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Modelling of salt migration in stabilised pavement materials

Modélisation de la migration de sel dans les matériaux de chaussées stabilisés avec du ciment

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ABSTRACT

This paper presents the results of a laboratory study undertaken to model the salt migration in cementitiously stabilised pavement materials. The experimental method involves the simulation of capillary rise in cylindrical specimens close to 300 mm in height with salt solutions located at the specimen bases. Solutions of salt concentrations 0, 5000, 10000, 20000, 30000 mg/L were used in the study. The pavement material, crushed basaltic rock, was stabilised with 2% or 4% of Portland cement by weight. The capillary rise was monitored manually and plots of rise versus time were produced. The fluid rose to the top in all specimens within 24 hours. The specimens were monitored for a period up to 27 days, and the salt crystallization occurred in most of the specimens. It was found that the salt crystals go back to solution when the atmospheric humidity increases over about 75%. The salt crystallization was more in 4% cement specimens than in 2% specimens, and this was attributed to the finer pore sizes available in 4% cement specimens. The migration of fluid was not significantly affected by salt concentration. It appeared that chloride ions moved freely with the fluid but sodium ions were somewhat retarded, possibly due to ion exchange.

RÉSUMÉ

Cette communication présente les résultats d'une étude de laboratoire entreprise pour modéliser la migration de sel dans des matériaux de construction de chaussées stabilisés au ciment. La méthode expérimentale consiste en la simulation de l'action capillaire dans les spécimens cylindriques de près de 300 millimètres de hauteur immerger à la base dans des solutions salines. Des solutions à des concentrations en sel de 0, 5000, 10000, 20000, 30000 mg/l ont été employées dans cette étude. Le matériau de construction des chaussées, basalte concassé, a été stabilisé avec du ciment de Portland (2% et 4% en charge pondérale). La montée du sel par action capillaire a été mesurée manuellement et des courbes correspondant à la vitesse de cette action ont été produites. Le fluide est monté à la surface de tous les spécimens en 24 heures. Les spécimens ont été surveillés pendant une période allant jusqu'à 27 jours, et la cristallisation du sel s'est produite dans la plupart des spécimens. On a constaté que les cristaux de sel se dissolvent de nouveau quand l'humidité atmosphérique atteint environ 75%. La cristallisation du sel s'est produite davantage dans les spécimens contenant 4% de ciment que dans des spécimens à 2%, et ce phénomène a été attribué à la porosité plus fine des spécimens contenant 4%de ciment. La migration du fluide n'a pas été sensiblement affectée par la concentration en sel. Il s'est avéré que les ions de chlorure se déplacent librement avec le fluide tandis que les ions de sodium ont été légèrement retardés, probablement en raison de l'échange ionique.

1 INTRODUCTION

Dryland salinity and rising watertables have been identified as a major problem facing Australia, leading to a reduction in agricultural production and damage to natural environment. Major reasons for this occurrence are reasonably well documented. More recently, however, it is recognised that dryland salinity and rising water tables can also significantly affect the urban infrastructure in salt-affected rural towns. Urban infrastructure under threat include roads, railway lines, bridges, buildings, pipelines, communication systems and other infrastructure such as concrete foot paths. Substantial costs are estimated to incur to the community and to other stake holders as a result of this on-going problem.

Despite the perceived significance, relatively less detailed research appeared to have been carried out or reported on this problem. The current paper presents some results of laboratory modelling carried out to examine the salt migration and crystallization in stabilised pavement materials. The test method involved the simulation of capillary rise of salt (NaCl) water through cement stabilised crushed rock specimens.

2 GENERIC CAUSES AND MIGRATION OF SALT

It is well recognised that water alone, when present excessively, can damage pavements. However, when salt is also present, the potential damage is likely to be exacerbated. There is significant benefit in understanding these effects separately so that the economic risks and remedial options can be more scientifically evaluated. There a number of ways salt can be introduced into a pavement base. These include ingress of saline groundwater, the use of salt-laden construction materials, the use of saline construction water and a combination of these (Kodikara et al., 2004). The primary damage due to salt occurs when salt crystallises in significant quantities causing materials to crack, deform, and separate at interfaces (e.g., lifting of the pavement seal from the base).

Salt crystallization occurs when salt concentrates due to migration and evaporation of saline water. It is possible to identify migration of salt in water due to a hydraulic head gradient (advection), a concentration gradient (diffusion), or a thermal gradient (Soret effect) or a combination of these (Mitchell, 1991). Out of these, perhaps, the most important may be the advective flow, which normally occurs in pavements as capillary flow. The current paper examines the salt migration due to capillary rise within stabilised materials, which can occur when free water is present close to the pavement base due to shallow or perched water tables.

3 LABORATORY MODELLING

3.1 *Pavement materials*

The selected pavement material was a crushed basaltic rock, commonly used for pavement construction in Victoria, Australia. The basic material properties of crushed rock were determined in the laboratory using Australian Standard test methods: standard maximum dry density =2204 kg/m^3, optimum water content =9.8%, specific gravity =2.97, linear shrinkage =0.8%, liquid limit=22%, plasticity index=3%. The crushed rock contained approximately about 10% fines, which are predominantly rock fragments.

The pavement material was stabilised with General Portland (GP) cement by adding 2% or 4% by weight for specimen preparation. This process simulates either construction of new or in-situ rehabilitation of old pavements using cementitious additives.

3.2 Specimen preparation

The stabilised mix was prepared by mixing a crushed rock sample with the designated amount of GP cement and water (at the optimum water content). The compaction was carried out in a specially designed split steel mould using Standard compaction energy (per unit volume) as per Australian Standard AS 1141.51-1996. The diameter was the same for all specimens at 105 mm, but the specimen heights varied between 276 and 297 mm. The specimens were retrieved from moulds and were wrapped in thin plastic sheets to prevent moisture loss. They were subsequently allowed to cure for two weeks at 18^0C. Specimens were then unwrapped and were allowed to air dry in a controlled laboratory environment until the weight became reasonably constant.

3.3 Test method and schedule

The test method simulated the capillary rise of salt solutions through stabilised specimens. The test method was a modification of Australian Standard AS 1141.53-1996 and was developed by Lee et al. (2004). Figure 1 shows a picture of the test set up. The tests were conducted in constant temperature cabinet maintained about 35^0C as shown.

The tests were started by placing dry specimens on coins (to allow uniform access of water to the base) in a tub containing salt solutions of up to a height of 20 mm. The salt water level of the tube was maintained constant by using a Mariotte bottle containing the same salt solution. Two specimens were placed in the tub. The specimens and the tub were covered with thin plastic sheets to prevent evaporation. The top specimen surface was, however, uncovered allowing evaporation to take place simulating a drying condition in the pavement material. In these tests, a seal was not placed on the pavement material as would be the case in the field after the pavement construction. The current boundary condition simulates either an uncovered pavement (unsealed or before the seal is placed) or a pavement with severely cracked seal.

Figure 1. A picture of test setup

Once the test was started, the height of water rise in the specimens was recorded. The marked change in the colour due to wetting allowed the record of capillary rise with reasonable ease. Since the rate of rise was rapid at the beginning and slowed as time progressed, it was necessary to take readings at staggered time intervals. The corresponding levels of the Marriott bottle were also recorded to compute the water influx into the specimens. In addition, observations were made of salt crystallization and any other changes on the surface or anywhere else on the specimens.

A total of ten tests were undertaken, with five tests each for specimens stabilised with 2% and 4% cement content. For each cement content, tests with tap water and NaCl solutions of 5000 mg/L, 10000 mg/L, 20000 mg/L and 30000 mg/L concentrations were performed. The tests were monitored for a period up to about a month.

3.4 Capillary rise results

Figures 2 and 3 show the capillary rise results for specimens with 2% and 4% cement contents with various salt solutions. The capillary rise is given above the water level at the base of the specimens. The capillary rise process is marked by a rapid initial rate of rise and subsequently a rate limiting rise. It is interesting to note that the rise curves appear to be similar irrespective of the NaCl concentration in the seeping solution. Figure 2 also includes a curve for tap water, which also matches reasonably well with the other curves. Figure 4 shows all the curves in one graph. It is evident that the liquid rises much faster in specimen with 2% cement content than in specimen with 4% cement. In all specimens, the water rose to the top within 24 hours, but those points are not marked because they were not captured exactly due to the limitations in visual and manual measurement.
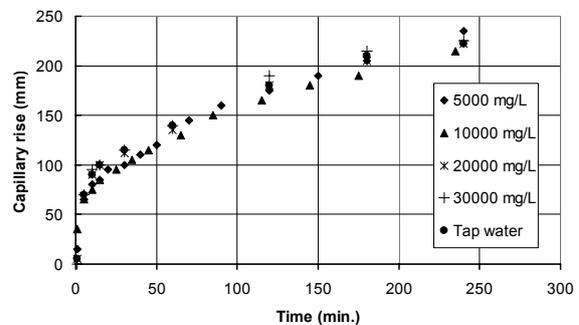

Figure 2. Capillary rise for specimen with 2% cement

3.5 Salt crystallization and concentrations

Detailed descriptions of observations of salt crystallizations were given by Kodikara et al. (2004a). Salt crystallization occurred visibly on the surface of all specimens, except in 2% cement specimen with 5000 mg/L solution during its 27 days of monitoring. Crystals seem to appear after about 6 six days, although the exact timing was not recorded. In both 2% and 4% specimens with 10000, 20000 and 30000 mg/L solutions, crystals disappeared or reduced in coverage sometime after their emergence. This may be attributed to the unexpected rise in the humidity in the control cabinets. According to thermodynamic phase equilibrium of NaCl salt solutions, crystallization would be stable only when the (micro) environmental relative humidity is lower than about 75%, and this does not depend very much on the temperature. The measurements confirmed that the relative humidity within the cabinets actually rose above 80% close to these events. Once the salt went back into the specimens, some seemed to have crystallized within the pore structure below the surface, as was evidenced by disintegrated specimens after the tests were completed. The other significant observation was that the salt crystallization appeared to favour finer pore sizes because generally more crystals were observed in 4% cement specimens that in 2% specimens (e.g., Figure 5).
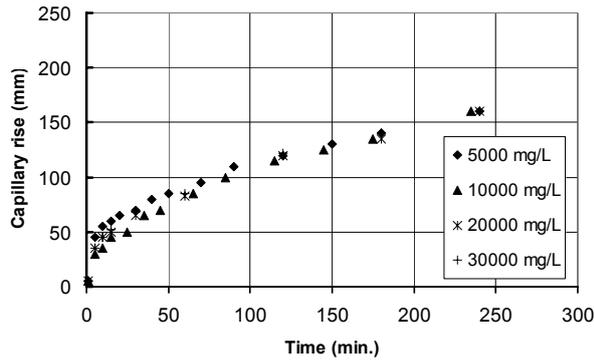
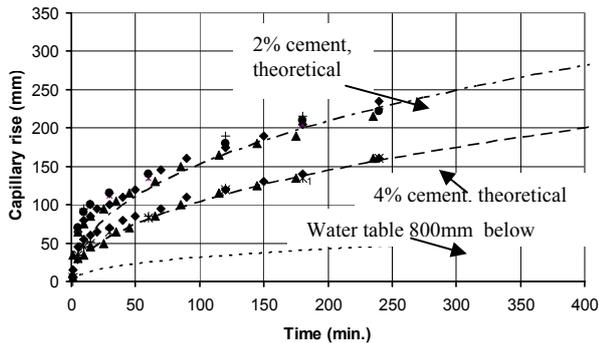Figure 3. Capillary rise for specimen with 4% cement

Figure 4. Capillary rise for specimen with 2% and 4% cement contents

4 THEORETICAL MODELLING

4.1 *Capillary flow*

As noted previously, gradients of hydraulic, thermal and chemical potentials (also electrical) govern the fluid flow in pavement materials, or generally in porous materials. Under the present conditions, the thermal gradient can be ignored because the tests were carried out in an approximately constant temperature environment. As noted by Lee *et al*. (2004), capillary rise process with water is dominated by the bulk water flow due to hydraulic potential generated by capillary suctions. Figures 2 and 3 confirm this because all the curves corresponding to specimens containing certain cement content (depicting similar pore structure) have fallen in a close band. Nevertheless, there seems to be some differences among different tests, which may partially be due to general material variability and experimental errors. Theoretically, however, these differences may have come due to chemical potential gradients created by moving ions in the solution within the pore matrix. As Mitchell (1991) has pointed out, this component, however, is significant for dense fine grained soils at low water contents, where the "osmotic efficiency" will become sufficiently high. It will be necessary to examine this difference more carefully in such materials.

Lee *et al*. (2004) developed a simplified procedure to analyse capillary moisture rise in stabilised pavement materials. They assumed that the fluid flow is dominated by bulk water flow that occurs at steady state near saturated conditions, and the flow features a sharp wetting front. The following equation was used to relate the rise (h) with the time (t):
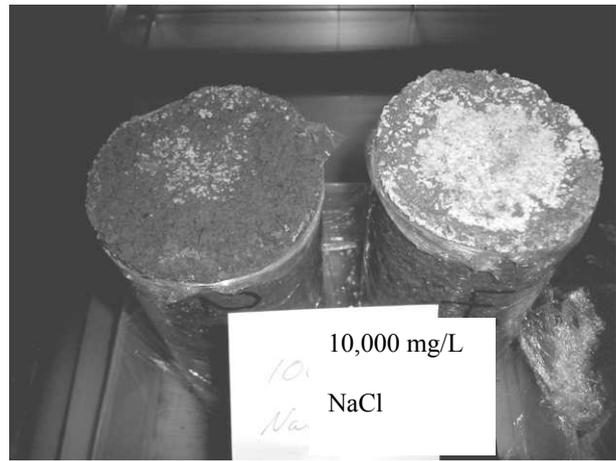

Figure 5. Salt crystallization in 2% (left) and 4% specimens with 10000 mg/L solution

$$t = -\frac{n}{k}h - \frac{n}{k}\left(h_o - h_w\right)\ln\left[1 - \frac{h}{\left(h_o - h_w\right)}\right] \qquad (1)$$

where, n is the effective wetted porosity, k is the applicable hydraulic conductivity, h_0 is the initial suction pressure potential in the matrix and h_w is the depth to water table from the base of the specimen.

Figure 4 shows the simulated capillary rise curves along with the experimental results. In this preliminary study, all the necessary parameters were not measured, but were fitted with judgement and previous experience on similar materials. The parameters obtained were: for 2% cement specimens, $k=9 \times 10^{-7}$ m/s, $h_0=700$ mm; and for 4% cement specimens, $k=3 \times 10^{-7}$ m/s; $h_0=900$ mm. The porosity of 0.27 was used for both specimens based on measurements. The depth to groundwater h_w is zero for laboratory specimens. Lee *et al*. (2004) showed that the hydraulic conductivity (and also the porosity) is lower for materials stabilised with higher cement contents. The conductivity values estimated from these simulations are about an order of magnitude higher than the values measured by Lee *et al*. (2004) for stabilised scoria. It may be that the stabilised crushed basaltic rock gives higher conductivity because it contains fewer fines. The simulations match reasonably well with the experimental results except at the initial phases, which are generally dominated by inertial forces. According to this analysis, the final rise expected in these materials (under simulated conditions) would be 700 and 900 mm for 2% and 4% cement materials. Figure 4 also shows a rise curve if the groundwater level was located 800 mm below the base of the 4% cement material. This indicates that not having free water at the base of the pavement can significantly reduce the effect of water rise and, therefore, the effect of salts. It should, however, be noted that, generally, more rigorous analysis would be required to capture all dominant processes.

4.2 *Salt concentration and crystallization*

Chemical analysis was undertaken on the sectioned specimens for cations and anions. The percentages (mg/kg) within the bulk material (obtained from leaching tests) were converted to likely concentrations in the pore fluid assuming a saturation of 75% at the end of the test (Lee *et al*., 2004). The results are presented as average values for mid of four sections down from top of the specimens (depth) in Figures 6 to 9. The concentrations at the base sections match reasonably with the corresponding salt solution concentrations. Then, there is a decrease in concentration followed by a sharp increase towards

the top. Concentrations at the top sections are well below the typical crystallization concentrations, which is over about 330000 mg/L for NaCl. This is expected, first, because they are averaged (over top 75 mm or so), and second, not all pores develop crystallization concentrations. Concentration profiles appear to indicate higher ion concentrations for solutions with higher salt concentrations. Generally, even after considering the fact that Cl ion (35) has higher molecular mass than the Na ion (23), the Na ion concentration is less than the Cl ion concentration indicating that Na may have undergone some ion exchange during its transport. This highlights the importance of treating ion streaming separately in salt transport and crystallization modelling, as suggested by Kodikara *et al.* (2004).

5 CONCLUDING REMARKS

The paper presented some results of laboratory modelling of salt migration in a stabilised pavement material. The capillary rise method presented can be used to study this process, but can be enhanced by automating the visual observations using digital recording. Then the main events such as the initiation and change of crystallization may be more accurately captured. The tests show that salt crystallization is a complex process depending on a number of variables including salt water concentration, atmospheric climate, the pore structure of the material, and the depth to water table. The test method has the potential to be used for producing guidelines and validating models to be used for design against salt attack.
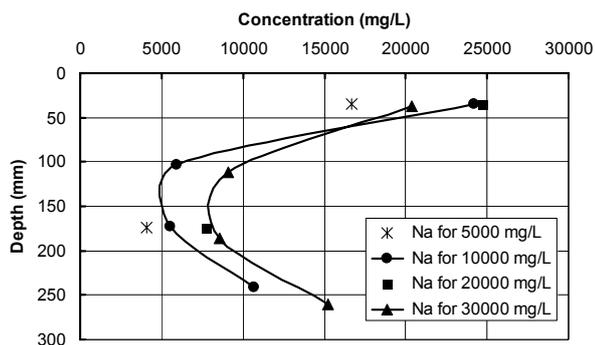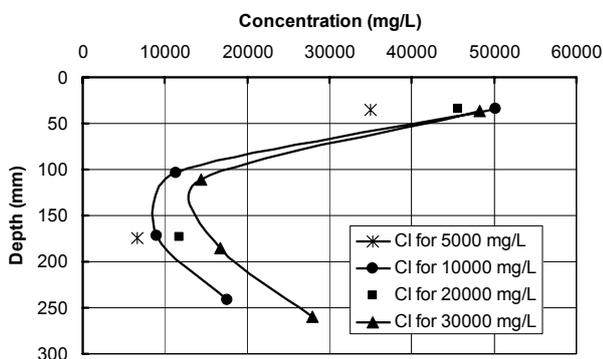

Figure 6. Na conc. for 2% cement specimens

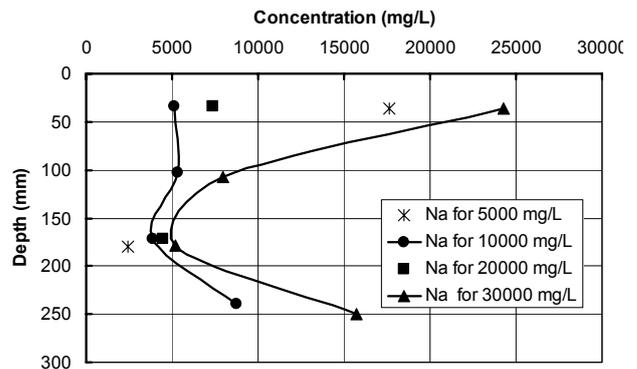Figure 7. Cl conc. for 2% cement specimens
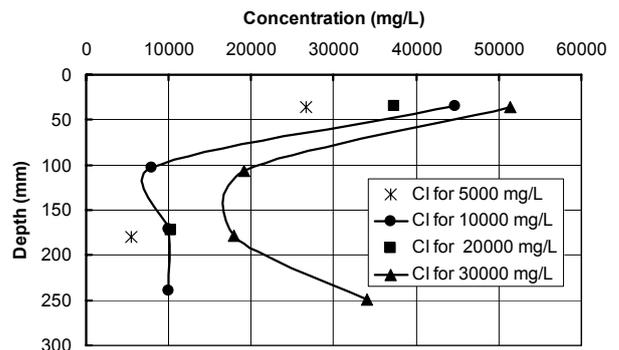

Figure 8. Na conc. for 4% cement specimens

Figure 9. Cl conc. for 4% cement specimens

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