASSIUM ACETATE SPREAD RATES SUMMARISED IN Table 3

1. Transport Scotland rates 15.6 and 31.2ml/m² - based on 20 and 40g/m² (converted to ml using density of 1.28g/cm3)
2. Limited spread rate guidance is available in the literature for Potassium Acetate. Suppliers typically recommend 15-25ml/m² for anti-icing and at least 30ml/m² for de-icing (50% concentration). Lower rates recommended for the 65% concentration.
3. Operational guidelines from different countries provide spread rates and guidance for different combinations of precipitation type and rate, road surface temperature, surface state and traffic volumes. These have been summarised in Table 3 using the Transport Scotland precautionary treatment matrix as a common layout.
4. The Clear Roads (2015) rates are the result of the Clear Roads Study 'Establishing Effective Salt and Anti-icing Application Rates'. Solid and liquid Sodium Chloride rates were developed based on a survey of practitioners. Potassium Acetate rates in this study were calculated providing equivalent freezing point depression to the sodium chloride spread rates (using eutectic curve data)

Table 3: Summary of Potassium Acetate treatment rates

Road surface condition		Summary of Treatment Guidelines (converted to ml/m²)				
		50%				65%
		Current TS rates	HE Area 2*	HE Area 3*	Clear Roads (2015)	Forth Bridge – Supamix
RST lower than or equal to plus 1°C but higher than minus 2°C	Frost	15.6	13.8	15.4	24.7	7.1
	Wet					
RST lower than or equal to minus 2°C but higher than minus 5°C	Frost	31.2	13.8	15.4	27.6	7.1
	Wet					
RST lower than or equal to minus 5°C	Frost/Wet	31.2*	13.8	15.4	31.2 (to -11.7°C)	7.1
RST lower than or equal to plus 1°C but higher than minus 2°C following rain (see note 1)	Frost/Wet	31.2*	13.8	15.4		10.7

Road surface condition		Summary of Treatment Guidelines (converted to ml/m²)				
		50%				65%
		Current TS rates	HE Area 2*	HE Area 3*	Clear Roads (2015)	Forth Bridge – Supamix
RST lower than or equal to minus 2°C but higher than minus 5°C following rain (see note 1)	Frost/Wet	31.2*	13.8	15.4		10.7
RST lower than or equal to minus 5°C following rain (see note 1)	Frost/Wet	31.2*	13.8	15.4		10.7
Hoar Frost	Frost/Wet	Not specified				
Freezing Fog	Frost/Wet	Not specified				
Freezing Rain	Frost/Wet	31.2*	13.8 (successive)		32.9 (to -3.3°C)	17.9

Road surface condition		Summary of Treatment Guidelines (converted to ml/m²)				
		50%				65%
		Current TS rates	HE Area 2*	HE Area 3*	Clear Roads (2015)	Forth Bridge – Supamix
Snow Accumulations up to 30mm	Frost/ Wet	31.2*	2 x 13.8		30 (to -3.3°C) 42.3 (to -11.7°C)	8.6 (light snow)
Snow Accumulations over 30mm	Frost/Wet	31.2*	2 x 13.8		30 to -3.3°C) 42.3 (to -11.7°C)	17.9 (heavy snow)
Hard Packed Snow/Ice	Frost/Wet	See clearance matrix	20			Up to 10mm 17.9 (>-5°C) 25 (<-5°C) Over 10mm (40g dry salt)

* Minimum rate should be increased with manufacturer's recommendations

2.3 De-icer performance field trials and laboratory tests

2.3.1 De-icing performance

De-icer performance is typically assessed from testing of freezing point depression and ice melting capacity.

A review was carried out with regard to Potassium Acetate and other alternative de-icer performance from laboratory and field test results and assessment of comparative performance to Sodium Chloride.

The eutectic curve shows how the freezing point of the solution varies with de-icer concentration and is a useful indication of the effective temperatures on damp and wet roads and resilience of treatments to light rain and snow, that can dilute treatments.

The current specification requires the freezing point of diluted de-icer solutions to meet the following requirements dependent on the concentration of the de-icer solution:

- Freezing point of a solution comprising one part formulated product plus 4 parts water, -5°C
- Freezing point of a solution comprising 2 parts formulated product plus 3 parts water, -12°C

On a weight percentage basis, these requirements equate approximately to solutions comprising 25% to 50% by weight of de-icer as formulated.

Water thicknesses and amounts as classified in the current NWSRG spread rate guidance are:

- Damp roads 0.03 to 0.05mm (30 to 50 ml of water per m^2)
- Wet roads 0.05 to 0.1mm (50 to 100ml of water per m^2)

Based on these amounts of water, spreading with the typical spread rates of 15 to 30ml/m^2 will result in dilution of the de-icer to within the 25% (15ml spread on a damp road or 30ml spread on a wet road) to 50% (30ml spread on damp road) range.

For the identified non-chloride liquid de-icers and sodium chloride brine, Table 4 shows the freezing points of 25% and 50% solutions of the de-icer. These freezing points are taken from the literature for pure chemical solutions at the concentration specified and will be comparable to de-icing products available.

Table 4: Freezing point of liquid de-icers

De-icer type	Freezing point (^{o}C)	
	25% w/w	50% w/w
Sodium chloride Brine (22%)	-3.2	-6.9
Potassium acetate (50%)	-5.2	-17.2
Potassium acetate (35%)	-4	-9.1
Potassium formate	Similar to acetate up to 50% dilution	

WTI (2017) summarized non-chloride based de-icers available on the market, including acetate, formate, glycol, and succinate based de-icing products. KAc was found to produce more ice melt and to be effective at very low temperatures compared to chloride based products.

Xie et al. (2016) compared the ice-melting capacities of sodium chloride (NaCl) and KAc using SHRP ice melting test methods at about -25°F. The study found that KAc exhibited a higher melting capacity than NaCl. The volume of ice melt increased from 0.2 to 1.4 mL for KAc, whereas for NaCl ice melt only increased from 0 to 0.8 mL in 60 minutes. Similarly, Gerbino-Bevins (2011) compared the performance of KAc and NaCl using the Shaker Test and found that KAc melted about twice as much ice as NaCl at 20°F and almost three times as much at 10°F.

Testing carried out by the Danish Road Directorate and the airports in Billund and Aarhus compared the ice melting abilities of dry salt and solutions of CMA (25%), KFm (30%) and NaCl (22%). Results showed the melting capacity of all the de-icing agents is almost similar when they are spread as a solution, with significantly higher melting capacity of solid NaCl. Testing was over the temperature range from -1 ºC to -10 ºC and showed significantly reduced melting capacity by temperatures below -2 ºC to -3 ºC.

2.3.2 Corrosion impacts

Field trials showed that all Chloride containing families of de-icers have corrosive effects, to different degrees, on both steel and aluminium, with Magnesium Chloride having impact on the chemistry of concrete itself. In comparison, Potassium Acetate-based de-icers have considerably less corrosive effects than those containing Chloride.

Road salt is most clearly damaging to bridge decks. The chloride ions in salt penetrate concrete and cause reinforcing steel bars (rebar) to rust, resulting in cracking and fragmentation of the surrounding concrete.

Acetate based de-icers are known to be non-corrosive to mild steel compared to chloride based de-icers. WTI (2017) reported that acetates have been found to be as corrosive as chlorides to galvanized steel. In addition, KAc based de-icers can impact asphalt pavement through emulsification of the asphalt binder (Pan et al. 2008). In concrete pavements, KAc can induce alkali-silica reactivity (ASR) on susceptible aggregates (Shi et al. 2009) and in concrete (Balachandran et al. 2011; Bérubé et al. 2002; Math et al. 2011).

The focus of research on KAc has been concerning its impact on road surfaces and structures. While KAc is favoured above NaCl because it has reduced corrosive impacts to mild steel, concerns have been raised for the use of KAc compared to NaCl. For example, Xie et al. (2015) carried out a comparative study of field cores taken from bridge decks in Nebraska which had been exposed mostly to KAc and bridge decks from Utah which had been exposed mostly to NaCl. The results showed that the concrete cores from Nebraska with bridge decks exposed mostly to KAc had exhibited more significant degradation, highlighting the negative impact that KAc can have on concrete structures and components.

Xie et al. (2019) found that samples of concrete exposed to magnesium chloride in the laboratory with repeated freeze-and-thaw cycles lost more strength than samples exposed to rock salt while showing no visual signs of damage. It was conclude that nano-sized crystals form within concrete samples resulting in stress buildup and calcium leaching in the concrete, both of which significantly reduced its strength. Cores from about 10 Oregon bridge decks that had been treated annually with magnesium chloride showed a significant compromise in splitting tensile strength, which is a property that affects cracking resistance and load-bearing capacity, by as much as 50 percent. They also saw an up to 60 percent reduction in the concrete's micro-hardness. The worst effects often occurred half an inch to one inch inside the sample, instead of on the concrete surface, so were not detected by visual inspection.

Like the field trials for KAc, laboratory tests found that KAc was damaging to pavements. For example, Alatyppo and Valtonen (2007) conducted laboratory and field tests in Finland based on airport pavements to showcase that acetate-based de-icers such as KAc can decrease the durability of asphalt pavements. Based on the studies, the high density and low surface tension of de-icing chemical facilitates the penetration of these chemicals to the bitumen and aggregate interface. In addition, de-icers are highly hydroscopic causing the exposed pavement to stay wet which in turn makes pavements prone to moisture damage.

Long-term testing over 11 years was carried out by the operators of the Storebælt East Bridge in Denmark (Finn Bormlund, Personal Communication) on the impact of solutions of CMA, KFm and NaCl on hot-dip galvanized pieces of steel with bolted connections as used on the crass barrier on the bridge. The work pieces were placed outdoor with the same climatic conditions as at the bridge, and on working days throughout the whole winter season sprayed with NaCl in a 24% solution, CMA in a 25 % solution and KFm in a 30 % solution. It was concluded that 24 % NaCl solution compared to alternative de-icing agents is less aggressive to hot-dip galvanized workpieces than KFm, however neutral compared to CMA.

Monitoring of the Storebælt bridge condition has shown no impact on steel and concrete from chlorides. The bridge girder on the suspension bridge is steel and the girder on the West bridge is reinforced concrete. The bridge edge girder and crash barrier is cleaned by use of clean water every spring just after a winter season. A survey in 2016 (Finn Bormlund, Personal Communication) made a survey of the edge girder on the west bridge in order to evaluate whether it should be necessary to seal the concrete surface. The result showed no corrosion on the rebars or chloride problems

2.3.3 Environmental impacts

Chloride and sodium (from sodium chloride (NaCl), or magnesium chloride (MgCl2), or calcium chloride (CaCl2)) can accumulate over time, potentially to levels posing risks to human health, water quality, aquatic flora and fauna, as well as the near road environment. The alternative non-chloride de-icers do not accumulate in the environment but exert a higher BOD as they are broken down in the environment, and some of these products are toxic to aquatic species.

3 Impacts of de-icers on highway structures

The following section reviews the direct and indirect impact of de-icers to major structures such as bridge and tunnels, vehicles and environment, etc. Literature reviews are also carried out to estimate the cost in order to monetise the impact.

3.1 Bridge Components

Corrosion is one of the biggest controllable factors that can affect major structures on highways, for example, bridges and tunnels. Corrosion can affect the structural integrity of bridges and tunnels in the form of gradual chemical erosion of metal, and it is estimated that 95% of structural damage on bridges can be traced back to some form of corrosion. The most common forms of deterioration are cracking, scaling and spalling. Salt has a long-term impact on metal part of bridges, concrete decks, utilities under the bridge and rebar, etc. Corrosion affects the structural integrity of bridges in five critical ways:

- Reduces the strength of individual structural elements - corrosion lowers the effective cross section of structural components, and this makes them perform in unexpected and unintended ways when stressed, leading to the partial or complete failure of individual elements, potentially weakening the overall structure.
- Lowered functional capacity - Corrosion can reduce the effective cross-sectional area of major bridge components, including beams and columns. This often reduces the shear capacity of individual sections and the ability to interact with sections connected to them. This leads to friction, vibration, and concussive action that the overall structure may not be able to sustain over time.
- Increased fatigue and reduced fatigue strength - Corrosion can impact the fatigue strength of steel components and connections. This is also known to accelerate cracking and pitting, which is often concentrated in certain areas.
- Decreased bond strength - The capacity of elements built from composite materials is dependent on how the concrete and rebar interact. Steel expands when it corrodes, this often weakens structural components, which can contribute to failure.
- Diminished ductility - Corrosion lowers the ability of metal sections of bridges to bend and twist. Maintaining this integrity is critical, especially in areas that experience earthquakes, shifting traffic loads, or extreme weather, especially winds.

The safety and durability of bridges designed from weathering steels are conditioned by the development of a sufficiently protective layer of corrosion products. Air pollution, microclimate around the bridge, time of wetness, structural solution of the bridge, and the position and orientation of the surface within the bridge structure all influence the development of protective layers on the surface of the weathering steel.

3.2 Concrete and Highway Structures

Concrete is a composite of stone and sand held together in a matrix of porous hydrated cement paste. Concrete is important for many parts of roads and also for bridges. In typical infrastructure application the concrete is structurally reinforced with a mesh of steel reinforcement bars (rebar), examples include bridge decks, support columns, joints, stringers, parking garages and drainage systems. Winter conditions and application of chloride based de-icing chemicals negatively affect concrete structures by deterioration of the concrete paste and corrosion of steel reinforcing bars. These impacts occur through the following processes.

- Freeze-thaw cycles: The expansive forces of freezing water in the cement pores causes surface scaling, the successive peeling of the surface layer, exposing the aggregate and allowing further penetration of the corrosive media.
- Depacification and pH reduction: Depacification refers to the breakdown of the passive layer of ferrous oxide that forms on the surface of steel rebar under alkaline environments.
- Corrosion cell development: Variations within the chemical makeup of rebar or in the structure of concrete promote the development or corrosion cells within the reinforcing steel.
- Delamination and spalling: As the steel rebar corrodes, the products of corrosion (rust) can occupy 2 - 13 times the volume of the original steel. The tensile forces exerted on the concrete structure is large enough to cause delaminating of the concrete and ultimately concrete spalling – the loss of large chunks of concrete from the structure.

3.3 Drainage

A proportion of the salt spread on to road surfaces is transported through drainage and storm sewage systems that consist of reinforced concrete culverts, metal pipes, grates, manhole covers, curbs and gutters. These drainage systems account for approximately 10% of highway construction and maintenance and their performance is essential for proper operation and safety. Studies by numerous state highway departments have concluded that road salt can influence corrosion of highway drainage systems, although other factors such as soil type, water alkalinity, traffic stress, vibration, silting, road settlement, and water abrasion play a greater role in maintenance and replacement cost.

3.4 Roadside Fixtures

Signposts, light columns, traffic signal circuitry, retaining walls, guardrails and noise barriers that are exposed to runoff, splash or traffic spray are vulnerable to damage from road salt. Replacement and maintenance of these fixtures can come at a considerable expense. Precautionary steps are now taken during installation of highway fixtures that greatly reduces corrosion rate. Wiring and fences are constructed of galvanized steel and light and signposts are supported by aluminium alloy tubing anchored with stainless steel bolts and guard rails are being constructed from galvanized steel or painted with a zinc rich primer.

3.5 Cost

Costs associated with bridges are related to maintenance and replacement costs associated with bridge damage. These costs include small routine maintenance regime cost and very large replacement cost for a part or even complete rebuild of the bridge. It has been concluded that the two biggest factors affecting the lifespan of bridges are time and how much chloride is used on them. Good design and maintenance can slow the effects of time on structures. Sound engineering coupled with leveraging-proven preventative measures can help avoid corrosive damage.

In the UK, it has been reported that from nearly 200 councils across England, Wales and Scotland that responded to the survey, out of a total 71,652 bridges, 3,177 (4.4% of the total) are classified as 'substandard' condition. Substandard is defined as being unable to carry the heaviest vehicles now seen on UK roads, including lorries of up to 44 tonnes. It is estimated that the one-off cost of clearing the total maintenance backlog council-managed road bridges in Great Britain has increased by 30%. From bridge experts it is estimated that 95% structural damage on bridges can be traced back to some form of corrosion. The most common forms of deterioration are cracking, scaling and spalling. However, budget restrictions mean they anticipate that only 343 of these will have the necessary work carried out on them within the next five years. It is estimated that it will cost the Government around £1.12bn to bring all the substandard bridges back up to perfect condition.

Stefan estimated the cost of spreading the salt (labour and equipment) at $150/ton (£201.65/ton cost in 2008). The past research from Transportation Research Board (TRB) study stated that state spending on de-icing chemicals and abrasives for snow and ice control makes up 20 to 30 % of the total costs. The remaining costs are labour (40%) and equipment (30%). Using a weighted average of $73/ton (£94.10/ton) spent on road salt in the TCMA as 30% of total costs, total costs would be $243/ton (£309.10/ton). At 40%, labour costs would be $97/ton (£120.10/ton) and at 30%, equipment costs would be $73/ton (£94.10/ton), giving a labour plus equipment subtotal of $170/ton (£215.09/ton). Using the more conservative value of $150/ton (£188.20/ton) for labour and equipment and TCMA salt use of 349,000 tons/year annual TCMA costs for labour and equipment are estimated at $52 million (£70 million).

Costs associated with infrastructure are based on damage to infrastructure and maintenance and replacement costs associated with this damage. A study by economist Vitaliano included an estimate of expenditures of an additional $332/ton (£430/ton) of salt per season for bridge maintenance. One ton of road salt results in $1,460 in corrosion damage to bridges, and indirect costs may be much higher (Sohanghpurwala, 2008).

In 1992 the NYSDOT increased its bridge painting budget from $10.3 million to $33.3 million with the expressed intent of combating corrosion. The TRB performed a rough calculation to estimate the nation-wide cost of repairing bridge decks damaged by salt over a 10 year period beginning in 1991. Using data from the National Bridge Inventory they estimated 7000 decks would need rehabilitation, with 300 to 700 needing repair each year. Using the average bridge size and the average rehabilitation cost (cost data taken from NYS DOT), the TBR estimated that nation-wide bridge repair costs would range from $50 million to $200 million per year over the projected 10-year period. The authors admit that future repair will be less severe due to advances in corrosion protection.

Dindorf C and Fortin C (2014) provided estimates of the cost of damage to the environment, vehicles and infrastructure caused by road salt. These have been converted to pounds sterling as shown in Table 5.

Table 5: Estimates of the cost of damage to the environment, vehicles and infrastructure caused by road salt

Cost Reference	Vehicle Corrosion	Road Maintenance	Tree Damage	Infrastructure Damage	Ecosystem Damage
Stefan et al. 2008		£645.00			
TRB 1991					
Sohanghpurwala 2008				£1,537.99	
Murray and Ernst 1976					
Murray and Brenner					
Adirondack Council 2009	£47.96	£810.00	£148.66		
Vitaliano 1992	£183.49				
Kelting and Laxson 2010*					£173-227.37

4 De-icing performance requirements

The literature was reviewed to identify any problematic conditions associated with winter service of carriageways on structures and the implications for treatment requirements.

Weather station data and treatment records were analysed for selected structures on the Transport Scotland network for the 2017/18, 2018/19 and 2019/20 winter seasons to assess the operating conditions where treatments have been carried out, and any implication for the required performance of the treatment methods used. The analysis was based on the surface temperature, amount of water on the road, and amount of precipitation during the periods where treatments were required to be effective.

Figure 1 and Figure 2 show the number of nights that occurred for different minimum road surface temperature and road condition.

Because of their increased exposure to air, the surface temperature of bridge decks usually tracks air temperature more closely than do the adjacent roadway sections and can show an accelerated rate of heat loss. When precipitation occurs, this condition often leads to icing of bridge decks while the adjacent roadway remains wet. This can be more common in early and late season.

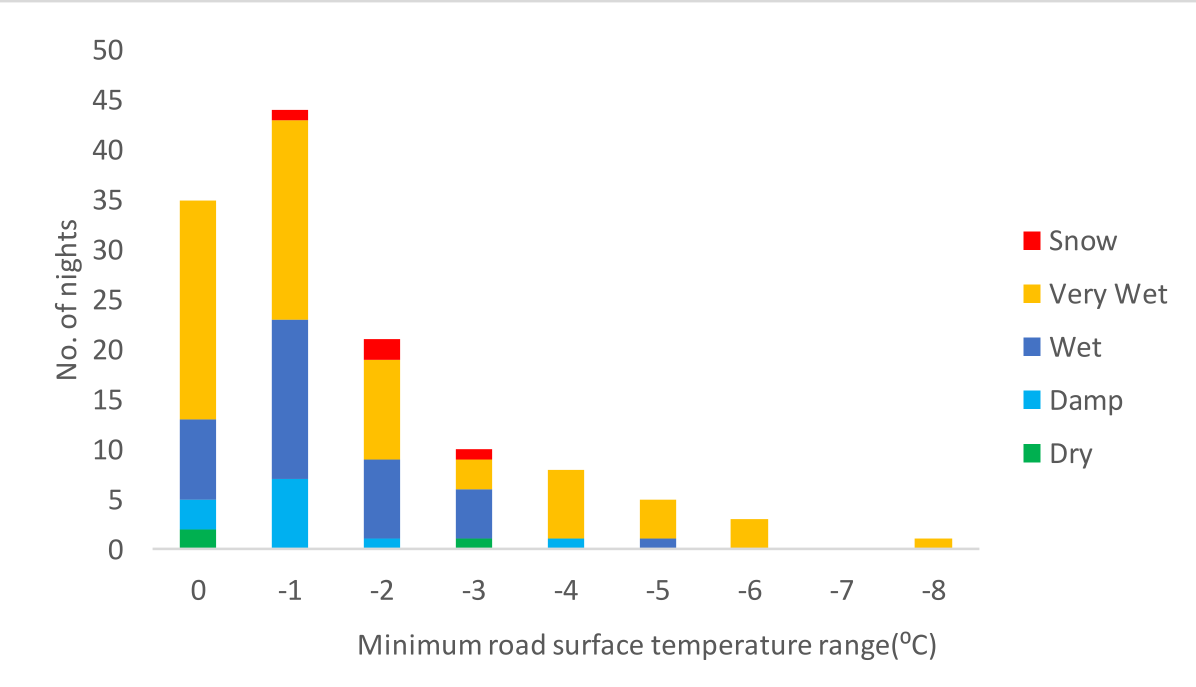

Figure 1: Summary of minimum RST and road condition on Forth Bridge for last three winter seasons

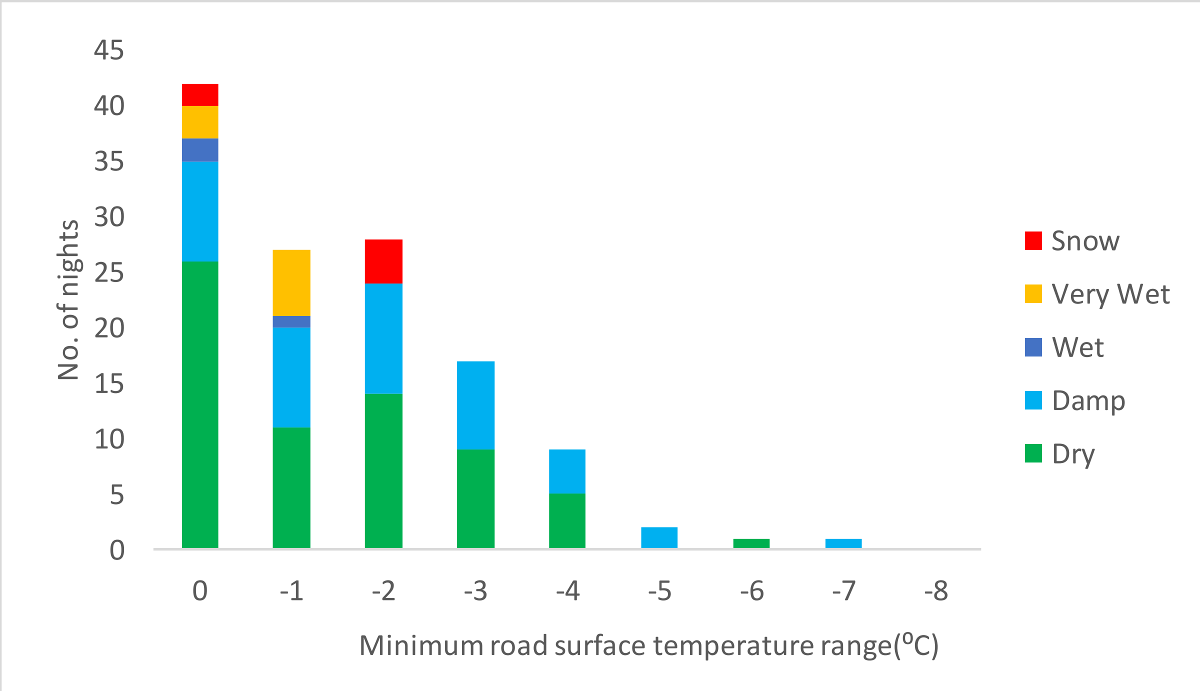

Figure 2: Summary of minimum RST and road condition on Kessock Bridge for last three winter seasons

5 Discussion of requirements

It is essential that any de-icer must meet certain specifications and performance criteria to ensure the usability of the de-icing products.

The current Transport Scotland requirements state that the Potassium Acetate product used must meet the Ministry of Defence Specification 68-118 (De-icing/Anti-Icing Fluid for Runways).

With reference to the information detailed in this review, this section discusses the necessary de-icing, corrosion and environmental requirements for effective treatments on bridges and structures and appraisal of the current performance requirements.

5.1 General requirements

The current requirements state that the material shall be a homogeneous fluid, free from deposit, suspended matter and other visible impurities.

It is also required to disclose, in confidence, details of the formulation used in manufacture and the method of manufacture. No changes to formulation, ingredients, method of manufacture or other agreed special requirements shall be made without the written consent of the Customer.

These are important requirements to retain, as it is essential for accurate spreading of correct amounts of de-icer that the concentration and physical properties of the liquid remain consistent. Impurities and other trace compounds may be detrimental to vehicles, assets and the environment.

5.2 De-icing performance

Weather and road conditions encountered on bridges in the UK are not typically extreme cold temperature scenarios, in which KAc and other alternative de-icers have advantages due to the improved low temperature ice melting performance and increased depression of freezing point. Large amounts of snowfall also typically occur in temperature ranges where NaCl has a more comparable ice melting performance and the road can be kept accessible.

As shown in Section 4, the majority of treatments typically occur for minimum road surface temperatures above -2^{o}C.

It is considered that current treatment guidelines specified for pre-wetted salt, and also spread rates demonstrated to be effective for brine and high brine-share spreading in Transport Scotland trials, will also be effective for treatments on bridges, but also have the same limitations for brine only spreading on wetter roads and during snow.

Where it is necessary to avoid spreading of sodium chloride on a structure, the 50% potassium acetate and formate solutions provide the lowest freezing point depression for the liquid de-icers across the range of dilution, and greater resilience to dilution from precipitation.

The review of literature and operational feedback, including weather station records on the Forth and Kessock bridges, has identified that the current spread rates for 50% KAc are providing effective treatments under the range of UK conditions. These de-icers can provide a complete solution for de-icing a structure i.e. a de-icing solution to cover the full range of conditions without reverting to salt or other solid de-icers.

For pre-cautionary treatments on damp surfaces or before frost, it is considered that the 50% potassium acetate and formate products currently used offer a significantly higher level of freezing point protection than required in UK conditions.

For these typical precautionary treatments, that will cover the majority of the required treatments, all of the other de-icer types covered in this review will also provide effective freezing point when spread at reasonable rates i.e. 15ml/m^2 for damp or frost, 30ml/m^2 on wetter roads or low temperatures below -5^{o}C.

Treatments with Sodium chloride brine, lower concentration potassium acetate and formate (to 30% concentration) and CMA (to 25% concentration) can provide good performance on damp roads and frost across the range of temperatures experienced on UK bridges and have been used successfully in operational practice.

Operational feedback from the review has highlighted that in heavy snowfall compacted snow can form with the lower concentration liquid de-icers and sodium chloride brine. Acetate and formate based products have been shown in laboratory testing to have similar ice melting performance, melting ice more quickly than sodium chloride and glycol based de-icers.

Freezing point depression can become limited to below -5^{o}C on wet roads and when diluted from precipitation or melting of snow/ice. On wet roads to 0.1mm water thickness (the upper limit of wetness for current NWSRG spread rate guidelines), spreading of 30ml/m^2 of de-icer will typically result in dilution to around 25% of the original de-icer formulation concentration. The difference between the freezing point depression between different de-icers reduces at this level of dilution, shown to be in the range from -3^{o}C (sodium chloride brine, CMA) to -5^{o}C (50% potassium acetate and formate)

The performance of de-icers will depend on the chemical properties of the de-icer, including if spread as a solid or liquid, but also the maintenance approach adopted. A key factor for treatment effectiveness is the repeat treatment frequency, or ‘cycle time’ between treatments, whether this is spreading of de-icer and/or ploughing. Treatments that have become diluted such that the road surface temperature is below the freezing point of the de-icer solution can still offer protection, as time is required for sufficient ice to form to impact the skid resistance. The repeat time required will depend on the degree of dilution and temperature difference between freezing point and road surface temperature. Similarly where the de-icer solution is providing a debonding layer below snow, repeat ploughing must be carried out before this layer freezes sufficiently to cause bonding of the snow to the road surface. Definitive and/or precise recommendations in this regard are difficult. Key varying factors that will influence treatment effectiveness during precipitation include precipitation type, intensity and amount, snow wetness, effectiveness of ploughing and cycle time and temperature (low point and variation with time).

There will be wider scope for choice of de-icers with lower effective temperatures where:

- Resources are in place for reduced treatment and ploughing cycle times i.e. 2 hours or less

- Operators have capability to switch between different de-icers on a day by day basis – e.g. reverting to salt or other solid de-icers in more severe conditions

Other factors to consider for treatment performance will be around longevity of treatments, particularly in prolonged drier, frost conditions. Based on comments from operators using Potassium Acetate, it is likely to offer advantages in terms of de-icing performance from greater longevity and eliminating the need for (or reduced top up rates) repeated de-icing and anti-icing treatments, however detailed information is not currently available from the literature to quantify the spread rate reduction or effect on retreatment frequency.

5.3 Corrosion and environmental requirements

It is apparent that controlling corrosion is one of the top threats to bridges and an important long-term contributary factor regarding reinstallation and replacement cost.

There are many ways to manage the threat of corrosion to bridges, in addition to the use of non-corrosive de-icer alternatives. Some of the important de-icer and bridge construction and maintenance issues are discussed in this section, and an indicative cost comparison presented for the use of non-corrosive de-icers

5.3.1 De-icer types

Section 3 of this review has highlighted the possible damages caused by salt and other de-icers, such as corrosion to reinforcing steel bar (rebar) in concrete structures, effects on concrete itself, structural steel, and roadside structures. Acetates and formates are generally considered non corrosive to highways materials, although there have been some reports of the corrosive effect of acetates and formates on galvanised steel as they react slowly with zinc (for example effecting crash barriers).

Table 6 provides a summary of the infrastructure and environmental effects. De-icing products can include corrosion inhibitors mitigating some of the effects, and it is important to obtain corrosion test data for the product being supplied.

The effects of sodium chloride can also be mitigated by optimising the use of salt, through use of appropriate spread rates. Spreading of pre-wetted salt (FS 30 and higher brine share) and also the use of brine only spreading can reduce the total salt load to the bridge and surrounding environment.

Table 6: De-icer infrastructure and environmental impacts

De-icer	Infrastructure	Environment
Sodium chloride	Corrosive to steel, aluminium, reinforced concrete	Harms vegetation, relatively low impact on water quality.
De-icers containing ABP	Similar to sodium chloride, potentially less corrosion of spreaders and street furniture	Similar to sodium chloride.
Calcium chloride	Corrosive to steel, aluminium and reinforced concrete	Damages vegetation, relatively low impact on water quality
Magnesium chloride	Corrosive to steel and aluminium, damages weak concretes	Damages vegetation, relatively low impact on water quality
Calcium magnesium acetate	Non-corrosive to most metals, moderately corrosive to galvanised steel	Benign – least harmful de-icer
Potassium acetate/formate	Non-corrosive to most metals, moderately corrosive to galvanised steel	Potassium formate slightly lower BOD than potassium acetate so less impact on water quality
Ethylene glycol	Non corrosive	High BOD and COD so damages water systems, toxic to mammals
Propylene glycol	Non corrosive	High BOD (higher than ethylene glycol) and COD, damages water systems
Urea	Non-corrosive	High BOD and COD, damages water courses by releasing ammonia and nitrates to water courses, toxic to aquatic life

NOTES:

Factors highlighted in red are high impact

Factors highlighted in green are low impact

BOD is biological oxygen demand and COD is chemical oxygen demand

5.3.2 *Corrosion tests*

As highlighted in Section 2.1, there are several de-icer standards available which specify various different laboratory corrosion tests. Relating laboratory tests to performance in the field is not a straightforward matter and will depend on the particular conditions and exposure of the bridge at each location.

There is a wide range of materials used in the construction of highway structures, but by far the most commonly used are concrete and steel (including galvanised coatings). Therefore, where corrosion is an issue, the focus of testing should be on these materials.

The approach taken in the CEN Technical Specification PD CEN/TS 16811-3:2015 is considered a suitable approach for assessing de-icers for bridge applications where corrosion performance is a requirement. This specification classes de-icers as Low, Average or Strong degree of corrosion based on testing of three reference materials:

- the non-alloy steel standard quality (S355 and S450) as defined in EN 10025-2 and -5;
- the non-alloy steel standard quality (S355 and S450) as defined in EN 10025-2 and -5, having received a galvanizing according to EN ISO 1461;
- the aluminium standard quality [EN AW 5754] according to EN 573-1, EN 573-2, EN 573-3 and EN 573-5.

The test standard describes a method for determination of corrosiveness by immersion/emersion of metal references in a liquid used as de-icing agent on roads. This test standard is an application of EN ISO 11130 on de-icing agents.

Where other particular materials are known to form critical aspects of the bridge structure, further specific tests might be specified.

5.3.3 *Assessment of bridge corrosion risk factors and mitigation*

Damage from application of de-icers, principally chloride based de-icers, is a significant risk to highway structures, through corrosion and deterioration of steel and concrete.

The most serious issue is corrosion of the bridge structure, i.e. bridge decks, superstructure and substructure. Signposts, light columns, traffic signal circuitry, retaining walls, guardrails and noise barriers that are exposed to runoff, splash or traffic spray are also vulnerable to damage from road salt.

This review has identified that bridges can be treated effectively with chloride de-icers without significant adverse effect, but this will critically depend on the construction, protection measures and maintenance practices followed. Modern standards and protection measures have improved significantly mitigating the risk of impacts from de-icing treatments.

The key factors impacting the bridge susceptibility are discussed below:

Bridge deck waterproofing

The effective waterproofing of bridge decks is essential to enhance the durability and longevity of the life of bridge. This prevents the ingress of water, road de-icing salts, and aggressive chemicals which would corrode the steel reinforcing bars in the concrete.

Requirements for the waterproofing and surfacing of concrete decks of highway bridges is provided in the Design Manual for Roads and Bridges section CD 358.

Drainage

Drainage systems that push water away from vulnerable metal parts like abutments and girders will help mitigate impacts. Many older bridges were built with systems that have end joints allowing water to spill directly onto girders.

It is important that drainage systems are regularly inspected and maintained to ensure water and corrosive chemicals are moved away from the structure.

Removal of silt and debris from kerb channels and drains will prevent blockages and subsequent collection or pooling of potentially corrosive water.

Structure Inspection

Inspecting bridges regularly, looking for initial signs of corrosive damage, can help prevent more costly repairs in the future. Safe and flexible lifts make it easier to access hard-to-reach sections of bridges that are often most vulnerable to corrosion

Inspections should not be limited to primary structural elements. Also, check things like the utility infrastructure suspended under bridges. Hangers and seals are often affected by corrosive substances.

Engineering Design

Bridge designs that eliminate or move the joint between the bridge and roadway off the main structure will mitigate risk from de-icer. Joints are the primary way chloride solutions seep into abutments. Placing them on the ends of bridges allows water and chloride solutions to drain away from vulnerable metal components.

Maintenance

Repairing cracks and potholes as soon as they happen will help prevent corrosive fluids from penetrating the roadbed and damaging the substructure below.

The washing down of bridge edge girders and crash barriers after a winter season is carried out by several operators, for example the Storebaelt bridge in Denmark.

Alternative Engineering Materials

Application of epoxy coating to the rebar embedded in concrete beams and pillars. This may not completely stop the corrosion process, but it will slow it considerably.

Use of less permeable concrete when building new structures and making repairs. It can help prevent water and chloride solutions reaching metal substructures.

Application of a sealer membrane between the deck and upper driving surface prevents seepage and pooling of corrosive solutions on and around vulnerable metal parts.

Salt application method

Accurate spreading of salt through pre-wetted or brine only treatments will minimise the amount of salt being spread directly onto the surrounding bridge structure.

5.3.4 Cost benefit comparison of use of potassium acetate and salt

An analysis was carried out to provide an indicative assessment of the costs and benefits of the current approach using potassium acetate de-icer i.e. "What are the costs and benefits of adopting acetate and how much benefit we can gain (based on a certain level of assumptions)?"

The cost for a treatment across all the bridges currently treated with potassium acetate is shown in Table 7 highlighting the higher cost for acetate spreading.

In calculating the costs, the following de-icer costs were used:

- Pre-wetted salt: £30/tonne
- Potassium acetate £600/tonne

The pre-wetted salt cost is the cost per tonne of pre-wetted salt as spread on the road, comprising rock salt for the dry salt component and white salt and water for the brine.

Table 7: Estimated cost per treatment

Length of Treatment	24000	m
Length of Treatment	24	km
Average Width	7.5	m
Area of Treatment (m^2)	180000	m^2
Estimated Cost (Pre-wetted salt,20g/m^2)	**£106**	**per treatment**
Estimated Cost (Potassium acetate,15.6ml/m^2)	**£2,113**	**per treatment**

Table 8 provides estimates of total de-icer cost for treatments over a winter season, based on assumptions for different numbers of treatments in different severity of winter.

Table 8. Estimated no. of treatments

Winter Severity	No of Treatments	Total Cost Pre-wetted salt	Total Cost Acetate
Mild	60	£6,360	£126,780
Average	90	£9,540	£190,170
Severe	120	£12,720	£223,978

The use of acetate would incur an additional cost in the order of £100,000 to £200,000 per winter season, based on this simple analysis.

Based on the cost information reviewed in Section 3.5, some costs for the impacts of salt spreading were estimated. As some of the values have been a historical value and from studies in the US, these rates are converted to currency in the UK and an inflation rate has been adopted to convert the rate to current rate. The higher range of value and a lower range of values are estimated separately from different literature sources shown in Table 9.

Table 9. Impact cost of damage from salt (£/tonne of salt)

	Vehicle Corrosion	Road Maintenance	Tree Damage	Bridge Damage	Ecosystem Damage	Total Cost
Low Estimate	£47.96	£645.00	£148.66	£1,537.99	£173	£2,552.61
High Estimate	£183.49	£810.00	£148.66	£1,537.99	£227.37	£2,907.51

The real cost will include the actual cost (the cost related to the material, labours) and the impact cost (the direct and indirect impact cost that is transformed into the monetary values).

A comparison was made, based on the average winter severity number of treatments, between the real cost of treatments with salt and potassium acetate. Comparison was made based on a range of acetate performance benefit, from equivalent damage to salt to no damage cost. Only the bridge damage impact costs were included from Table 9. As shown in Table 10, the acetate starts to gain positive benefit if its reduction of damage cost can reach 50% of the salt damage cost.

The use of potassium acetate requires a significant additional de-icer cost, however this analysis may indicate that the overall resulting cost benefit may be positive from the reduction in damage costs.

It should be noted that although cost-benefit analysis is a relatively straightforward tool for deciding whether to use a product, the cost rates are based on assumptions and are difficult to monetise.

Table 10. Comparison of real costs for salt and potassium acetate

Performance	Salt Real Cost	Acetate Damage Cost	Acetate Real Cost	Difference	Benefit Gain
0	£363,339	£353,799	£543,969	£180,630	-£180,630
10%	£363,339	£318,419	£508,589	£145,250	-£145,250
20%	£363,339	£283,039	£473,209	£109,870	-£109,870
30%	£363,339	£247,659	£437,829	£74,490	-£74,490
40%	£363,339	£212,280	£402,450	£39,110	-£39,110
50%	£363,339	£176,900	£367,070	£3,730	-£3,730
60%	£363,339	£141,520	£331,690	-£31,650	£31,650
70%	£363,339	£106,140	£296,310	-£67,029	£67,029
80%	£363,339	£70,760	£260,930	-£102,409	£102,409
90%	£363,339	£35,380	£225,550	-£137,789	£137,789
100%	£363,339	£0	£190,170	-£173,169	£173,169

6 Conclusions

- Alternative de-icers to salt are used on corrosion sensitive structures in the UK and worldwide, but special arrangements and non-corrosive de-icers are not always specified for winter service.
- The review has identified a range of solid and liquid de-icers applied for bridge treatments. Treatments with sodium chloride brine and pre-wetted salt are used on many structures, including major suspension and cable stayed bridges, with reliance on protection techniques and construction to prevent corrosion.
- The current spread rates for 50% potassium acetate are providing effective treatments under the range of UK conditions. These de-icers can provide a complete solution for de-icing a structure i.e. a de-icing solution to cover the full range of conditions without reverting to salt or other solid de-icers.
- For pre-cautionary treatments on damp surfaces or before frost, it is considered that the 50% potassium acetate products currently used offer a significantly higher level of freezing point protection than required in UK conditions.
- Treatments with sodium chloride brine, lower concentration (to 30% concentration) potassium acetate and formate, and CMA (to 25% concentration) can provide good performance on damp roads and frost across the range of temperatures experienced on UK bridges.
- There will be wider scope for choice of de-icers with lower effective temperatures where:
    - Resources are in place for reduced treatment and ploughing cycle times i.e. 2 hours or less
    - Operators have capability to switch between different de-icers on a day-by-day basis – e.g. reverting to salt or other solid de-icers in more severe conditions
- Where alternatives to salt are used, the choice of any de-icer and application (spread rates, spreader performance etc.) should provide equivalent or better performance to treatments with salt carried out in accordance with accepted treatment guidelines e.g. the NWSRG Practical Guide section 'Spread rates for precautionary salting'.
- This review has identified that bridges can be treated effectively with chloride de-icers without significant adverse effect, but this will critically depend on the construction, protection measures and maintenance practices followed. Modern standards and protection measures have improved significantly mitigating the risk of impacts from de-icing treatments.
- The use of potassium acetate requires a significant additional de-icer cost, however this analysis may indicate that the overall resulting cost-benefit may be positive from the reduction in damage costs.

References

World Road Association (2018). Snow and Ice Databook.

World Road Association (2019). International development of application methods of de-icing chemicals - state of the art and best practice

United States Federal Highway Administration (US FHWA) (1996). Manual of practice for an effective anti-icing program: A guide for highway winter maintenance personnel.

Xie N, Dang Y, Shi X (2019). New insights into how MgCl2 deteriorates Portland cement concrete. Cement and Concrete Research, 2019; 120: 244 DOI: 10.1016/j.cemconres.2019.03.026

Ministry of Defence Standard 68-118 (2002). De-icing/Anti-Icing Fluid for Runways

Zhang J, Das D, Peterson R, Goering D (2007). Comprehensive Evaluation of Bridge Anti-icing Technologies – Final Report. Department of Mechanical Engineering, University of Alaska Fairbanks.

New Zealand Transport Agency (NZTA) (2012). Appendix D – CMA Best Practice Guideline.

Booth C, Jordan R, Evans, M (2011). Review of corrosion inhibitors and their benefits to the Highways Agency, Published Project Report PPR927, Wokingham, Berkshire: Transport Research Laboratory (TRL).

Walker R (2010a). De-icing Materials and Corrosion – Laboratory Testing Report.

Walker R (2010b). De-icing Materials and Corrosion – Site Trial.

SAE AMS 1435 (Liquid Runway Deicing/Anti-Icing Product)

CEN/TS 16811-3 Other solid and liquid de-icing agents - Requirements and test methods

Clear Roads (2015). Establishing Effective Salt and Anti-icing Application Rates. Task 2: Update Guidelines. Blackburn and Associates.

Peeling J and Evans M (2017). A review of recent research and operational experience in the use of alternative de-icers. CLIENT PROJECT REPORT CPR2386. Wokingham, Berkshire: Transport Research Laboratory (TRL).

United States Federal Highway Administration (US FHWA) (1996). "Manual of practice for an effective anti-icing program: A guide for highway winter maintenance personnel.

Blackburn RR, Bauer KM, Amsler Sr. DE, Boselly SE and McElroy AD (2004). "NCHRP Report 526 – Snow and Ice Control: Guidelines for Materials and Methods", Transportation Research Board, Washington D.C.

The Western Transportation Institute (2017). TRS1706 Field Usage of Alternative Deicers for Snow and Ice Control. Minnesota Department of Transportation.

Xie N (2016). Impacts of Potassium Acetate and Sodium-Chloride Deicers on Concrete. Journal of Materials in Civil Engineering: 04016229.

Evans M (2019). Trials of Brine Spreading Performance on Scotland's Roads: 2018-19, *Published Project Report PPR927*, Wokingham, Berkshire: Transport Research Laboratory (TRL).

NWSRG (2019a). Spread rates for Precautionary Salting.

NWSRG (2019b). Treatments for Snow and Ice.

Appendix A Specification 68-118 (De-icing/Anti-Icing Fluid for Run Ways)

Table A1: Summary of the requirements from Specification 68-118

Requirement	Assessment methods
The material shall be a homogeneous fluid, free from deposit, suspended matter and other visible impurities.	Submit evidence that the material complies (not specified in more detail)
Meet specified test requirements	Detailed in Table A2.
Disclose in confidence, to the Customer, details of the formulation used in manufacture and the method of manufacture. No changes to formulation, ingredients, method of manufacture or other agreed special requirements shall be made without the written consent of the Customer.	
Submit evidence, in the form of certification by the Original Equipment Manufacturer (OEM) that the solution is approved by the OEM for use in conjunction with specific aircraft. **Submit evidence of all airfield trials.**	Not relevant for roads use

Table A2: Test requirements for samples taken from the supplied de-icer

Table 1 Test Requirements

Test	**Property, Units**	**Requirement**	**Method of Test**
1	Appearance	See clause **5**	Visual examination
2	Particulate matter retained on a grade P40 sinter, % (m/v)	0.01 max	(see **ANNEX A**)
3	pH value of a solution comprising one part formulated product plus 9 parts water	9.0 max 6.0 min	pH meter with glass indicator electrode
4	Flash-point (Pensky-Martens), °C	65 min	BS EN 22719 Part 404

5	Depression of freezing point : Freezing point of a solution comprising one part formulated product plus 4 parts water, °C Freezing point of a solution comprising 2 parts formulated product plus 3 parts water, °C	-5 max -12 max	ASTM D1177
6	Corrosivity towards selected metals and alloys : Loss in weight per panel, mg Gain in weight per panel, mg Visible	5.0 max 1.0 max No adherent corrosion deposits, etching or pitting of the surface when viewed at a magnification of x10	(see **ANNEX B**)
7	Corrosivity towards magnesium alloys : Loss in weight per panel, mg Visible	5.0 max No pitting or etching of the surfaces when viewed at a magnification of x10	(see **ANNEX C**)
8	Crazing of polymethylmethacrylate	No crazing	(see **ANNEX D**)
9	Effect on paint films	No penetration of the top coat	(see **ANNEX E**)
10	Effect on rubber : Volume Change, % Mass Change, % Visible	5 max 5 max No visible deterioration	(see **ANNEX F**)
11	Effect on composite materials : Loss in interlaminar shear strength, % Visual appearance of composite and fluid	7.0 max No change	(see **ANNEX G**)
12	Apparent Viscosity, mPa s : at 0 °C, at -15 °C	120 max 350 max	(see **ANNEX H**)
13	De-icing, %	>80 de-icing, 30 min after application	(see **ANNEX J**)
14	Holdover, %	≥80	(see **ANNEX J**)

Effective Winter Service Treatments on Major Structures

A review was undertaken to understand the basis of the current and any future specification for treatments on structures, applicable to Transport Scotland requirements but also to inform future guidance issued by the National Winter Service Research Group (NWSRG). The review has identified a range of solid and liquid de-icers applied for bridge treatments and corrosion sensitive structures in the UK and worldwide, but special arrangements and non-corrosive de-icers are not always specified for winter service. The review has identified that treatments with sodium chloride brine and salt are used on many structures, including major suspension and cable stayed bridges, without significant adverse effect with reliance on protection techniques and construction to prevent corrosion. This will critically depend on the construction, protection measures and maintenance practices followed. Modern standards and protection measures have improved significantly, mitigating the risk of impacts from de-icing treatments, and key factors impacting the bridge susceptibility are identified in the review. A comparison was made between the real cost of treatments with salt and potassium acetate. The analysis indicated that acetate starts to gain positive benefit if its reduction of damage cost can reach 50% of the salt damage cost. The use of potassium acetate requires a significant additional de-icer cost; however, this analysis may indicate that the overall resulting cost - benefit may be positive from the reduction in damage costs.

TRL
Crowthorne House, Nine Mile Ride,
Wokingham, Berkshire, RG40 3GA,
United Kingdom
T: +44 (0) 1344 773131
F: +44 (0) 1344 770356
E: enquiries@trl.co.uk
W: www.trl.co.uk

ISSN 2514-9652

ISBN 978-1-913246-71-6

PPR1001