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Performance of 25-year-old silica fume and fly ash lightweight concrete blocks in a harsh marine environment

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ABSTRACT

This paper presents the long-term durability performance of semi-lightweight concrete containing various levels of supplementary cementing materials (SCM) and steel fibers when exposed to a harsh marine environment for up to 25 years. Concrete specimens (305 × 305 × 915 mm [1 × 1 × 3 ft.]) were casting using W/CM in the range of 0.26 to 0.60.

The depth of chloride penetration was greater than 90 mm (3.5 in.) for all the control specimens (without fly ash and silica fume). However, mixes containing both silica fume and fly ash (with W/CM ranging from 0.40 to 0.60) performed very well resulting in chloride penetration of approximately 40 mm (1.6 in.) during the same period. The results from the chloride permeability testing also indicate significant increases in the resistance to chloride-ion penetration for ternary concrete containing fly ash and silica fume.

1. Introduction

The penetration of chloride ions in concrete typically arises from concrete located in a marine environment and/or exposed to road salts. Although concrete is currently designed to withstand chloride ingress, it is inevitable that chlorides will eventually reach the surface of the reinforcement and initiate corrosion of the steel. Chloride-induced corrosion is the leading cause of premature deterioration of reinforced concrete, which may lead to a reduction in strength, serviceability and even loss of the structure [1]. Increased resistance to chloride ingress can be achieved by, among other things, the implementation of a low water-to-cementitious (w/cm) ratio, the addition of supplementary cementitious materials (SCMs), and the application of membranes or sealers.

Pozzolanic materials such as fly ash and silica fume are beneficial in reducing the porosity by reacting chemically with portlandite (calcium hydroxide), resulting in the formation of additional C-S-H, which densifies the matrix. The use of fly ash and silica fume has been shown [2, 3] to improve the durability performance, by increasing chloride binding, decreasing chloride penetrability and improving the mechanical properties. Researchers [2, 4, 5] have also argued that the presence of SCM either increases or decreases the chloride threshold required to initiate corrosion. Trejo and Tibbits [4] found that systems containing 20 to 40% fly ash have an average chloride threshold that is about 12% of the chloride threshold of mixtures containing no fly ash and proposed that this reduction might outweigh the benefit of increased resistance to chloride-ion penetration and actually reduce the time to corrosion when fly ash is used.

Fly ash and silica fume are suited for use together in a ternary blended cement as silica fume compensates for the low early strength of fly ash addition, whereas fly ash compensates for the low workability issues of silica fume [6]. The two SCMs also refine the pore structure by reducing both the pore size and connectivity, and increase tortuosity. The addition of fly ash is also beneficial in reducing chloride penetration through chloride binding. Thomas et al. [7] found that fly ash showed an increase in binding, and silica fume showed a decrease in binding capacity. An increase in C-S-H is generally considered to increase chloride binding capacity, however Beaudoin et al. [8] suggests that the degree of binding is dependent on the (C/S) ratio, which may explain the reduced binding capacity of silica fume. The improved binding capacity of fly ash is mainly a result of its alumina content, which results in chemical binding and the formation of Friedel's salt ($3CaO{\cdot}Al_2O_3{\cdot}CaCl_2{\cdot}10H_2O$) [1, 9, 10].

The addition of lightweight aggregate is also beneficial in reducing the penetration of chlorides as a result of the superior contact zone (interfacial transition zone or ITZ) between the cement paste and lightweight aggregate (LWA). Thomas and Bremner [11] studied the performance of lightweight aggregate concrete containing slag after 25 years in a harsh marine environment and found the performance of blocks containing LWA was improved compared to blocks produced

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Fig. 1. Treat Island platform pictured at just above mid-tide level.

with normal density aggregates; this finding is consistent with earlier studies [12–16]. Holm et al. [16] found that the refinement of ITZ only occurred with LWA that has a porous outer layer. This results in the penetration of cement hydration products into the outer pores thereby creating a dense matrix between the two materials.

This paper presents the durability performance of semi-lightweight concrete containing various levels of fly ash and silica fume exposed to a harsh marine environment for 24 and 25 years.

2. Experimental

In 1978, the Canadian Centre of Mineral and Energy Technology (CANMET) initiated a long-term study to determine the performance of concrete prisms (305 × 305 × 915 mm [1 × 1 × 3 ft.]) made with and without supplementary cementing materials (up to 80% by mass of cementing material in some cases), plastic and metal fibers, and plain and epoxy-coated reinforcement. Between 1978 and 1994, 14 different series (Phase I to XIV) of concrete mixtures were placed at the mid-tide level (see Fig. 1) at the Treat Island exposure site [11, 17–21].

Treat Island (see Fig. 1) is an outdoor exposure site operated by the U.S. Army Corps of Engineers, U.S.A. and lies in the Passamaquoddy Bay, part of the Bay of Fundy near the town of Eastport in Maine, U.S.A. [22]. Concrete specimens on this site are exposed to approximately 100 cycles of freezing and thawing per year; the tides at the site are also among the highest in the world (6 m [20 ft]).

This paper is associated with Phases VI and VII of this study, which investigated the performance of air-entrained lightweight concrete containing various levels of steel fiber-reinforcement, fly ash and silica fume. The blocks had been exposed to tidal conditions in the Bay of Fundy for almost 25 years representing approximately 18,250 cycles of wetting and drying, and 2500 cycles of freezing and thawing.

2.1. Materials

In 2010, ten prisms from Phase VI and VII were retrieved from the mid-tide level at Treat Island following 25 and 24 years of marine exposure, respectively. These blocks were produced using two Portland cements, one fly ash and two silica fumes. The chemical composition of all constituents can be found in Table 1. Concrete specimens were produced from five series (S, T, U, V and W) as part of two phases (three series from Phase VI and two series from Phase VII) of mixtures with different nominal water-to-cementing-materials ratios ranging from W/CM = 0.26 to 0.60 as presented in Table 2.

Concrete specimens in Phase VI were cast using a Portland cement (Type II PC) with a C_3A content of 6.10% (Bogue calculation) and varying levels of both silica fume (SF1) from Becancour, Quebec, Canada and fly ash (FA) from Lingnan, Nova Scotia, Canada. These blocks were cast with and without hooked-end steel fibers (50 mm × 0.5 mm [2 in. × 0.02 in.], at 2.5% by weight of cement). Control mixtures containing only Portland cement were also cast in this phase.

Phase VII comprised of only two mixtures, both with silica fume; there was no control mixture for this phase. These specimens were cast using a Portland cement (Type I PC) with a C_3A content of 9.90% (Bogue calculation) and a silica fume (SF2).

Concretes from both phases were cast using a natural sand from Blagdon, New Brunswick, Canada and an expanded shale from Minto, New Brunswick as a coarse aggregate with a maximum nominal diameter of 25 mm (1 in.). No fibers were used in this phase.

The mixtures in Phase VI were produced using a counter-current pan mixer whereas the mixtures in Phase VII were produced in a commercial ready-mixed concrete plant.

All concrete mixtures from both phases were air-entrained with a sulphonated hydrocarbon air-entraining admixture in order to achieve a target air content of 6 ± 1%. A naphthalene high-range water reducing admixture was also used in both phases to ensure a slump between 80 and 120 mm (3.15 and 4.75 in.)

2.2. Specimens

All specimens (305 × 305 × 915 mm [1 × 1 × 3 ft]) were cast in two layers of equal depth with each layer vibrated with an internal vibrator. Upon completion, the concrete was struck off with a wooden straight edge and then covered with wet burlap and plastic in order to cure. The prisms were demoulded after 24 h curing in laboratory air and then covered in wet burlap and plastic sheeting. Prims were cured for 90 days prior to being shipped to Eastport for subsequent transport by boat to Treat Island. In addition to the prisms, two 102-mm × 204-mm diameter cylinders were cast in order to measure the compressive strength following 28-days of moist curing.