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Effects of deicers on the performance of concrete pavements containing air-cooled blast furnace slag and supplementary cementitious materials

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ABSTRACT

This study investigates the effects of continuous deicer exposure on the performance of pavement concretes. For this purpose, the differences in the compressive strength, the changes in the dynamic modulus of elasticity (DME) and the depth of chloride ingress were evaluated during and after the exposure period. Eight different concrete mixtures containing two types of coarse aggregates (i.e. air-cooled blast furnace slag (ACBFS) and natural dolomite) and four types of binder systems (i.e. plain Type I ordinary portland cement (OPC) and three combinations of OPC with fly ash (FA) and/or slag cement (SC)) were examined. These mixtures were exposed to three types of deicers (i.e. $MgCl_2$, $CaCl_2$, and NaCl) combined with two different exposure conditions (i.e. freezing-thawing (FT) and wetting-drying (WD)). In cold climates, these exposure conditions are the primary durability challenges that promote the physical deterioration of concrete pavements. The results indicated that among the studied deicers, $CaCl_2$ had the most destructive effect on the tested concretes while NaCl was found to promote the deepest level of chloride ingress yet was shown to have the least damaging impact on concretes. The microstructure evaluation revealed that the mechanism of concrete deterioration due to the deicer exposure involved chemical reactions between the deicers and concrete hydration products. The use of FA or SC as partial replacements for OPC can offset the detrimental effects of both deicers and FT/WD cycles.

1. Introduction

During their service life, concrete pavements are exposed to different environmental conditions including numerous freezing-thawing (FT) and wetting-drying (WD) cycles, which can negatively affect their mechanical and durability properties [1,2]. The FT damage in concrete occurs by two mechanisms [3]: 1) the formation of ice in the capillaries or air voids and, 2) expulsion of liquid towards unfrozen areas of the matrix. Freezing of liquid increases its volume (by about 9% - for water) and leads to the expulsion of excess water. During this event, cracks can occur when the dilating pressure caused by the freezing of water in the capillary pores exceeds the tensile strength of the concrete. In many cases, these cracks propagate severely due to the repeating FT cycles, leading to additional pressure and further damage to the concrete.

Unlike FT cycles which induces internal stress through the freezing of liquid inside the matrix, WD cycles accelerate the deterioration of concrete through the combined effects of capillary suction and diffusion [4]. During the wetting cycle, the capillary suction drives water along with the deicer-originated chloride ions inside the concrete. During the drying cycle, some water evaporates from the pores, leaving the chloride ions and, in some cases, deposits of crystal salt within the pores. These crystal salts are mainly formed by the chloride ions that can diffuse in all directions inside the concrete. This process recurs for every single WD cycle and leads to the accumulation of ionic particles including chloride ions in the concrete. The deposit of chloride ions promotes deterioration through three different mechanisms [5]: 1) chemical reactions between deicers and cement paste/aggregate; 2) physical deterioration such as salt scaling; and 3) aggravating aggregate-cement reactions such as a cation-exchange mechanism that affects the

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List of abbreviations

ACBFS	Air-Cooled Blast Furnace Slag
ANOVA	Analysis of Variance
ASTM	American Society for Testing Materials
CH	Calcium Hydroxide/Portlandite
C-S-H	Calcium Silicate Hydrate
DME	Dynamic Modulus of Elasticity
DW	Distilled Water
EDX	Energy Disperse X-Ray
FA	Fly Ash
FT	Freezing-Thawing
GGBFS	Ground-Granulated Blast Furnace Slag
IN	Indiana
INDOT	Indiana Department of Transportation
LS-Mean	Least Square Mean
M-S-H	Magnesium Silicate Hydrate
OPC/PC	Ordinary Portland Cement/Portland Cement
RH	Relative Humidity
SC	Slag Cement
SCM	Supplementary Cementitious Material
SEM	Scanning Electron Microscopy
SSD	Saturated Surface Dry
WD	Wetting-Drying

alkali-carbonate reactivity in the presence of magnesium chloride ($MgCl_2$) or calcium chloride ($CaCl_2$).

Efforts to produce a sustainable concrete pavement have led to the use of alternative materials as substitutes for the generally used ingredients such as OPC and natural aggregates. One of the main forces behind the drive to reduce the usage of OPC is related to the carbon dioxide (CO_2) emission associated with the production of OPC. It is estimated that the production of OPC contributes to 5-7% of the global CO_2 emission [6–11]. Approximately, about 0.73–0.99 ton of CO_2 is released for each ton of OPC produced. Most of it results from the limestone decomposition and emissions from the burning of fossil fuels in the cement kilns [12]. In recent years, the depletion of existing natural resources aggregates, restrictions on developing new quarries and increase in demand for concrete production have also increased the sustainability concerns in the concrete industry. To overcome and/or mitigate these concerns, air-cooled blast furnace slag (ACBFS) and supplementary cementitious materials (SCM) (e.g., FA and SC/ground granulated blast furnace slag (GGBFS)) have been widely used as partial or full replacement for, respectively, natural aggregate and OPC [13–27].

Recent work by Aghaeipour and Madkhan [28] has indicated that 40% replacement of OPC with GGBFS increased the compressive strength of concrete specimens by about 5% after 90 days of curing. The compressive strength was later reduced by 5% after 300 cycles of FT [28]. Their findings also showed that 20% replacement of OPC with GGBFS had no considerable effects in the compressive strength of concrete specimens [28]. The addition of fly ash has also been reported to improve the mechanical properties of concrete [29]. Maslehuddin et al. [23] compared the mechanical properties of concretes made with steel slag and those made with crushed limestone aggregate. The experimental results showed that the compressive strength of steel slag aggregate concrete was slightly higher (i.e., about 5%) than that of crushed limestone aggregate. The same study also reported no significant difference was observed on the flexural and split tensile strength between steel slag aggregate concrete and crushed limestone aggregate concrete. In another research conducted by Faleschini et al. [24], it was reported that the total replacement of coarse aggregate with electric arc furnace slag increased the values of the elastic modulus, tensile strength, and compressive strength by more than 20%, at w/cm of 0.4 and 0.45.

This study aims to investigate the effects of using ACBFS, a by-product of iron industry, as a substitute for natural aggregate in pavement concretes. Four types of binder systems, including one plain system (OPC only), two binary systems (20% FA + 80% OPC and 25% SC + 75% OPC), and one ternary system (17% FA + 23% SC + 60% OPC) were used in this study. In addition, the effects of three types of deicers (i.e., NaCl, $MgCl_2$, and $CaCl_2$) on the performance of pavement concrete under simulated FT and WD conditions were also examined. The performance of concretes was assessed through the determination of the loss in the compressive strength, the changes in the value of the DME of prismatic concrete specimens, and the chloride penetration depth. The evolution in concrete microstructure caused by the chemical reaction between the deicers and the hydration products was assessed using the scanning electron microscope (SEM) equipped with the energy-dispersive X-ray (EDX) detector.

2. Materials and methods

This section provides information regarding the characteristics and properties of the materials as well as the mixture proportions used to prepare concrete specimens. In addition, this section describes the statistical design and analysis of the experiments performed in this study.

2.1. Materials

Two types of coarse aggregates (i.e., ACBFS and dolomite) with the maximum size (D_{max}) of 25 mm and one type of fine aggregate (i.e., natural siliceous sand) with the D_{max} of 9.5 mm were used in preparing the concrete mixtures. These aggregates satisfied the properties and gradations requirements of the Indiana Department of Transportation (INDOT) [30]. The saturated surface dry (SSD) specific gravity and absorption values of all aggregates are shown in Table 1. Fig. 1 shows the gradation of the aggregates alongside with the requirements for #8 coarse aggregate and #23 fine aggregate as per INDOT's requirement for aggregates used in paving application [30].

Three different deicing solutions were used in this study: sodium chloride brine (NaCl), magnesium chloride brine ($MgCl_2$), and calcium chloride brine ($CaCl_2$). Distilled water (DW) (although not being a deicer) was also used as a reference soak liquid for evaluating the effects of the deicers. Sodium chloride brine was prepared by mixing rock salt with water to produce a 28.4% sodium chloride solution. NaCl solution was then diluted with deionized water to obtain concentrations of 14% and 23% for FT and WD exposure conditions. The equivalent total ions (i.e., anions and cations) concentration of these represented, respectively, 5.5 M and 10.5 M solutions. The concentrations of $MgCl_2$ used in FT and WD exposure conditions were also adjusted to be 5.5 M (15% by weight) and 10.5 M (25% by weight) of total ions concentration, respectively. Similarly, $CaCl_2$ was also diluted to reach the concentrations of either 5.5 M (17% by weight) or 10.5 M (28% by weight) for FT and WD exposure conditions, respectively.

The selection of concentrations of deicers for the use in this study was based on the results of the previous study [1], which examined the deicing practices in both Indiana as well as other states.