JOINT TRANSPORTATION RESEARCH PROGRAM

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Investigation of Use of Slag Aggregates and Slag Cements in Concrete Pavements to Reduce the Maintenance Cost

Introduction

This project originated in response to the reported field cases of deterioration of pavement concrete containing air-cooled, blast furnace slag (ACBFS) aggregates. Although the root causes of the observed deterioration were not always entirely clear, some of the concerns appeared to be related to the physical characteristics and chemical composition of the slag aggregates themselves. These included such issues as the perceived variability of specific gravity and porosity of aggregate particles, as well as the fact that such aggregates can contain the soluble calcium sulfide (CaS). The presence of this compound has been linked to the formation of secondary ettringite, which can deposit in the existing air-void system, thus making it less effective in offering freeze-thaw resistance to concrete.

The main purpose of this research was to evaluate the influence of using air-cooled blast furnace slag (ACBFS) coarse aggregate as a replacement for natural dolomite coarse aggregate on the mechanical properties and durability of pavement concrete mixtures. All mixtures containing ACBFS were designed to meet the requirements of Indiana Department of Transportation (INDOT) specifications for pavement concrete. The scope of the study included evaluation and analysis of the effects of ACBFS on concrete properties in the presence of three different types of deicers ($CaCl_2$, $MgCl_2$, and NaCl). These evaluations were conducted under simulated temperature cycles that represented exposure to freezing-thawing (FT) and wetting-drying (WD) conditions.

Eight different concrete mixtures were produced in the course of this study. These mixtures were prepared using two types of coarse aggregates, ACBFS and (for comparison with the typical INDOT mixtures) dolomite. Four different binder systems were used, including: (a) plain – 100% portland cement (PC); two types of binary binder systems, (b) 20% fly ash (FA) + 80% PC and (c) 25% slag cement (SC) + 75% PC; and a single ternary system, (d) 17% FA + 23% SC + 60% PC.

Each mixture was used to prepare several types of specimens for laboratory testing. The test performed on fresh concrete included determination of slump, unit weight, and entrained air content. The mechanical properties of the hardened concrete were assessed by conducting compressive strength and flexural strength tests. The durability of concrete was assessed by periodically measuring relative dynamic modulus of elasticity (RDME) and by monitoring the length changes of the prismatic specimens. The changes in the physical appearance of specimens exposed to either FT or WD conditions were documented at different stages of the exposure cycles. The depth of chloride ion penetration was measured after completion of the exposure period. The combined effects of the deicer/exposure conditions on the microstructure of the concrete were evaluated using scanning electron microscopy (SEM) analysis on the specimens after completion of the exposure test.

Findings

This study demonstrated that air-cooled blast furnace slag (ACBFS) can safely replace the natural coarse aggregate in a typical pavement concrete. Potential benefits of using ACBFS aggregate in pavement concrete include improved quality of the paste due to the possibility of internal curing and reduced risk of alkali-silica reaction (ASR) due to the absence of an active form of silica in the aggregate particles. The specific gravity of ACBFS is also lower than that of a typical natural aggregate, thus resulting in a larger volume of concrete for the same weight (an economical benefit). However, it should also be realized that ACBFS has lower resistance to the abrasion compared to dolomite and it contains calcium sulfide, which can dissolve and release sulfide into the pore solution. That sulfide can subsequently oxidize and convert to sulfate, thus increasing the potential for sulfate-related problems. Moreover, in some cases, the leaching of calcium sulfide (CaS) from ACBFS particles was found to create intraparticle porosity, which may weaken the aggregate. With that said, none of these were found to have any measurable negative impact on the durability of concrete under the conditions used in this study. This is mostly because, as discussed below, the durability of concrete was primarily controlled by the type of the binder system and the type of the deicer used.

Under the exposure conditions used in this study (i.e., FT and WD cycles in the presence of the deicers), the durability of pavement concrete was highly improved in cases where part of the portland cement was replaced by either fly ash, slag cement, or a combination of these materials. The observed improvement is attributed to a reduction in the amount of calcium hydroxide present in the hydrated matrix (due to pozzolanic reaction) and to densification of the matrix by formation of additional C-S-H (also due to pozzolanic reaction). Both of these processes reduced the vulnerability of the matrix to chemical attack by chloride-based deicers. In addition, the use of slag cement reduces the total alkali content of the pore solution (especially at later ages), which is beneficial with respect to minimizing the potential for dissolution of calcium sulfide from ACBFS aggregate.

In terms of their role in concrete deterioration, calcium chloride was found to be the most aggressive deicer, followed by magnesium chloride and sodium chloride, respectively.

The mechanisms of deterioration of concrete exposed to $CaCl_2$ and NaCl deicers were found to be similar. Specifically, in both cases, the deicers reacted with calcium hydroxide, producing expansive compounds that resulted in deterioration of concrete matrix. This, in turn, allowed for more extensive penetration of water and deicers into the concrete matrix. However, the deterioration rate of $CaCl_2$ was found to be much faster than that of NaCl. The faster deterioration rate observed in the presence of $CaCl_2$ can be attributed to the formation of calcium oxychloride.

Two most common concrete deterioration mechanisms triggered by the exposure of $MgCl_2$ involved its reaction with calcium hydroxide and calcium—silicate-hydrate (C-S-H) to produce $CaCl_2$ and magnesium-silicate-hydrate (M-S-H), respectively. Unlike C-S-H, M-S-H does not have binding capacity and thus reduces the strength of the concrete.

Statistical analysis has proven to be an effective tool in assessing the significance of several different variables (i.e., type of binder system, type of aggregate, type of deicer, and type of exposure conditions) in affecting concrete properties. Moreover, Tukey's multiple comparison method was found to be suitable for differentiating the impact of different levels within a specific factor.

The benefit cost analysis has proven that air-cooled blast furnace slag (ABCFS) is economically feasible alternative to natural stone to be used as a coarse aggregate in pavement concrete.

Implementation

The results from this study revealed that ACBFS is a viable alternative for natural coarse aggregate to be used in pavement concrete. The usage of fly ash, slag cement, and the combination of both as partial replacement of portland cement was found to not only improve concrete's strength at later ages, but also to increase concrete durability in the presence of deicers and under the FT/WD exposure conditions used in this study. Among the three types studied, the calcium chloride ($CaCl_2$) deicer was found to be the most aggressive in terms of inducing damage to the concrete. The next (in terms of its deteriorative effects) was the magnesium chloride ($MgCl_2$) deicer, followed by sodium chloride (NaCl). Thus, it is advised that the use of these deicers on plain concrete pavements should be more strictly monitored and restricted to cases where other deicers cannot provide the required safety of roadways.

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