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Case study

Corrosion of metals exposed to 25% magnesium chloride solution and tensile stress: Field and laboratory studies

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ABSTRACT

The use of chemicals for snow and ice control operations is a common practice for improving the safety and mobility of roadways in cold climate, but brings significant concerns over their risks including the corrosive effects on transportation infrastructure and motor vehicles. The vast majority of existing studies and methods to test the deicer corrosivity have been restricted to laboratory environments and unstressed metals, which may not reliably simulate actual service conditions. As such, we report a case study in which stainless steel SS 304 (unstressed and externally tensile stressed), aluminum (Al 1100) and low carbon steel (C1010) coupons were exposed to 25% $MgCl_2$ under field conditions for six weeks. A new corrosion test-bed was developed in Montana to accelerate the field exposure to this deicer. To further investigate the observed effect of tensile stress on the corrosion of stainless steel, SS 304 (unstressed and externally stressed) coupons were exposed to 25% $MgCl_2$ solution under the laboratory conditions. The C 1010 exhibited the highest percentage of rust area and suffered the most weight loss as a result of field exposure and $MgCl_2$ sprays. In terms of ultimate tensile strength, the Al 1100 coupons saw the greatest reduction and the unstressed and externally stressed SS 304 coupons saw the least. The ability of $MgCl_2$ to penetrate deep into the matrix of aluminum alloy poses great risk to such structural material. Tensile stressed SS 304 suffered more corrosion than unstressed SS 304 in both the field and laboratory conditions. Results from this case study may shed new light on the deicer corrosion issue and help develop improved field testing methods to evaluate the deicer corrosivity to metals in service.

1. Introduction

Clearing snow and ice from roadways is critical for the public safety [1,2] and improved mobility [3] in cold climate. Large amount of solid and liquid chemicals (also known as deicers) are commonly used for such operations. Deicers applied on the roadways often contain chlorides as freezing point depressant due to their affordable cost. A recent survey of highway maintenance agencies indicated that sodium chloride (NaCl) was the commonly used deicer, followed by magnesium chloride ($MgCl_2$), agro-based products, Calcium Chloride ($CaCl_2$) and others [4]. However, NaCl is rarely used and minimally effective below pavement temperatures of 10 °F [5]. $MgCl_2$ is the next best deicer which exhibits better ice melting performance at cold temperatures [6,7] and it is also less expensive than $CaCl_2$ and other agro-based products. Recently, many transportation agencies have been using $MgCl_2$

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directly or combining $MgCl_2$ with other chloride based salts for winter road operations.

Despite the benefits, the use of chemical deicers brings significant concerns over their risks including the corrosive effects on transportation infrastructure and other assets [8–10]. Corrosion of bare, coated, or embedded metals in the presence of deicers poses a significant risk to the value, performance, serviceability and reliability of motor vehicles, steel bridges, and reinforced concrete structures [11–15]. While this issue has been extensively studied as early as in 1970s [16], recent decades have seen increased use of chloride deicers in the roadway environment and the increased use of $MgCl_2$ in place of traditional salt (NaCl) or salt brine.

Considering the substantial hidden costs associated with deicer corrosion, it is important to test the corrosivity of chemical deicers before their use on the road surface. To this end, there are four common test methods used, i.e., the Pacific Northwest Snowfighters (PNS)/NACE TM0169-95 corrosion test method, the Society of Automotive Engineers (SAE) J2334 test method, Strategic Highway Research Program (SHRP) H-205.7 test method and the American Society of Testing and Materials (ASTM) B117 test method [17,18].

The vast majority of existing studies and methods to test the deicer corrosivity have been restricted to laboratory environments and unstressed metals, which may not reliably simulate actual service conditions. Most methods measure the weight loss of unstressed metals as a result of deicer exposure and mainly differ in the exposure regime of corrosion coupons. They are conducted under well-controlled laboratory conditions and thus fail to mimic the corrosion performance of metals in the field. There are a wide array of factors affecting the corrosion behavior of metals in the field deicer environment, which may include changes in temperature and relative humidity, time of wetness, wind speed, solar radiation, and presence of other contaminants. Additionally, the metallic structures or components in the service environment are often subject to mechanical stresses, instead of being unstressed. It has been reported that an externally applied tensile stress can aggravate the corrosion of certain metallic alloys in neutral 3.5% NaCl solution [19]. In the extreme case, the joint action of corrosion and tensile stress can result in a form of corrosion known as stress corrosion cracking.

In this context, the main objectives of this case study are to:

- present a test-bed developed for controlled field deicer exposure of metals;
- compare the corrosion behavior of bare metals in the field and in the laboratory; and
- develop a test method of bare metals with both deicer exposure and tensile stress incorporated.

To this end, we present the development of an atmospheric exposure site with custom-made test racks in Montana, a cold-climate state in the United States. With this test-bed, the corrosion of externally tensile stressed Type 304 stainless steel (SS 304), and unstressed SS 304, C 1010 carbon steel, and 1100 aluminum alloy periodically exposed to neutral 25% $MgCl_2$ solution was investigated. In addition, we present an accelerated laboratory test protocol that integrates external tensile stress with electrochemical corrosion of metallic coupons.

2. Methodology

2.1. Capabilities of the test-bed and laboratory facility

The main purpose of the outdoor facility was to evaluate the corrosion behavior of bare metals in a field environment with controlled deicer exposure. The corrosion test-bed was deployed in Lewistown, MT and featured the capacity to simultaneously test the corrosivity of a given chemical to eighteen unstressed metallic coupons and four externally stressed coupons over time. In the preliminary setup, a constant tensile stress was applied by hanging a concrete block on one side of the corrosion coupon which was fixed to a rigid pulley on the rack using a plastic coated steel rope. Such external loads providing external stress for the corrosion coupons can be readily replaced, depending on the testing requirements.

To simulate the periodical exposure of metallic structures or components to deicers, an automated spray system was built on top of the test tack with polyvinyl chloride (PVC) pipes, spray nozzles, timers and a 689-kPa (100-psi) water pump. The spray nozzles are well spaced so as to provide a uniform distribution of deicer spray over the corrosion coupons. There are ten spray nozzles on top of the rack which could spray the deicer solution at a pre-determined rate. The replaceable weight providing stress to metallic coupons and the automated spray system are illustrated in Fig. 1(A) and (B). Fig. 1(C) and (D) show the unstressed coupons placed on the wooden holder and the schematic top view of the test rack and coupon layout, respectively. The test racks have been designed to ensure that the corrosion coupons do not have direct contact with any other metal and to minimize any potential cross-contamination between corrosion coupons. The corrosion coupons have direct contact either with wood (unstressed coupons) or with plastic shielded ropes (externally stressed coupons). The sprayer system can automatically spray the chemical deicer periodically or randomly based on the input provided to the timer.

Furthermore, the test-bed facility has a weather station that measures parameters such as air temperature, solar radiation, wind speed, humidity, and precipitation. The outdoor facility can be monitored all day by using a remotely operated camera.

To compare the results of externally stressed coupons from the field test, a customized laboratory test was developed. Specifically, an electrochemical cell was designed as shown in Fig. 2, featuring a hollow cone-shaped plastic tube with the corrosion coupon insert. Narrow end of the plastic tube is sealed with rubber. Both ends of the coupon extending beyond the cone are gripped by the Materials Testing Systems (MTS) machine which can apply various mechanical loads to simulate the external tensile stress as deployed in the field test. A deicer solution can fill inside the cone during the test duration.