



Strength and corrosion properties of Portland cement mortar and concrete with mineral admixtures

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ABSTRACT

This work aims to validate the design assumptions by the California Department of Transportation in order to better define the strategies used to design concrete structures with adequate corrosion mitigation and thus a “maintenance-free” service life. To this end, various laboratory tests were conducted to investigate the compressive strength and chloride diffusivity in mortar and concrete samples with cement partially replaced by various minerals (class F and class N fly ash, ultra-fine fly ash, silica fume, metakaolin, and ground granulated blast-furnace slag), the porosity of mineral concretes, the freeze-thaw resistance of mineral mortars in the presence of deicers, and the effect of supplementary cementitious materials on the chloride binding and chemistry of the pore solution in mortar.

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1. Introduction

Concrete is the most widely used man-made building material in the world, owing to its versatility and relatively low cost. Concrete has also become the material of choice for the construction of structures exposed to extreme conditions [1]. Furthermore, sustainability has become an increasingly important characteristic for concrete infrastructure, as the production of Portland cement (the most common binder in concrete) is an energy-intensive process that accounts for a significant portion of global carbon dioxide emissions and other greenhouse gases [2,3]. As such, even slight improvements in the design, production, construction, maintenance, and materials performance of concrete can have enormous social, economic and environmental impacts.

There are a variety of approaches to enhancing the sustainability of concrete and reducing its environmental footprint. One attractive approach is to enhance the durability of concrete infrastructure, since durability is a key cornerstone for sustainability. According to the ASCE 2009 *Report Card for America's Infrastructure*, \$2.2 trillion needs to be invested over 5 years to ‘bring the nation's

infrastructure to a good condition” [4], which highlights the urgent need for research devoted to longer-lasting and “maintenance-free” concrete materials. There is general agreement that the most effective improvement in concrete durability can be achieved at the design and materials selection stage of a project by using adequate concrete cover and high-quality concrete. Usually, an increase in the thickness of the concrete cover leads to beneficial effects, because it increases the barrier to the various aggressive species moving towards the reinforcement and increases the time for corrosion to initiate. In reality, however, the cover thickness cannot exceed certain limits, for mechanical and practical reasons [5]. In light of advances in concrete technology and requirements of the AASHTO Load and Resistance Factor Design (LRFD) for a 75-year design life, the California Department of Transportation (Caltrans) adopted the approach of using the chloride diffusivity through concrete to determine the concrete cover requirements for structures subjected to chloride-bearing environments [6]. For instance, for bridge members exposed to corrosive soil or water (containing more than 500 ppm of chlorides), the maximum water-to-cementitious-materials (w/cm) ratio shall not exceed 0.40. Mineral admixtures conforming to ASTM Designation C 618 Type F or N (e.g., fly ash – FA) are required for all exposure conditions, except for ‘non-corrosive’ exposure conditions. For such bridge members as precast piles and pile extensions exposed to corrosive conditions, mineral admixtures conforming to ASTM Designation C 1240 (e.g., silica fume – SF) may be required. The

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minimum concrete cover required for bridge members ranges from 1 to 5 in., dependent on the bridge member type and exposure condition [6].

Recent years have seen increasing interest in environmentally-friendly concretes (EFCs), which utilize industrial byproducts or waste materials and thus benefit the environment. Among them, mineral admixtures such as fly ash, silica fume, and slag – have been used to partially replace cement in concrete while shown to enhance concrete durability and improve resistance to chloride diffusion. They are also known as supplementary cementitious materials, or SCMs. Like other state DOTs, Caltrans has developed concrete mixes for corrosion mitigation of structures with the aid of such SCMs. However, the work to date has been based on diffusion coefficient data for low permeability, mineral admixture concretes selected from available literature, which may not represent the materials and exposure conditions seen in California. Furthermore, a significant amount of variability exists in determining chloride diffusion coefficients as an indicator of concrete durability. First, values of chloride diffusion coefficient usually vary from 10^{-13} m²/s to 10^{-10} m²/s in relation to the concrete properties and the exposure conditions. In particular, these values depend on the concrete pore structure and on all the factors that determine it, such as: mix design parameters (w/cm ratio, type and proportion of mineral admixtures and cement, compaction, curing, etc.) and presence of cracks. The chloride diffusion coefficient is also a function of chloride exposure condition (submerged, splash, atmosphere, etc.) and the length of exposure, partly due to hydration of slowly reacting constituents such as blast furnace slag or fly ash [5]. When the chloride diffusion coefficient is used to evaluate the risk for reinforcement corrosion and to forecast the service life of concrete structures, chloride threshold is a very important parameter, the value of which is still a subject of controversy. In reality, the determination of chloride diffusion coefficient and chloride threshold is often affected by the method of chloride analysis. Second, existing chloride permeability tests are either very time-consuming for high-quality concrete mixes or too biased to provide reliable chloride diffusion coefficients.

The objectives of this research are to validate chloride diffusion coefficients of mineral admixture concrete mix designs currently developed by the Caltrans for corrosion mitigation, and to verify the adequacy of existing measures to mitigate corrosion caused by exposure to marine environments and deicing salt applications.

2. Experimental

2.1. Sample preparation

In light of the representative concrete mixes and chloride exposure conditions in California, a preliminary design for the laboratory investigation was developed, in the form of a matrix of 18 concrete mix designs that need to be evaluated (see Table 1). All these concrete mix designs feature a water-to-cementitious-materials (w/cm) ratio of 0.40. The concrete mix design without any mineral admixtures is used as a control. These mix designs were determined in close consultation with the Caltrans Corrosion Technology Branch staff. On the basis of Table 1, multiple trials were conducted in order to achieve reasonable workability of fresh concrete (slump) for each mix design. For this study, an ASTM specification C150-07 Type I/II low-alkali Portland cement from the Ash Grove Montana City Plant (Clancy, MT) was used. Coarse aggregates (with maximum size of 3/4" or 19 mm) and fine aggregates (clean, natural silica sand) were purchased from the JTLGroup (Belgrade, MT). Glenium 3030™ and Micro-Air™ were used as the ASTM C 494 Type A/F water reducing agent and the ASTM C 260 air-entraining agent respectively and at the dosage per the instructions.

After the trials, the two Class N fly ash designs (at 25% replacement level) were excluded from further investigation with approval of the Caltrans technical panel, since these two mixes could not achieve desired slump and air content with the specified w/cm ratio of 0.4 even with the excessive amounts of multiple water-reducers. This left 16 concrete mixes for the study as shown in Table 2. These concrete mixes had a coarse-aggregate-to-cementitious-materials ratio varying between 2.17 and 2.86 and a coarse-to-fine-aggregates ratio between 1.51 and 1.54. Such variations were necessary in order to achieve reasonable slump and air content, similar to the field construction scenarios during batching operations. Note

that the actual air content achieved deviated from the target air content in Table 1 in spite of the multiple trials for each mix design. It was also noticed that concrete made using a smaller lab mixer with same formulation usually had lower air content than using a larger lab mixer.

For each mix design, at least three replicate 12" by 6" (diameter 305 mm × height 152 mm) concrete cylinders and at least three replicate 4" by 8" (diameter 102 mm × height 203 mm) compression cylinders were prepared. The coarse aggregates and fine aggregates were oven-dried and then potable water was added in the amount twice as much as their absorption capacity (e.g., 1.8%). The aggregates were then soaked for 24 h to ensure that they had fully absorbed moisture and had moisture in excess of the surface-saturated-dry (SSD) condition. The saturated aggregates and the excessive water were used in the mix, taking into account the excessive water when calculating the w/cm ratio. The fine and coarse aggregates were added to the 2-cubic-foot (57-L) mixer and mixed until a homogeneous mixture was obtained. Then the cement was added and mixed again until a homogeneous mixture was obtained. Next, water was added from a graduated cylinder and mixed until the concrete is homogeneous and of the desired consistency. The batch was remixed periodically during the casting of the test specimens and the mix container was covered to prevent evaporation. Slump and air content measurements were performed by the ASTM C 143 and C 173 methods respectively, to check the workability and quality of the freshly mixed concrete; and the data are shown in Table 2. Fresh concrete was cast into hollow poly(vinyl chloride) piping cylinders and then carefully compacted to minimize the amount of entrapped air. The cylindrical samples were demolded after curing for 24 h with over 90% relative humidity. After demolding, the samples were cured in the moist cure room (with over 90% relative humidity) for another 359 days before the accelerated chloride migration test. For testing of chloride diffusivity, slice specimens with diameter of 2" (51 mm) and thickness of 1" (25 mm) were cored from the center of cured cylinders to minimize possible effects of surface evaporation and air entrapment on the permeability of slice specimen. Cores were removed from the concrete according to the ASTM C42/C 42 M (2004) *Standard Test Method of Obtaining and Testing Drilled Cores and Sawed Beams of Concrete*. The specimen thickness was chosen based on two considerations. It is thick enough to reasonably represent the heterogeneity nature of the concrete and to consider the maximum aggregate size (3/4"). It is not too thick so that the accelerated chloride migration test can be completed in reasonable time frame.

Furthermore, nine mortar mixes (mixes 1, 3, 5, 7, 9, 11, 13, 15, and 17 in Table 2) were prepared without any coarse aggregates, water-reducer, or air-entraining agent. The w/cm ratio of the mortar samples was set at 0.45 instead of 0.40, in light of workability concerns. For each mix design, at least three replicate 2" by 4" (diameter 51 mm × length 102 mm) cylinders for diffusivity testing, at least sixteen replicate 1 7/8" by 1 1/2" (height 48 mm × diameter 38 mm) cylinders for freeze-thaw testing, and at least nine replicate 2" by 4" (diameter 51 mm × length 102 mm) compression cylinders were prepared. This aims to shed light on the role of coarse aggregates and to better interpret the chloride diffusion data in concrete containing various types and amounts of mineral admixtures. For mortar samples, cement is mixed with water at a low-speed hand mixer for 5 min. Subsequently, fine aggregates, with a maximum size of 1.18 mm in diameter, were added, after which the slurries were stirred for 3 min. The fine aggregates were prepared to SSD condition in advance. All the slurries were cast into hollow poly(vinyl chloride) piping cylinders and then carefully compacted to minimize the amount of entrapped air. The cylindrical samples were demolded after curing for 24 h with over 90% relative humidity. After demolding, the samples were cured with over 90% relative humidity for another 89 days before the accelerated chloride migration test. For testing of chloride diffusivity, slice specimens with a thickness of 8 mm were cut from the center of cured cylinders to minimize possible effects of surface evaporation and air entrapment on the permeability of slice specimen. This was done using a low-speed saw equipped with a diamond blade.

2.2. Mechanical testing

All the compression strength testing of mortar and concrete samples was conducted in accordance with ASTM C873/C873 M – 04e1 *Standard Test Method for Compressive Strength of Concrete Cylinders*. The compressive strength of concrete samples were first calculated by dividing the measured ultimate strength by the area of specimen cross-section, then multiplied by the length/diameter correction factor when necessary, and finally presented in the unit of psi, or pounds per square inch. The concrete cylinders were 4" by 8" (diameter 102 mm × height 203 mm) and cured for 90 days before testing, whereas the mortar cylinders were 2" by 4" (diameter 51 mm × length 102 mm) and cured for 1 day and 28 days respectively, prior to the compression testing. The compressive strength of each mix design was obtained by averaging the data from at least three replicate cylinders. Young's modulus (in GPa) and modulus of toughness (in kJ/m³) were also analyzed for mortar samples based on the stress-strain curve.

2.3. Electro-migration and natural diffusion

To rapidly measure the chloride diffusivity in the high-quality concrete and mortar samples, a modified version of rapid migration test, i.e., *accelerated chloride migration test (ACMT)*, was conducted. The ACMT periodically measures the

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