A REVIEW OF THE EFFECTS OF SALINITY ON ROAD PAVEMENTS AND BITUMINOUS SURFACINGS

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ABSTRACT

Damage to roads in Australia as a result of salinity is predicted to increase considerably over the next 40 years and result in a substantial rise in road maintenance costs. As a result of land use and climatic changes, both rural and urban roads are predicted to become more susceptible to the effects of salts primarily due to dryland and urban salinity.

The effects of salinity on roads have been reported both in Australia and worldwide since the early 1900s. This paper reviews research undertaken on the effects of salts on roads focussing on two primary themes, namely salt damage to bituminous surfacings and salt stabilisation of unsealed pavements. The sources of salts in roads and the risk, and cost, of salinity related damage to the Australian road network are also discussed.

INTRODUCTION

The effects of salinity on roads have been reported both in Australia and worldwide since the early 1900s. Research conducted in Australia and overseas over the past 10 to 20 years has concluded that salts concentrating within road pavements are likely accelerate deterioration of road surfacings and pavements. The risk, and cost, of salinity related damage to road pavements, while already considerable, is expected to increase substantially over the next 10 to 40 years. This emerging issue represents a significant financial and engineering risk to road asset managers.

This paper reviews research undertaken on the effects of salts on roads focussing on two primary themes, namely salt damage to bituminous surfacings and salt stabilisation of unsealed pavements. The effects of salts on rigid pavements are outside the scope of this work.

SALINITY AND ROADS

Salinity, as it applies to road pavements and soils in general, refers to the presence of salts in solution plus readily dissolvable salts in the soil (Spies and Woodgate 2005). Naturally occurring salts present in soils may originate from (Taylor 1991):

- wind-borne salts from ocean spray or sedimentary deposits (i.e. dune sand, clay particles)
- salts from ocean spray dissolved in rainwater then deposited inland
- salts present in marine sediments at the time of deposition (i.e. during periods when the land was partly covered by sea)
- weathering of soil and rock materials.

In arid and semi-arid climates salts are infrequently leached from the soil by rainfall and the evaporation and transpiration of water at the soil surface exceeds rainfall. Consequently, net movement of water is upward in the soil profile and salts accumulate at or near the surface of these arid-region soils (McBride 1994).

The extent to which various salts interact with soil particles depends largely on their solubilities. Sodium and calcium chloride salts are very soluble, salts like gypsum are only slightly soluble and salts like calcium carbonate are even less soluble (Robbins et al. 1991). The most common naturally occurring salt in Australia is sodium chloride. However, soils contain a mixture of salts typically in various proportions of the sodium, calcium and magnesium cations and the chloride and sulphate anions (Taylor 1991; Spies and Woodgate 2005).
While authors typically identify three primary sources of salts in road pavements, points one, two and three below (Kodikara et al. 2004; McRobert et al. 2008), this review proposes that there are actually four primary sources:

1. environmental salinity (saline groundwater, dryland salinity, dry-saline land or urban salinity)
2. salt-laden construction materials
3. saline construction water
4. salt introduced as part of a dust suppression or stabilisation process.

Migration and accumulation of salts may occur as a result of any of the above sources or a combination thereof. Of the four primary sources of salts in road pavements, environmental salinity is the least well understood and, due to land use and climatic changes, presents the greatest risk to road assets.

The source(s) of soluble salts in a road pavement may be an important consideration for design guidelines, material and construction specifications and mitigation measures. However, salt source is largely irrelevant when assessing the effect of salts on pavement performance. More important aspects for pavement performance are the pavement material, type of clay within the pavement material and the composition, solubility and concentration of salts present.

It should also be noted that there a numerous methods for measuring the salt content in soils. Conversion of results from one study to another is often extremely difficult and approximate due to the different extraction methods used, analysis techniques employed and units reported. For the purposes of this review an approximate relationship of one percent total soluble salts (TSS) by dry weight of sample equivalent to 2,000 parts per million total dissolved salts (ppm TDS) of a 1:5 soil:water extract has been adopted. Salt damage to bituminous surfacings

The first significant study on salt damage to bituminous surfacings was conducted by Cole and Lewis (1960) who investigated deterioration of compacted base courses and subgrades beneath bitumen sealed water catchments in Western Australia. Failure of the bitumen surfacing was characterised by a complete lack of bond between the bitumen and the underlying surface.

Studies of failed and sound areas identified that physical changes had occurred beneath the failed areas. Gravels and sandy loams, initially well compacted, were found to have transformed into loose, fluffy, unstable materials. Chemical analysis of the soluble salt content of the material directly beneath the surfacing was conducted. Failed areas were found to have high total soluble salt (TSS) contents, in excess of 0.5% TSS by dry weight. Sound areas were found to have low soluble salt content. The majority of catchments tested overlay saline water tables and the authors considered it possible that the observed concentration of salts at the soil surface was associated with upward movement of salts in moisture from the saline water table.

Simple laboratory studies were also conducted by Cole and Lewis (1960) on the effect of increased NaCl content on the stability of compacted soil samples. Low NaCl content samples showed no deterioration while higher NaCl content samples were observed to fret, with an increased rate of deterioration correlating with increasing salt content.

Cole and Lewis (1960) commented that the exact nature of the damage process observed in the field and laboratory was not known at the time. However, the authors hypothesised that observed physical changes were due to either salt crystallisation or changes in the absorbed cations on the clay. It should be noted that the bitumen surfacings studied by Cole and Lewis (1960) were thinner than bituminous surfacings used for modern roads and therefore are likely to have been more permeable and allow greater evaporation than those used today.

**Damage Due to Salt Laden Construction Materials**

Following reports of blistering road surfacings in many areas of South Africa in the 1960's, Weinert and Clauss (1967) undertook a detailed investigation of two affected sites. High concentrations of soluble salts in the road pavement materials were recorded and determined to be the cause of blistering of the road surfacing and debonding of the surfacing from the pavement. Chemical analysis showed that the predominant salts were sodium and magnesium sulphates, which originating from the pavement material – a mine waste.

The work by Weinert and Clauss (1967) was followed by a series of papers produced by the National Institute for Transport and Road Research (CSIR) in South Africa (Netterberg 1970;
Netterberg et al. 1974; Blight 1976; Netterberg 1979; Netterberg 1984; Buckle et al. 1987). Damage, in the form of blisters ranging from slightly raised domes that did not seriously crack the surfacing to blisters 150 mm across and 25 mm high, were observed (Blight 1976).

The majority of the work undertaken by CSIR investigated pavement materials which incorporated quartzite waste from industrial mine processes. Sulphate salts from the presence of sulphuric acid in this waste was determined to have caused the observed damage. While this is a fairly specific issue, many of the conclusions drawn from this work are relevant to the broader topic of soluble salt damage to roads including:

- physical damage occurs when soluble salts leach upwards from either the pavement or underlying material by evaporation of water through the surfacing
- physical damage will usually occur in areas of perennial or seasonal moisture deficiency
- damage is due to salts crystallising beneath the surfacing causing debonding of the surfacing, cracking and blistering
- damage may be prevented by providing a relatively impermeable surfacing layer
- damaged pavements may be repaired by removing the damaged surfacing and replacing it or by overlaying it with an adequately impervious surfacing.

Damage to bituminous surfacings due to salts present in construction materials, similar to that studied by CSIR in South Africa, was also reported around the same time in Australia. For example, Fielding and Babos (1985) presented a number of case studies of salt damage to roads in Victoria. Sulphide bearing source rock was observed to cause staining of linemarking, deformation and staining of thin asphalt surfacings and staining of bituminous seals. The authors determined that damage to the surfacing was due to source materials with high iron sulphide content, volumetric growth of course aggregate particles due to oxidation and hydration of sulphide minerals and/or concentration of soluble salts at the pavement surface through capillary rise and evaporation, and subsequent crystallisation.

The work by Weinert and Clauss (1967), CSIR in South Africa and Fielding and Babos (1985) highlighted the effects saline construction materials may have on thin bituminous surfacings. These studies provided guidelines for identifying salt damage to surfacings and drew attention to the physical changes which may result from salt accumulation beneath pavement surfacings. These works laid the foundation for subsequent studies on the mechanisms of salt damage to surfacings.

**Damage Due to Saline Groundwater**

The first study which comprehensively discussed the concept of damage to roads through salt accumulation originating from saline groundwaters was by Fookes and French (1977). While touched on by Cole and Lewis (1960), previous studies on salt damage to roads had focussed primarily on soluble salts present in construction materials. From field observations and material testing of roads in the Middle East, Fookes and French (1977) defined five ground moisture zones as shown in Figure 1.

*Figure 1: Moisture zones after Fookes and French (1977).*

Of the zones defined by Fookes and French (1977), four are relevant to roads:

- the zone of saturation below the level of the groundwater table
- the zone of intermittent saturation due to groundwater fluctuations
- the capillary moisture zone
- the zone of intermittent moisture due to rainfall infiltration, dew and similar processes.

Fookes and French (1977) related the likely mechanisms and severity of damage from soluble salt accumulation to the ground moisture zones. The authors identified the most damaging situation to be that where the road pavement is situated towards the lower half of the zone of capillary moisture movement.

The work by Fookes and French (1977) provides a platform for relating studies of environmental salinity in other technical fields, particularly work by environmental scientists, hydrologists and hydrogeologists investigating dryland and urban salinity, to road pavements and surfacings.

**Damage Due to Saline Compaction Water**

A third primary source of salts in road pavements was identified by Januszke and Booth (1984; 1992a; 1992b) as saline construction water. The authors reported severe problems of seals blistering, debonding of the surfacing and edge failures on the Stuart Highway in South Australia. They also noted that similar problems had been experienced on other roads in the previous 20 years and in some areas salt crystallisation has been observed on the seal. The authors concluded that the observed damage was due to very saline bore water used in construction, the base material which contained significant soluble salts and the mode of construction which resulted in a base course high in fines and dissolved salts. The predominant salt was found to be sodium chloride.

The work by Januszke and Booth (1984; 1992a; 1992b) has parallels with the work conducted on saline construction materials in that the issue is fairly specific, being limited to areas where saline groundwater or sea water is used in road construction. However, this work highlights the need to identify and control, where possible, all potential sources of salts entering the road formation. While the use of saline compaction water may be unavoidable in some areas, the associated impacts may be minimised or controlled by applying knowledge about how salts move within roads and the mechanisms of salt damage gained from other research.

**Fundamental Salt Damage Mechanisms**

Horta (1985) described the occurrence of salt damage in North Africa and provided a detailed examination of the internal structure of blisters, the growth of salt whiskers and crystallisation pressures. Salt damage to surfacings in the Sahara was found to be a result of halite (NaCl crystals) exerting very high crystallisation pressures, resulting in heaving of the pavement surfacing. Horta (1985) noted that these crystallisation pressures could be expected to increase with temperature and aridity and to decrease with pavement material permeability. A contrast between salt heaving and frost heaving was provided with the similarities between the two highlighted. Techniques to prevent salt heaving were also discussed.

The most significant study exploring the fundamental mechanisms of salt damage to pavement surfacings was sponsored initially by the British Overseas Development Administration (ODA) and subsequently in association with the Transport and Road Research Laboratory (TRRL) (Obika et al. 1989; Obika and Freer-Hewish 1990; Obika et al. 1992; Woodbridge et al. 1994; Obika et al. 1995; Obika 2001). This study provided a global context, and discussed climatic constraints, for salt damage to pavements to occur. The study included an extensive laboratory program and field investigation primarily focussing on salt damage to thin bituminous surfacings.

The laboratory study measured salt accumulation in samples prepared at a range of NaCl concentrations, with various surfacings and temperature/humidity conditions, using climatic cabinets. The results demonstrated that migration and accumulation of salt to the surface of a compacted pavement is a function of evaporation which in turn is related to temperature and humidity. The laboratory study was also able to show that, in the absence of groundwater, dissolved salts were still able to migrate and crystallise at the surface (refer Figure 2) through dissolution in pore water.
Subsequent scanning electron microscopy and x-ray analysis revealed that different crystal structures formed under various environmental parameters and surface conditions. This highlighted that the form of crystallisation is a significant factor in whether damage to the surfacing and pavement occurs, and if so the extent of the damage. The effect of one salt on the solubility of another was also noted in the context that the local soluble salts and concentrations could have a significant effect on the environmental parameters required for salt crystallisation. Crystallisation mechanisms and crystal pressures were also discussed as a mechanism of explaining the degree of damage resulting from salt hydration.

The ODA / TRRL laboratory study showed a significant increase in salt content at the surface of the samples as relative humidity decreased, which was amplified at higher temperatures. Analysis revealed negligible damage to constant climatic condition samples despite significant salt accumulation at the pavement surface. Samples subjected to cyclical conditions were found to suffer severe damage despite having comparatively low salt contents. The authors concluded that this confirmed that repeated crossing of salt crystal thresholds (crystallisation, rehydration, recrystallisation) was primarily responsible for the surface damage. Obika et al. (1992) noted that sodium chloride whiskers formed during crystallisation beneath road surfacings grew preferentially in materials of finer porosity. The authors concluded that pavement materials high in fines are particularly susceptible to salt damage. Bituminous prime coats were found to be particularly susceptible to salt damage, whereas bituminous reseals were more resistant.

As part of the ODA / TRRL study a field trial was conducted in Botswana. The field trial incorporated both saline and non-saline subgrade and consisted of 12 test sections plus control sections (Woodbridge et al. 1994). A single pavement material was selected for all sections and the salt concentration of both the pavement material and compaction water was varied. Each section was subdivided according to the prime applied and the period of time between pavement construction and application of the prime. All sections were subsequently resealed prior to trafficking. Test sections were trafficked for 18 months and monitoring was continued beyond the trafficking period to assess the effect of traffic on development of salt damage.

Woodbridge et al. (1994) noted the following trends in the salt content of pavement materials:

- static or slight decrease in the salt content of pavement materials constructed on the non-saline subgrade with time
- an increase, generally, in the salt content of pavement materials constructed on the saline subgrade with time. It should be noted that in two sections there was no increase which the authors could not explain
- the difference in damage between the saline subgrade and non-saline subgrade test sections could not be explained by the salt content of the pavement materials alone.

Woodbridge et al. (1994) concluded that reseals are significantly more resistant to salt damage than primes. Also, application of a reseal within 3 days was observed to reduce the occurrence of salt damage to the prime. The authors concluded that single reseals should be capable of resisting salt damage at pavement material salt concentrations up to approximately 0.5% total soluble salts (TSS). Double seals were thought to be capable of resisting salt damage at salt concentrations up to 1.0% TSS. Under trafficking double seals were observed to prevent salt damage when salt concentrations in the pavement material reached 1.5% TSS. However, when subsequently untrafficked, damage occurred rapidly, including in sections with lower salt concentration. The authors also concluded that traffic opposed the upward force created by salt crystallisation and assisted in maintaining bond between the surfacing and the pavement.

The ODA study culminated with publication of design guidelines for prevention and repair of salt damage to thin bituminous surfacings (Obika et al. 1995; Obika 2001). These design guidelines addressed factors influencing salt damage including climate, geology and hydrogeology, material characteristics, pavement surfacing design and construction, salt content field and
laboratory testing methods, risk evaluation, design procedures for damage prevention and repair techniques. To date these remain the most comprehensive guidelines for prevention of salt damage to thin bituminous surfacings worldwide.

**Recent Australian Studies**

In Australia, recent research into the effect of salinity on roads commenced with a study commissioned by Main Roads Western Australia (MRWA) (McRobert and Foley 1999). This study reviewed salinity and waterlogging impacts on the main road network in the south west of Western Australia. Current and future costs in constructing and maintaining affected road assets were predicted and the feasibility and cost-effectiveness of mitigation strategies were reviewed. The authors concluded that salinity and waterlogging was causing significant environmental stresses to the road network including pavement and surfacing damage, effects on concrete structures and impacts on roadside vegetation. Preliminary studies indicated that around 230 km of main roads were already affected by high watertables and salinity in the south west of Western Australia. This represented over 3% of the regional main road network. Based on a trend of rising watertables, the authors commented that the affected road length in Western Australia was likely to double in the subsequent 10-20 years.

Following the MRWA study (McRobert and Foley 1999), additional publications (McRobert et al. 2003; McRobert et al. 2003) were produced over a period of 5 years. These augmented and updated the earlier work, primarily in the areas of developing risk assessment methodologies, quantifying the extent roads affected by salinity and waterlogging and refining estimates of costs associated with salinity and rising watertables. These studies did not involve any physical testing or field investigations. Neither the original MRWA study nor the subsequent publications separated the effects of salinity from those of waterlogging.

The initial Australian study culminated in an Austroads report titled *Salinity and Rising Watertables – Risks for Network Asset Management* (Houghton et al. 2004). This report identified areas of the road asset at risk of being affected by dryland salinity and rising watertables, provided an indication of the types and extent of damage occurring, assessed the potential cost implications associated with mitigating these impacts, and outlined generic methods of reducing the impact of salinity and rising watertables on road assets. This report was largely concerned with raising awareness of the extent of salinity and rising watertables and the economics associated with mitigation and treatment of these areas, as opposed to the underlying engineering implications. The report by Houghton et al. (2004) recommended a number of avenues for further research including a focus on the engineering implications of increases in salinity and rising watertables.

In 2005/06 ARRB, on behalf of Austroads, commenced a project titled *Managing the Impacts of Rising Watertables and Salinity on Pavement Performance* (Beavis and Ellis 2007; McRobert et al. 2007; McRobert et al. 2007; McRobert et al. 2008; McRobert et al. 2008). The primary aims of this project were to identify how saline groundwaters enter road formations, better describe the failure mechanisms associated with salinity damage to road pavements, and develop correlations between the presence of saline watertables and pavement deterioration.

Following completion of a review of recent literature relating to salinity damage to roads, a geophysical survey and associated pavement material geochemical sampling and testing was undertaken at a trial site near Forbes, NSW. This site was selected on the basis that the pavement was showing obvious signs of distress, was located in an area of a high saline watertable and accurate traffic, maintenance and construction information for the site was available. An electromagnetic survey was conducted along the test site. Subsequent site investigations consisted of a series of test pits from which the pavement profile was determined and samples taken for determination of material characteristics and geochemical analysis. Of the 8 test pits, one was located within an adjacent local road where significant salt scalds were visible on the verges and second was located within the road verge. The remaining six locations were chosen to test both distressed and non-distressed pavements.

Benkelman beam deflection testing and dynamic cone penetrometer (DCP) testing was conducted in the location of each test pit. A total of 26 samples of pavement material and two samples of the source material, directly from the borrow pit, were taken for analysis. Samples were tested for CBR, grading, compaction, Atterberg limits, Texas triaxial and geochemical analysis which included x-ray diffraction, scanning electron microscopy and pore water solute
geochemistry (pH, total dissolved salts, electrical conductivity of 1:5 extracts and analysis of major cations and anions).

A broad correlation was established between the height of the road surface (AHD) and conductivity results from the electromagnetic survey. However, no correlation was evident between the height of the road surface above the watertable and conductivity results. The authors noted that surprisingly the highest conductivity readings being recorded at the break of slope not the area where the height between the watertable and road surface was lowest.

McRobert et al. (2008) reported a reasonable correlation between conductivity measured by the electromagnetic survey and total dissolved salts (TDS) determined from 1:5 soil-water extracts of the test pit samples. However, no correlation was found between TDS and moisture content in the pavement samples. It should be noted that EM surveys are an indirect method of estimating salinity. A number of limitations exist in correlating EM conductivity readings to actual salinity concentration, particularly on small-scale applications such as employed in McRobert et al. (2008). One limitation is that conductivity readings are affected by material type, material variation and layer thickness. Pavement material characteristics and pavement layer thickness varied significantly along the trial site and therefore conductivity readings would also be expected to vary regardless of changes in actual pavement salinity. It should also be noted that electrical conductivity is influenced by both salinity and moisture content and culverts, steel reinforcement and surrounding metal objects may have a significant effect on readings.

Geochemical analysis revealed that soluble salts were present in only very low concentration, less than 50 ppm TDS (1:5 extract) equivalent to less than 0.05% TSS by dry weight, in the two samples taken from the borrow pit. Concentrations in excess of 1,500 ppm TDS (1:5 extract), equivalent to approximately 0.75% TSS by dry weight, were found in some samples taken from the road pavement (Beavis and Ellis 2007). As town water with negligible soluble salts was used for compaction the authors concluded that it was likely salinity of the pavement materials would have been negligible at the time of construction. The primary implication being that accumulation of soluble salts in the pavement between construction and the time of sampling was due to environmental salinity.

Chlorides and sulphates were found to be the dominant anions and sodium, magnesium, calcium and potassium the dominant cations. However, analysis indicated two distinct groupings of salt precipitation within pavement samples. Beavis and Ellis (2007) noted that the two salt precipitation groupings were different types of salt, not different amounts of the same salt. The authors concluded that these differences were associated with distinct salt concentration processes which varied spatially within the road structure. The authors hypothesised that the spatial variation observed was due to differing evaporation and temperature trends within the pavement and the presence of, and variation in, concentrations of different salt species.

While not reported by McRobert et al. (2008), no relationship between salt concentration and deflection measurements was apparent. Similarly, no relationship was evident between salt concentration and laboratory soaked CBR. This suggests that any relationship between salinity and pavement performance indicators needs to acknowledge the effect of other factors such as pavement material, pavement thickness, subgrade support and moisture content.

Unfortunately very little investigation work was conducted by McRobert et al. (2008) outside of the roadway. This prevents comparison of the concentration, and composition, of salts in the pavement with those of the surrounding environment. The spatial variation in salt concentration and composition across a road pavement was also not assessed. It should also be noted that McRobert et al. (2008) did not consider or assess the effects of salinity and moisture separately; the authors effectively treated salinity and rising watertables as a single issue.

However, the two Austroads projects, Houghton et al. (2004) and McRobert et al. (2008), succeeded in furthering knowledge primarily on identification of areas at risk of salinity and waterlogging, economic analysis of potential costs to the road network, broad-scale risk assessment methodologies for roads identified as at risk and understanding the influence of local salts, environmental conditions and pavement materials on damage mechanisms.

Other Works

In Australia over the last 10 years there have also been a number of other publications relating the effects of salt on roads (Porter and Clifton 2001; Bell 2003; Goh et al. 2005; Graham 2005;
Vorobieff (2005). The majority of these publications utilised published works, discussed earlier, along with specific technical knowledge to infer implications for the extent of roads likely to be affected by salinity, impacts of salinity on roads, methods for rehabilitation of salt affected roads or road design guidelines for reducing the risk of salinity damage to roads. Very few physical studies, either laboratory or field based, have been conducted. The two exceptions are a laboratory study at Monash University (Kodikara et al. 2004a; Kodikara et al. 2004b) and electromagnetic field work and limited laboratory testing conducted in Western Australia (Street and Petrusma 2004; Street 2007).

Kodikara et al. (2004b) summarised published literature on the mechanisms and factors affecting salt damage to roads, complemented by reference to relevant unsaturated soil principles. While presenting little new theory, this paper provides a very good overview of current knowledge of the scale of the problem, generic causes of damage and sources of salts in roads, mechanisms of salt damage to roads, migration of salts, salt crystallisation, salt types, climatic effects and treatments and preventative measures. The authors also raised a number of interesting queries on the effect of salts on roads. These included whether the cumulative effect of the wet/dry cycling during rain and dry periods, and the associated effect of rehydration and subsequent crystallisation of salts, has a significant effect on the degradation of the pavement matrix and interfaces. The effect on pavements of osmotic pressure generated by salt accumulation was also raised.

Kodikara et al. (2004a) conducted a laboratory study and subsequent modelling of salt migration in cementitiously stabilised road pavements. The laboratory study involved observations of capillary rise in unsealed stabilised pavement specimens when positioned in a saline water bath and placed in a constant temperature cabinet. The authors reported that in all cases fluid rose to the top of the samples within 24 hours. Within 27 days salt crystallisation had occurred on the surface of most specimens. Salt crystallisation was found to be greater for 4% cement specimens than 2% cement specimens. The authors postulated that this difference was due to the smaller pore sizes of the 4% cement specimens. Moisture movement was found to be significantly influenced by salt concentration. Subsequent chemical analysis showed that salt concentrations in lower sections matched reasonably with the corresponding salt solution. A sharp increase in salt concentration was apparent in top sections. Generally a greater proportion of chloride ions compared with sodium ions was found in top sections of the specimens. This indicated to the authors that the chloride ions moved more freely with moisture movement compared to the sodium ions, possibly due to ion exchange. The authors commented that these results highlight the importance of considering ion streaming separately in salt transport modelling (Kodikara et al. 2004).

Street and Petrusma (2004) conducted a study of salt damage to roads in Western Australia by undertaking an electromagnetic (EM) survey of a 500 km length of road. The conductivity data collected for 200 km of the Great Eastern Highway was then compared with corresponding road condition data. While no correlation between conductivity and road condition was found for the entire dataset, the authors claimed that a large proportion of the data showed a trend towards poor road condition with increased conductivity. However, from the graph of conductivity verses rutting published by the authors it would appear any relationship would have very high variability and low statistical correlation. Street and Petrusma (2004) concluded that it appeared road condition data needed to be normalised to reflect the age of the road pavement and surfacing however this was not possible with the data available. The authors hypothesised that areas of high conductivity which were found to have good road condition may be a result of recent rehabilitation or resurfacing treatments in response to salt-related damage. This highlights the need for detailed road maintenance history when investigating salt impacts on existing roads.

Street and Petrusma (2004) also measured conductivity across the Great Eastern Highway. Conductivity was found to vary transversely across the road, with generally lower conductivity in the middle of the road and higher conductivity on the pavement edges and outside of the road formation (refer Figure 3). However, it should be noted that conductivity is influenced by both salinity and moisture content and moisture would be expected to vary in a similar distribution transversely across a road. Higher average conductivity, in the order of 30%, was observed for the upslope side of the road when compared with the downslope.
Following on from the EM survey study Street (2007) conducted a limited laboratory program investigating the effect of salt on pavement materials. Samples of pavement material were compressed in cubes and placed in a water bath containing varying concentrations of NaCl and Na$_2$SO$_4$. Capillary rise was observed over a period of 3 weeks prior to strength testing. While the method of testing was not documented, the author reported that higher NaCl concentration correlated to increased material strength, while the presence of reduced pavement material strength. Almost no information on the laboratory study conducted, either the method used or results obtained, is publicly available so comparison with other works was not possible.

SALT STABILISATION OF ROAD PAVEMENTS

Salt was first used as a dust palliative for unsealed road pavements around 100 years ago and by the 1930s was being used in a number of countries for the stabilisation of base and subbase materials (Burggraf et al. 1932; Downey et al. 1939; Looker et al. 1939; Mainfort 1969). Salt has also been used in the treatment of subgrades. While salts have been used for dust suppression at various times in most states of Australia, they are rarely if ever used these days due to the availability of proprietary dust suppression products. Despite significant research being conducted, particularly in the US, the use of salt stabilisation has not been widely adopted (Jones et al. 2008). Historically, the most common salts used for stabilisation of road pavements are sodium chloride and calcium chloride; however, magnesium chloride has also been used.

In a review of dust-control techniques for unsealed roads, (Foley et al. 1996) concluded that chlorides provide the most satisfactory combination of ease of application, durability, cost and dust control for arid and semi-arid areas. However, they were also found to be susceptible to leaching and may not provide sufficient effectiveness for a second year.

Lohnes and Coree (2002) conducted a review of literature on the effectiveness of dust suppression methods and found that calcium chloride was one of the two most widely used treatments. Calcium chloride was reported to attract moisture and increase the surface tension of water in the pores, resulting in a lower rate of evaporation and thereby reducing dust generation. However, the authors noted that it had a short duration of effectiveness.

Singh and Das (1999) conducted laboratory tests with mixtures of several soils and a gravel with clay stabilised with rock salt and brine (both sodium chloride). The laboratory study included Atterberg limits, compaction, unconfined compression strength (UCS), CBR, indirect tensile strength (ITS) and cyclic triaxial testing. Salt content, by dry weight, was varied from 0.5 to 2.5% by dry weight. The 0.5% salt content was found to have no influence on the liquid or plastic limit. A slight decrease in the liquid limit and a slight increase in the plastic limit were observed with increasing salt content. Using the modified AASHTO compaction test the dry unit weight was found to increase with salt content and the optimum moisture content was reduced by salt treatment. CBR testing showed significantly higher CBR values for salt treated samples. Similarly UCS, shown in Figure 4, and ITS increased, albeit slightly, with increasing salt content. The addition of rock salt was found to produce a marked increase in resilient modulus.
The US Department of Agriculture Forest Service (DAFT) use relatively high concentrations of calcium chloride salt in stabilisation of unpaved road surfaces with low traffic volumes and have conducted a number of studies on the effectiveness of this technique for unsealed roads (Monlux 2003; Monlux and Mitchell 2007). In one study, a number of test sections on three roads were stabilised with 1.0% to 2.5% of salt by weight of aggregate, mixed into the road surface to a depth of approximately 50mm, monitored for 2 to 4 years and compared with untreated sections (Monlux 2003). A follow-up study replicated the practices of the first on a larger scale and included other types and forms of chloride salts, construction techniques, aggregates and climates (Monlux and Mitchell 2007).

In comparing salt stabilised test sections with untreated sections, salt stabilised road surfaces were found to be more resistant to ravelling, have significantly lower grading requirements and lower aggregate loss (Monlux 2003; Monlux and Mitchell 2007). For example, the average grading interval for stabilised sections was eight times that of unstabilised sections. Salt stabilised sections were also found to reduce dust by approximately 90%. The authors concluded that other benefits of salt stabilisation included reduced surface erosion and sedimentation, improved safety from reduced dust and less frost penetration.

A variety of authors have concluded that salt stabilisation (Thornburn and Mura 1969; Singh and Das 1999):

- generally produces higher maximum dry density at lower moisture content
- reduces moisture content changes in soils
- increases the strength, but the extent of the increase varies
- does not appear (by x-ray diffraction) to change the mineralogy of most soils
- decreases the permeability
- is beneficial even after the salt is leached out from the compacted soil.

There is some agreement that the mechanisms involved in salt stabilisation of road pavements are primarily due to ion exchange on the clay (Singh and Das 1999). The water film bonds between soil grains are also strengthened, improving cohesion (Thornburn and Mura 1969).

It should be noted that under natural conditions a single salt (such as used in salt stabilisation) would only be a portion of those present. Due to preferential cation exchange on clay particles this is likely to have a significant effect on the clay chemistry and resulting pavement impacts.

Amounts ranging from 0.5% to 3.5% (by dry weight) have been used for salt stabilisation with amounts of 0.5% to 1.5% common. Figure 5 compares the typical range of salt concentrations used for stabilisation of unsealed pavements with the range causing damage to thin bituminous
surfacings. From Figure 5 it is clear that salts may have both a positive and negative effect on roads and that the interaction between the mechanisms involved in salt stabilisation and those causing salt damage to thin bituminous surfacings need further study.

![Typical Salt Stabilisation Range](image)

**Figure 5: Salt concentration range – stabilisation and thin bituminous surfacing damage.**

### EXTENT OF ROADS AT RISK OF ENVIRONMENTAL SALINITY

Both rural and urban roads are susceptible to the effects of environmental salinity in the form of dryland salinity, dry-saline land or urban salinity. The risk, and cost, of salinity related damage to road pavements, while already considerable, is forecast to increase substantially over the next 10 to 40 years. The National Land and Water Resources Audit (NLWRA 2001) estimated that by 2050 the area of land in Australia with high potential to develop dryland salinity (refer Figure 6) will increase fourfold. By 2050 over 67,000 km of road is predicted to be at high risk from shallow saline watertables and that road maintenance costs in just these areas will increase from $50-100 million to $168-380 million (Houghton et al. 2004). The scale and cost of medium risk areas was not quantified in the audit but may be of a similar order of magnitude.

![Areas at high risk of dryland salinity by 2050 after NLWRA (2001).](image)

**Figure 6: Areas at high risk of dryland salinity by 2050 after NLWRA (2001).**

Salt-affected soils occur most often in arid and semi-arid climates but they can also be found in areas where the climate and mobility of salts cause saline waters and soils for short periods of time (Sparks 2003). However, for the most part, in humid regions salt-affected soils are not a problem because rainfall is sufficient to leach excess salts out of the soils, into groundwater.

As discussed earlier the issue of salt damage to roads is not limited to Australia. Blight (1976) first linked the occurrence of salt damage to roads to areas of perennial or seasonal moisture deficiency. Following on from this works Obika et al. (1989) discussed the climatic constraints for salt damage to pavements to occur and the locations where damage had been reported, in the context of global arid and semi-arid zones (refer Figure 7).
This provides a global context for the problem and highlights that salt damage to roads could occur, and in many cases has occurred, in areas throughout the world including Australia, Southern Africa, Northern Africa, South America, North America, the Middle East and Asia.

CONCLUSIONS

The effects of salinity on road pavements and bituminous surfacings have been reported both in Australia and worldwide since the early 1900s. Research into the effects of salts on roads can be divided into two themes: salt damage to thin bituminous surfacings and salt stabilisation of unsealed pavements. The dual effect of the two, the interactions between them and the implications for the Australian road network warrant further study.

The impact of salts on performance of thin bituminous surfacings, and the mechanisms involved have been studied extensively over the past 50 years. Research conducted by Austroads in Australia, CSIR in South Africa and the ODA and TRRL in Africa and the Caribbean has shown that concentration of soluble salts beneath bituminous surfacings can lead to debonding of the surfacing, cracking and blistering of the surfacing. The primary mechanism of salt damage has been attributed to salt crystallisation, with repeated crossing of crystallisation thresholds observed to significantly increase damage mechanism. Bituminous primes have been found to be susceptible to salt attack at concentrations as low as 0.2% by dry weight, while reseals have been found to be resistant to salt attack at concentrations of 1.0% and above.

Significant research has also been conducted on the beneficial effects of salts in the stabilisation of unsealed road pavements, typically involving either NaCl or CaCl\(_2\) at concentrations in the range 0.5% to 1.5% by dry weight. Salt stabilisation has been found to reduce surface correction (grading) requirements, reduce aggregate loss, reduce dust, generally produce higher maximum dry density, reduce moisture content changes, increase pavement strength and decrease permeability.

To mitigate the risk of salinity related damage to new roads the majority of Australian road authorities specify maximum limits for the salt content of construction materials and compaction water. Other mitigation measures which may be adopted include (Obika 1995; Obika 2001):

- washing pavement materials to remove excessive amounts of salts
- minimising the period of time between completion of pavement construction and application of bituminous surfacing
- increasing the thickness / reducing the permeability of the surfacing
- use of bitumen emulsion in place of cutback bitumen
- incorporation of an impermeable layer within the pavement structure.
While migration and accumulation of salts may occur as a result of salt-laden construction materials, saline construction water or salt introduced as part of a dust suppression or stabilisation process, environmental salinity is the least well understood salt source and presents the greatest risk to road assets. It is estimated that road maintenance costs in areas deemed at high risk of dryland salinity alone will more than triple between 2000 and 2050.

The risk of salt damage to roads is not limited to Australia and various authors have highlighted that salt damage to roads could occur, and in many cases has occurred, in many areas arid and semi-arid regions of the world including Australia, Southern Africa, Northern Africa, South America, North America, the Middle East and parts of Asia.

REFERENCES


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