



Performance of rapid-repair concrete in an aggressive marine environment



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HIGHLIGHTS

- The durability performance of ettringite-based binders in terms of chloride penetration and corrosion is presented.
- Calcium sulfoaluminate cement based binders result in an increased corrosion rate compared to other ettringite-based binders.
- The abundance of ettringite results in a decrease in chloride binding due to the reduced ability of Friedel's salt to form.
- The newly developed ettringite-based binder results in a corrosion performance similar to Portland cement.

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ABSTRACT

Rapid-repair concretes are currently used to repair structures such as bridge decks, substructure elements on bridges (e.g. piers and columns), pavements, and components of buildings. Rapid-repair concretes must not only achieve a high-early strength in a short period of time (e.g. 20 MPa in 3 h) but must also survive for the remaining life of the structure. One way of achieving high early-age strength is the use of ettringite-based cements; in these cements early strength is attributed to the rapid formation of ettringite by incorporating, in the binder, calcium sulfo-aluminate cement or a combination of calcium aluminate cement and calcium sulfate. Although research has proven that early-strength is achievable, there exist limited published durability data for these systems. This paper presents data on the performance of a number of rapid-repair materials placed at the high-tide level of a marine exposure site (Treat Island, Maine, USA) which experiences approximately 100 freeze-thaw cycles a year making it one of the harshest environments for concrete in the world. A number of concretes were studied including an ordinary Portland cement (PC) and a high-early strength Portland cement (HEPC) as references, PC accelerated by calcium aluminate cement (CAC) with calcium sulfate (C\$), PC accelerated by calcium sulfo-aluminate (C\$A(2)-PC), and calcium sulfo-aluminate belite (C\$A(1)-C₂S) cement on its own. Reinforced concrete specimens were monitored on a yearly basis to evaluate the corrosion condition of the steel. After three years of exposure, reinforced concrete beams from each mix were returned to the laboratory to determine chloride profiles, and to conduct X-ray diffraction (XRD) and microstructural investigation using scanning electron microscopy (SEM) coupled with energy dispersive X-ray (EDS) analysis.

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1. Introduction

The corrosion of reinforcement is one of the leading causes of premature deterioration in concrete structures in North America. 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. 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 and sealers.

Ettringite-based (rapid set) concretes are used in applications where construction time is limited in order to avoid the disruption of the travelling public. They are currently used to repair bridge decks, substructure elements on bridges (i.e. piers and columns), pavements, and components of buildings. Ettringite-based concretes are capable of achieving a very-high early compressive

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strength (i.e. 20 MPa in 3 h) and are also intended to last the remaining life of the structure. High-early strength is achieved by the rapid formation of ettringite ($C_3A \cdot 3C\$, H_{32}$) in the first few hours of hydration by using a binder typically comprised of calcium sulfo-aluminate (C\\$A) cement or calcium aluminate cement (CAC) plus calcium sulfate (C\\$).

The discovery of calcium aluminate cement (CAC) occurred in the early 1900s, where it was discovered that alumina-rich calcium aluminate had very good cementing properties [1]. CAC was originally developed as a sulfate resistant cement although also has adopted a number of other properties including rapid hardening, abrasion and impact resistant, use at low temperatures and heat resistant. CAC results in a phenomenon known as conversion where metastable hydration products initially formed convert into stable products as both time and temperature increase. Conversion results in an increase in porosity and a concomitant decrease in strength due to the formation of these stable hydration products [1–4]. The elimination of conversion has been studied by numerous authors including Lamberet and Scrivener [3] who found that by adding PC and C\\$ not only eliminates conversion, but results in rapid strength gain. Numerous authors have presented on the strength evolution of these systems [3–5], which have a similar strength evolution to C\\$A based binders [5], although there exist no published durability data on these systems.

Marine concrete structures are exposed to very harsh conditions. The constant exposure to seawater results in physical damage and strength loss as a result of corrosion of the embedded steel [6]. One of the harshest marine environments in the world is found at Treat Island, located off the coast of Eastport, Maine in the Passamaquoddy Bay, which is part of the Bay of Fundy. A beach located on the western side of the island has been used as a materials research exposure site for more than 75 years and specimens stored on the beach experience approximately 100 freeze-thaw cycles a year. Reinforced concrete specimens placed at the high-tide level are where corrosion is at its maximum due to the wetting and drying as a result of the tides, which are world renown as the highest in the world, reaching elevation changes greater than 6 m. At this level both chlorides and oxygen are available to, respectively, initiate and sustain corrosion. Corrosion is initiated if the concentration of chlorides at the depth of the steel is greater than the chloride threshold required to destroy the passive layer and initiate corrosion. However, the penetration of chloride may be mitigated through the effect of chloride binding. Chlorides are mitigated from reaching the surface of reinforcement by either becoming physically or chemically bound to cement hydrates [7–9]. Monosulfoaluminate (AFm) phases, which are abundant in PC based systems are generally known to bind chlorides through chemical substitution, whereas the C-S-H phase is considered to physically bind chlorides [8]. The chemical interaction between chloride ions and Monosulfoaluminate (AFm) phases results in the formation of Friedel's salt ($3CaO \cdot Al_2O_3 \cdot CaCl_2 \cdot 10H_2O$; FS) [9]. Limited binding data exist on ettringite-based binders although many have found that ettringite (AFt), has a much lower if not inability in binding chlorides [9–11]. Zibara [12] found that the ability of a system to bind chlorides is attributed to the content of calcium aluminates and calcium aluminoferrites, which lead to the formation of Friedel's salt. Although rapid strength in systems containing CAC and C\\$ or C\\$A is achieved through the early formation of ettringite, there is concern in terms of corrosion resistance due to the inability of ettringite to bind external chlorides.

The repair of concrete structures is a never-ending process. Approximately \$1 billion is spent to repair marine piles in the United States alone [13]. In tidal areas, rapid-repair concretes are required for repair applications where time is of the essence and the repair must be placed and cured between tides.

This paper presents the corrosion performance of reinforced beams placed at the high-tide level of Treat Island for approximately three years. Corrosion measurements, chloride penetration profiles, X-ray diffraction (XRD) and scanning electron microscopy (SEM) analysis were conducted on a number of repair materials.

2. Experimental

2.1. Materials

Three rapid-repair (ettringite-based) binders were studied together with an ordinary Portland cement (PC) and a high-early-strength Portland cement (HEPC) as a control. The first repair system is a newly-developed ternary system composed of ordinary Portland cement (PC), calcium aluminate cement (CAC) and a source of calcium sulfate (C\\$) and is designated as PC-CAC-C\$. A ratio of 2.2 to 1 parts of CAC to C\\$ was used whereas Portland cement accounted for 70% of the total cementitious content. The second cement used was a calcium-sulfoaluminate (C\\$A) cement with belite (C_2S) and is designated as C\\$A(1)- C_2S . The third system is comprised of a second C\\$A source blended with 70% PC and is designated as C\\$A(2)-PC. The proportions of the three ettringite-based binders previously introduced were developed based on previous work conducted by Lamberet [3]. The proportions were also adjusted to achieve a three-hour compressive strength of at least 20 MPa and a working time in excess of 15 min.

The fourth cement is a high-early strength Portland cement (HEPC). The fifth and final cement is an ordinary Portland cement (PC), which acted as a control. The chemical composition of these cements is presented in Table 1. The ordinary Portland cement (PC) used as the control was the same Portland cement used in both the PC-CAC-C\$ and C\\$A(2)-PC systems.

All mixes were prepared with a 19-mm graded crushed siliceous gravel and a natural siliceous sand. In order to achieve maximum workability without increasing the water content, a liquid polycarboxylate-ether base superplasticizer was used in all mixes except for the control (PC). In addition, citric acid ($C_6H_8O_7$), a common natural preservative was used as a retarder in the PC-CAC-C\$ system at a dosage of 0.38% by mass of CAC-C\$ in the mix. All mixtures were air-entrained with a neutralized vinsol resin to achieve an air content between 5 and 7% according to CSA A23.1. A summary of mixture proportions and properties is found in Table 2. Compressive strength results after 3 h, 1 and 28 days are also shown. Rapid-strength cements are characterized according to ASTM C1600 [14], which requires very rapid hardening (VRH) and ultra-rapid hardening (URH) cement types to reach compressive strengths of 15 and 28 MPa in three hours, respectively. A commonly-used criterion in the industry is the attainment of 20 MPa at three hours.

PC-CAC-C\$, C\\$A(1)- C_2S and C\\$A(2)-PC systems reached compressive strengths of 33.5, 35.5 and 22 MPa, respectively, after three hours. The HEPC concrete was proportioned using a high dosage of superplasticizer and non-chloride accelerator (calcium nitrite) and is based on a commercially-used concrete designed to achieve a flexural strength of 2.8 MPa in 4 h.

2.2. Specimen preparation

Reinforced concrete prisms ($150 \times 150 \times 530$ mm) were produced with two (450-mm long) 10 M rebars (nominally 11.3 mm diameter); a standard "black" carbon steel bar was placed 50-mm from the top surface and a 316 stainless-steel bar was placed 50-mm from the bottom surface. After curing under wet burlap for 24 h, the samples were demoulded and covered in wet burlap at standard room temperature for 28 days. The beams were

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