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Fiber reinforced mortar affected by alkali-silica reaction: A study by synchrotron microtomography

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ABSTRACT

Alkali-Silica reaction (ASR) is a physicochemical process that can deteriorate concrete and is a recurring engineering problem. In this study three different cylindrical samples affected by ASR were prepared: a plain mortar and two composite mortars containing fibers (polypropylene and a polymer hybrid), which were analyzed at the microtomography (μCT) beamline 8.3.2 at the Advanced Light Source (ALS). In general, three different features were observed during the 136 day observation period: (1) aggregate dissolution, (2) crack propagation from inside the aggregate, through the cement matrix, and at the ITZ, and (3) the alkali-silica gel filling cracks and voids. In addition, accelerated mortar bar tests were utilized to observe ASR's expansive effect in the plain and composite mortars, and the fibers' ability to restrain expansion due to ASR.

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1. Introduction

Alkali-silica reaction (ASR) is a physiochemical deterioration mechanism in Portland cement (PC) based concretes that contain reactive siliceous aggregates. During PC hydration, alkalis are released and enter the concrete pore solution, raising the pH. Silica networks in the reactive siliceous aggregates then begin to depolymerize and form alkali-silica gel. With time and ion migration, the alkali-silica gel begins to produce expansive forces within the concrete matrix. When the expansive forces exceed the tensile strength of the surrounding aggregate and/or PC paste, cracks develop in the concrete. The cracking not only results in reduced strength of the concrete, but opens up pathways for other deleterious agents. For instance, CO_2 can follow the crack path and carbonate the PC matrix, lowering the concrete pH, and chloride ions can migrate along the crack to the imbedded steel reinforcement. Both of which destroy the steel's ability to form a passive layer and protect the reinforcement steel from corrosion. Likewise, oxygen can diffuse along the crack to the reinforcement steel, which facilitates the oxidation of the steel. As the steel corrodes, the reinforced concrete composite loses its ability to carry tensile forces, which leads to repairs being necessary or a reduced service life for the reinforced concrete structure.

Many chemical approaches have been developed to mitigate ASR. One of the earliest found solutions was to limit the alkali content in the cement; however, some aggregates are prone to react at very low alkali contents [1,2]. Another solution is to use pozzolan in the concrete mix, such as fly ash, silica fume, natural pozzolan, or rice husk ash [3–7]. Pozzolans, which contain reactive silica by nature, react with the calcium hydroxide in the PC paste to form additional calcium silicate hydrates (C-S-H). This lowers the porosity of the paste, which hinders ion mobility, slowing ASR's kinetics. Ground granulated blast furnace slag (GGBFS) can also be utilized to mitigate ASR. GGBFS acts to dilute the PC (as do all supplementary cementing materials), thus lowering the calcium and alkali hydroxides released to the hydrated paste from the PC, and it reduces the porosity [8]. Lithium salts have been shown to be very effective at mitigating ASR [9]. They can be added to the initial concrete mix to prevent ASR, driven by a potential into an existing structure suffering from ASR, or used to form aggregate passivation layers on aggregates susceptible to ASR [9–12].

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In addition to the chemical mitigation strategies, physical mitigation strategies have also been developed. ASR needs water to proceed; therefore, one strategy is to limit the water in the concrete pores. Silane coatings have been shown to repel water while allowing vapor to escape from concrete, which lowers the relative humidity or water in the concrete pores [7,13]. Fibers can be added to the concrete to increase its tensile strength, which can work to keep cracks from forming and to aid in keeping any cracks that do form closed [14–18]. Fiber reinforced polymer (FRP) wraps can be applied to damaged concrete to help restore load bearing capacity.

Various models have been proposed for ASR's effect on concrete [19]. Stark et al. [20] give an explanation of the ASR mechanism considering: chemical reaction preferences, crack propagation, stressed aggregate, osmotic pressure, pore distribution, reaction rim formation timing, and silica gel formation. Pignatelli et al. [21] developed a poro-mechanical model with two isotropic internal variables: a) a chemical damage caused by the pressure generated by the expanding ASR gel on the solid concrete skeleton and b) a mechanical damage associated to the strength and stiffness degradation induced by the external load. Ben Haha et al. [22] utilized image analysis to measure the void and crack content of aggregates affected by ASR, and Dunant and Scrivener [23] built a finite element model linking microscopic damage observations with macroscopic free expansion. Their simulations showed that macroscopic damage and expansion where strongly linked to the microstructural localization of ASR (i.e. aggregate surface, pockets in the aggregate, or homogeneous aggregate expansion). Additionally, they suggest ASR damage is produced in three different regimes: a) the expansion is caused by the cracking of the aggregate and the elastic deformation of the paste, b) both aggregate and paste cracking drive the expansion, and c) the expansion is driven by paste cracking and the exhaustion of reactive materials [24].

The previously proposed models have been supported by experimental work, and most of them used conventional microscopy techniques to investigate features and validate their observations. Scanning electron microscopy (SEM) and transmission electron microscopy (TEM) are invasive and destructive techniques because the samples have to follow a preparation process before investigating them. Such preparation can modify the morphology and the microstructure of the sample, which can mislead the interpretation. Lately, synchrotron microtomography (μCT) has become an important non-destructive method of observation in material science. Few investigations on concrete have been carried out, but they demonstrate the capabilities of μCT for understanding the internal physical behaviors and chemical reactions. For instance, Burlion et al. [25] investigated the distribution and variation of porosity in leached mortar. Gallucci et al. [26] investigated the microstructure of cement paste phases by identifying the grey scale differences at different dates of curing. Finally, Voltolini et al. [27] performed a quantitative characterization of the microstructural features found in ASR affected mortars. Three main kinds of voids due to three different mechanisms were found: a) cracks from ASR expansion, b) irregular shaped voids due to the aggregate particle dissolution and c) bubbles due to the mortar preparation. Using morphological parameters a volume fraction calculation was performed for each kind of void in order to separate each mechanism. However, this work only show results for samples cured at 27 days, making it difficult to understand how ASR initiates and evolves with time.

This investigation studied at the microscale ASR's effect in plain and fiber reinforced mortars. A plain mortar and two fiber reinforced mortars, using two types of fibers, were observed by μCT from 2 through 136 days. Crack formation and propagation, aggregate dissolution, and silica gel formation are some of the observed features, which confirm the capabilities of μCT as non-invasive technique for materials inspection. Additionally, mortar bars were utilized to evaluate the fibers' ability to control ASR induced expansion [28].

2. Materials and methods

2.1. Materials

A monofilament polypropylene (PP) fiber (approx. 50 μm in diameter and 13 mm long) and a relatively new hybrid (bi-component) fiber [29] (approx. 17 μm in diameter and 18 mm long), were used. The hybrid fiber is composed of an ethylene acrylic acid copolymer sheath (EAA ~1.7 μm thick), coaxially extruded with PP fiber core (15 μm in diameter). Because of its carboxyl functional groups, the EAA sheath is expected to act as a reactive layer, enhancing the adhesion or bonding between the reinforcing PP fiber and the cement matrix [30]. Both fibers were provided by The Dow Chemical Company (DOW®). ASTM Type I PC and a reactive sand, siliceous fine aggregate selected from natural sand deposits with mixed mineralogy, were utilized. In a previous study, the sand was characterized by X-ray fluorescence, X-ray diffraction, and SEM and had been shown to be susceptible to ASR [12]. In bulk the sand, contains 3.3% Na_2O and 4.1% K_2O. The sand is composed of 37% quartz (SiO_2), 1% calcite ($CaCO_3$), 44% albite ($NaAlSi_3O_8$), 2% anorthite ($CaAl_2Si_2O_8$), 2% microcline ($KAlSi_3O_8$), and 14% orthoclase ($KAlSi_3O_8$).

2.2. Methods

Two types of experimental approaches were implemented during this investigation. The first was an expansion bar test and the second was the observation of the microstructural effect of ASR by means of μCT imaging and rendered 3D volumes.

For the expansion test, three specimens of size 2.54 × 2.54 × 27.94 cm (1 in. × 1 in. × 11 in.) were prepared for each of the three mixes (a control sample without fibers, a second sample containing PP fibers, and the third sample composed of hybrid fibers) and kept in an accelerated ASR environment, a modified version of ASTM C 1260 was utilized [28]. The test was modified by using a finer sand gradation (38.5% 0.60–1.18 mm, 38.5% 0.30–0.60 mm, and 23% 0.15–0.30 mm) corresponding to the smallest three aggregate sizes specified by ASTM C 1260 renormalized to 100% and lower temperature (50 °C). This curing temperature was selected to accelerate the ASR effect without approaching the polymer fiber melting point. The sand gradation was mainly chosen to better accommodate the small μCT sample molds and to not dominate the μCT field of view with aggregates. The w/c ratio was set to 0.47, a sand-to-cement ratio of 2.25, and a fiber volume of 1% when mixes contained fibers. The sealed samples were demolded after curing for 24 h at 21 °C, and then stored in 1 M NaOH solution at 50 °C for 126 days. The mortar bars were measured three times per week for the entire duration of the study. The differences in length change measurements between the smallest and largest length change for a set of 3 bars steadily increased from near zero initially to 0.01, 0.05, and 0.03% for the plain, PP fiber, and hybrid fiber mortars, respectively, at 126 days.

For the μCT studies, composite mortar cylinders (7 mm diameter and 3 cm long) were fabricated to accommodate the transmitted x-rays and to facilitate mounting into the μCT's three-jaw chuck. Three cylinders were prepared, the control (without fibers), one containing PP fibers, and one containing hybrid fibers. The fibers were cut to ~5 mm so they could fit along the cylinder's transverse direction. Samples utilized the same mix proportions and curing conditions (3 cylinders stored in 50 ml of 1 M NaOH at 50 °C) as the accelerated mortar bars. The plain and hybrid fiber mortars

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