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Performance of high-volume fly ash concrete in marine environment

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ABSTRACT

This paper presents the durability performance of concrete incorporating high-volumes of fly ash exposed to a harsh marine environment for 19 to 24 years. Concrete specimens (305 × 305 × 915 mm [1 × 1 × 3 ft.]) were cast using W/CM in the range of 0.31 to 0.46, various types of fly ash with replacement levels of 56 or 58%, and various types of normal density and lightweight aggregates.

Surface erosion/scaling was seen on all specimens; the extent of erosion was slightly worse for fly ash concrete with normal density aggregate compared to the controls (without fly ash), but fly ash concrete with two of the three lightweight aggregates exhibited severe surface erosion.

Laboratory testing included taking cores from each block and determining the existing chloride profile, compressive strength and “chloride permeability” (ASTM C1202).

The depth of chloride penetration was found to be in excess of 100-mm (4 in.) for the concrete specimens without fly ash, whereas the presence of fly ash significantly decreased the depth of penetration to approximately 30 and 40 mm in specimens containing either normal density or lightweight aggregate, respectively. The increased penetration in the concrete with lightweight aggregates is attributed to the surface erosion observed with these concretes. The results from the chloride permeability testing also indicate significant increases in the resistance to chloride-ion penetration for fly ash concrete.

1. Introduction

The production of Portland cement accounts for approximately 7% of global anthropogenic CO₂ emissions [1]. Hence, there is a need to reduce carbon emissions by lowering the amount of Portland cement used [2]. The use of high-volume fly ash (HVFA) concrete has recently gained popularity as a durable and sustainable alternative to ordinary Portland cement concrete. Similar to other supplementary cementing materials (SCM) such as natural pozzolans, silica fume and slag, fly ash is an environmentally friendly alternative to ordinary Portland cement as it is an industrial by-product. In a number of countries around the world, only a portion of the fly ash produced is currently being used in concrete; for example only twenty-four of the forty-four million tons of fly ash produced in the United States in 2015 were used as a cementing material in concrete (either as a component of blended cement or as a separate addition at the concrete mixing stage) [3].

Fly ash is normally used to partially replace Portland cement at relatively low levels of 15 to 25% (by mass). However, many authors have demonstrated that replacement levels of between 40 and 60% fly ash can produce good strength development, and excellent resistance to alkali-silica reaction, freezing and thawing, chloride-ion penetration, sulphate attack and water permeability [4–9]. It has also shown to

reduce heat of hydration and the risk of thermal cracking [8,9]. However, the performance of HVFA concrete in applications where deicing salts are applied is a concern due to the perception of increased surface scaling [10]. Bouzoubaa et al. [11], reported that HVFA concretes generally have comparable or superior mechanical and durability performance to concrete without fly ash, the exception being inferior salt-scaling resistance of fly ash content. The inadequate deicing salt scaling resistance has also been reported by others [12].

It has been shown in laboratory and field studies that fly ash can mitigate corrosion by hindering chloride penetration as well as decreasing the content of free chlorides. Fly ash reacts pozzolanically with calcium hydroxide to produce calcium-silicate hydrates (C-S-H), which produces a more refined pore structure and reduces permeability. It has also been reported to increase aluminate hydrates and produce a C-A-S-H gel, which increases the capacity to bind chlorides compared to ordinary Portland cement (OPC) concrete [13]. Dhir et al. [13], found that the chloride binding ability increased up to replacement levels of 50% by mass and then declined at 64%. An increase in binding ability of HVFA concrete may be attributed to the high alumina content in fly ash, which results in the chemical binding of chlorides and the formation of Friedel's salt. Thomas et al. [14–18], studied the performance of concretes containing high volumes of fly ash (up to 50%) exposed in

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a marine environment for 10 years and found that the resistance to chloride penetration increases as the fly ash content increases. However, it was found that poorly-cured, low-strength fly ash concrete carbonated at a much faster rate than straight ordinary Portland cement, as a result of the decreased amount of $\text{Ca}(\text{OH})_2$ [14,17]. Thomas [19] also reported that fly ash appears to decrease the chloride threshold required to initiate corrosion. He found that fly ash replacement levels of 0, 15, 30 and 50%, resulted in chloride thresholds of 0.7, 0.65, 0.5 and 0.2% by mass of cementitious material, respectively. The decrease in threshold values with increasing fly ash content is assumed to be the result of a reduced OH^- content leading to an increased Cl^-/OH^- in the pore solution [20,21]. Despite the lower chloride threshold values, fly ash concrete was found to provide better corrosion protection due to its higher resistance to chloride penetration.

In 1978, the Canadian Centre of Mineral and Energy Technology (CANMET) initiated a long-term study to determine the performance of concrete prisms ($305 \times 305 \times 915$ mm [$1 \times 1 \times 3$ ft.]) made with and without supplementary cementing materials, plastic and metal fibers, and plain and epoxy-coated reinforcement. Between 1978 and 1994, nearly 300 concrete specimens, as part of 14 separate phases (Phases I to XIV), were placed at the mid-tide level at the Treat Island exposure site [22,23].

Treat Island is an outdoor exposure site operated by the U.S. Army Corps of Engineers, U.S.A. and is located in Passamaquoddy Bay, which runs into the Bay of Fundy. The site is exposed to the highest tides in the world (6.2 m [22 ft.]) as well as 100–160 freezing-and-thawing cycles per annum making it one of the harshest concrete environments in the world [24].

This paper presents results from testing concrete blocks from Phase VIII, XI and XIII, which contained 56 or 58% fly ash, incorporating either lightweight or normal-density aggregates, that were removed from Treat Island following 19 to 24 years of marine exposure. The testing included the determination of mechanical properties, depth of chloride-ion penetration, and “chloride permeability” by electrical conductance.

2. Materials and methods

This paper is concerned with evaluating concrete from Phases VIII, XI and XIII of the CANMET study in which specimens were placed in the tidal zone of the Treat Island exposure site in 1987, 1990 and 1992, respectively. In 2011, following 19 to 24 years of exposure, a total of thirteen prisms were retrieved from Treat Island. It was originally intended that all of the blocks would be removed once they reached an age of 25 years. However, concerns about the deterioration of the mid-tide wharf at Treat Island necessitated early retrieval.

The first CANMET study on high-volume fly ash (HVFA) concrete (Phase VIII) was initiated in 1987 when eight blocks from four mixes containing 56% fly ash were placed at the mid-tide level at Treat Island; control mixes (straight Portland cement concrete) made to the same workability, consistency and air content were placed at the same time. The second study (Phase XI) was initiated in 1990 when twelve blocks from three mixes containing 56% fly ash with various lightweight aggregates (LWA) were placed on the exposure site. Finally, in 1992, sixteen blocks (Phase XIII) were placed at the same location. These blocks were cast using a range of different fly ashes at a replacement level of 58%.

2.1. Materials

Three ASTM C150 Type I Portland cements (OPC) and six ASTM C618 fly ashes were used as part of this study. The composition of all cementitious materials used are given in Table 1, together with the calculated Bogue compositions, while mix proportions together with fresh concrete properties are given in Table 2. PC-1, PC-2 and PC-3 had C_3A contents of 11.0, 6.4 and 11.9% (Bogue calculation), respectively.

FA-1 was obtained from a plant in Lingan, Nova Scotia, Canada, whereas FA-2 to FA-6 were obtained from plants across the United States.

Concrete prisms were cast using a W/CM ranging from 0.31 to 0.46. Fly ash replacement levels of 56% were used in Phases VIII and XI, whereas a replacement level of 58% was used in Phase XIII. In all mixes, a sulphonated hydrocarbon type air-entraining admixture was used in order to achieve an air content of 5 to 8%. In order to maintain a relatively low W/CM in HFVA systems, a moderate dose of a high-range naphthalene-based superplasticizer was used in order to achieve a slump of 150 ± 25 mm (5.9 ± 1.0 in.). Concrete in Phase VIII was cast using a normal density gravel as the coarse aggregate while Phase XIII was cast using a crushed limestone as the coarse aggregate. Both aggregates had a nominal maximum size of 19 mm (0.75 in.). Concrete for Phase XI was cast using light-weight aggregates (LWA) from sources in New Brunswick, Canada (designated as BA1), West Germany (designated as BB2) and New York state (designated as BC1). Both BA1 and BB2 were expanded shales whereas BC1 was an expanded clay. All three aggregates had a nominal maximum size of 12.5 mm (0.5 in.). The fine aggregate used in all phases was a natural sand. Note that the range in W/CM was 0.31 to 0.39 for the HVFA concrete mixes but the “control” mixes (without fly ash) in Phase VIII had W/CM values of 0.38 and 0.46.

2.2. Specimens: fabrication, coring and exposure condition

All prisms ($305 \times 305 \times 915$ mm [$1 \times 1 \times 3$ ft.]) were cast in two layers of equal depth with each layer consolidated using an internal vibrator. 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. Prisms were cured for 90 days prior to being shipped to Eastport, Maine, for subsequent transport by boat to Treat Island. Specimens were placed on a platform which is located at the mid-tide level. Treat Island is exposed to 100–160 freeze-thaw cycles and the highest tides in the world—up to 6.2 m (22 ft.). The seawater has an average annual temperature of 5°C (40°F) and a chloride concentration of 19,300 ppm (3.52% salinity).

2.3. Items of investigation

Two 95-mm (3.75 in.) and two 108-mm (4.25 in.) concrete cores were taken along the centerline of the top (hand finished) face of each block; the cores were cut directly through the blocks and were approximately 305 mm (12 in.) in length. The larger-diameter cores were used to measure the compressive strength, whereas the smaller-diameter cores were used to produce specimens for the rapid chloride permeability test (RCPT) and to determine existing chloride profiles. Compressive strength (ASTM C39) was conducted on 108-mm (4.25 in.) diameter cores by removing a length of approximately 38 mm (1.5 in.) from each end of the core to provide the specimen with an aspect ratio of 2. RCPT (ASTM C1202) was conducted on 50-mm (2 in.) long specimens cut from the centre portion of the 95 mm (3.75 in.) diameter cores in order to minimize chloride concentration resulting from the exposure of seawater. Note in the case of the HVFA concrete mixtures, these test specimens were beyond the depth of penetration of chlorides from seawater but it was not possible to get chloride-free samples for the control mixtures as chlorides had penetrated to the middle of the blocks. Existing chloride profiles were conducted on the outer 95 mm (3.75 in.) of each core by profile grinding the cores in 2-mm (0.08 in.) increments. The resulting powder samples were analyzed for chlorides relative to depth. The chloride content at each layer was determined by digesting powder samples gained from profile grinding in nitric acid and performing potentiometric titration with silver nitrate. Chlorides were determined for each layer until the background chloride concentration was reached for the fly ash concrete, or to a maximum depth

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