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Wetting and drying of concrete using aqueous solutions containing deicing salts

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ABSTRACT

A series of wetting and drying tests were performed on concrete using different aqueous solutions containing deicing salts. The rate of fluid absorption was generally lower for aqueous solutions containing deicing salts than it was for water. In addition, less fluid was absorbed for samples exposed to aqueous solutions containing deicing salts than for samples exposed to water. The change in the rate of aqueous fluid absorption was proportional to the square root of the ratio of surface tension and viscosity of the absorbed fluid. Concrete that has been exposed to solutions containing deicing salts showed less mass loss during drying. Measures of equilibrium relative humidity over the salt solutions are used to interpret drying behavior. Experimental data indicates that concretes that had previously been exposed to deicing solutions can also exhibit reduced rate of absorption, even if water is the fluid being absorbed.

1. Research need and significance

Some jointed plain portland cement concrete pavements in freezing prone climates have shown premature deterioration at the longitudinal and transverse joints. While some have attributed this damage to a chemical attack, inadequate air entrainment, poor mixture design, inadequate constituent materials, or poor construction practices, it is the hypothesis of the authors of this paper that this joint deterioration may be attributed, at least in part, to preferential absorption of fluid at joints. This hypothesis was developed based on observations from the field that show these deteriorated locations frequently occurred at low spots in the pavement, where water has accumulated on the pavement, where joint sealers were damaged, or where the joint does not appear to have opened thereby trapping water [1]. Preferential fluid ingress at joints could increase a variety of damage mechanisms including deleterious chemical reactions, crystallization pressure, or freeze thaw damage that may degrade the concrete. To fully evaluate fluid ingress at the joints it is essential that the wetting and drying behavior of concrete is evaluated using aqueous solutions containing deicing salts.

This work is limited in scope as it considers only the ingress of aqueous solutions over short time periods and does not explicitly consider any chemical reaction that occurs between the aqueous solution and the concrete. This information is intended to provide reference for those developing tests to evaluate potential deicer-concrete interactions [2], for developing tests on fluid absorption, for evaluating fluid absorption in concrete [3], for input parameters in computer simulation of fluid ingress at joints [4], and for potential approaches to limit joint deterioration like penetrating sealers for possible use in concrete pavements [5].

2. Research objectives

The objective of the present paper is to evaluate: (1) the effect of initial equilibrium moisture content and sample conditioning on the rate of fluid absorption in concrete, (2) the wetting and drying behavior of concrete in the presence of deicing solutions, (3) the effect of change in fluid properties due to presence of deicing salts on the fluid absorption and drying rate of concrete, and (4) the effect of residual salts on the re-absorption of water. The

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findings of this paper have direct implications toward predicting the long-term performance of concrete pavements and provide insight to the underlying mechanism of premature joint deterioration.

3. Fluid absorption in porous materials

Fluid absorption is a frequently used test to provide an indication of the durability of hardened concrete, as it is simple to perform. Several standard tests exist for measuring water absorption including ASTM C 1585-04 [6], BS 1881-99 [7], and ASTM D6489-99 [8]. While the concept behind these tests is very similar, there are differences in how the samples are conditioned, treated, and tested. In each of these tests water is typically used as the fluid that is being absorbed. Hall [9] discusses that water can interact with the cement matrix adding complexity to the interpretation of results. To overcome some of these limitations or to indicate how absorption can be reduced by fluid composition other solutions have been tested [9–14].

MacInnis and Nathawad [15] assessed the absorption of an aqueous solution consisting of a NaCl deicing salt and reported a decrease in absorption. Sutter et al. [16] reported that sorptivity decreased from highest to lowest in the order of water, NaCl, $CaCl_2$ and $MgCl_2$. Similar data has recently been observed by Janusz [17]. As a result, it can be observed that concrete exposed to deicing salt solutions absorb fluid at a slower rate than they would absorb water; however the previous work has not related this behavior to the fluid properties or described the influence of salt concentration or properties of the aqueous solution.

The results of one-dimensional fluid absorption tests (assuming negligible gravitational effects) are typically reported as the cumulative water absorbed per surface area (surface from which water is absorbed) versus the square root of wetting time. Eq. (1) is frequently used to describe the water absorption (total volume of fluid absorbed) and the sorptivity (related to the rate of absorption) [18].

$$i = S\tau^{1/2} \tag{1}$$

where i (mm^3/mm^2) is the cumulative water absorption, S ($mm/s^{1/2}$) is the sorptivity, and τ (s) is the elapsed time. It should be noted that additional equations have been proposed to account for time dependent properties [19].

Hall et al. [9] proposed that the diffusion would scale proportionately with the ratio of surface tension (γ) and viscosity (η) of the fluid. Hall further related this to sorptivity since sorptivity is related to the square root of diffusion. Kelham [20] derived an expression for fluid absorption (Eq. (2)) that shows the relationship between depth of penetration and the square root of the ratio of surface tension and viscosity.

$$x(\tau) = \sqrt{\frac{4k\gamma\cos(\theta)\tau}{p\eta r}} \tag{2}$$

where $x(\tau)$ (mm) is the penetration depth, γ (N/mm) is the surface tension, θ (rad) is the liquid–solid contact angle, p (Dimensionless) is the porosity of the medium, r (mm) is the pore radius, k (mm^2) is the intrinsic permeability of the material, and η (Pa·s) is the viscosity of fluid. An expression similar to Eq. (2) was derived by Scherer and Wheeler [21] for stone consolidates.

Previous research using organic fluids has shown an absorption rate that scales proportionally with the square root of the ratio of surface tension and viscosity of the fluid $((\gamma/\eta))^{(1/2)}$. This work will use this approach to attempt to interpret results from absorption tests that used aqueous solutions containing deicing salts.

4. Properties of deicing salt solutions

Physical properties of pure solutions were gathered from literature and compared with measured values for the industrially available deicing solutions tested in this research, and they are provided here for convenience in one location. The properties of the deicing solutions will be used in interpreting the wetting and drying results, discussed later in this paper. This section is divided into four sections. The first three sections describe the influence of the deicing solutions in terms of surface tension, viscosity, and equilibrium relative humidity over the aqueous solution. Section 4 describes the specific gravity of the solution as a function of concentration as this is used to determine the volume of solution absorbed during the absorption test.

4.1. Surface tension of deicing salt solutions

Fig. 1a shows surface tension measurements at different concentrations for the three solutions used in this research: NaCl, $CaCl_2$, $MgCl_2$. The surface tension for NaCl was obtained from [10], $CaCl_2$ from [22] and $MgCl_2$ from [23]. A ring tensiometer was used with a resolution of 0.1 mN/m for the industrial deicers tested in this study. The tensiometer was cleaned between measurements following ASTM D971-04 [25]. The tensiometer was first calibrated using de-ionized water, which provided a value of 71.0×10^{-6} N/mm. A series of three measurements were performed for each solution, with the average reported.

The closed points in Fig. 1a are the values measured for the industrially available solutions. The lines represent values taken from literature for pure salt solutions at different mass concentrations. While the general trends are consistent, differences between the industrial deicing salts and literature values may be due to impurities or other additives. However, further work is needed to examine this in greater detail.

4.2. Viscosity of deicing salt solutions

Fig. 1b shows a comparison of the viscosities for the solutions used in this research between pure solutions taken from literature and measurements of the deicing solutions. Viscosity measurements for the industrial deicers were performed using a rheometer. The rheometer kept the solution being tested at 23.0 ± 0.02 °C and from the torque applied to the fluid that causes a shear from which the viscosity can be found. Calibration of the device was performed using a reference standard.

The dashed lines presented are viscosities at different concentrations and are taken from literature [10,22–24], while the points represent measured viscosities of the industrially available solutions. Again, differences between literature values and those of the solutions measured can be explained by differences in possible additions or chemistries of the industrial deicers.

4.3. Relative humidity of deicing salt solutions

Relative humidity measurements were performed on the salt solutions using a combination relative humidity and temperature sensor (±0.8% RH at 23 ± 0.1 °C). The relative humidity probes were mounted in a 75 mm × 68 mm stainless steel cylinder that was placed over a water jacketed sample cup holder. The water jacket was connected with a water bath at a constant temperature of 23.0 ± 0.1 °C.

Fig. 1c shows the relative humidity measured over salt solutions for a wide range of solution concentrations. As the concentration increased the relative humidity over the solution decreased. The measured relative humidities of these unsaturated salt solutions