Synergistic effects of ASR and fly ash on the corrosion characteristics of RC systems

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HIGHLIGHTS

- Synergistic effects of ASR and fly ash on D_a and T_i were assessed.
- Fly ash reduces expansion caused by ASR.
- Results indicate that ASR gel resist chloride transport.
- When some ASR gel is produced, the gel can fill voids and slow chloride transport.

ARTICLE INFO

ABSTRACT

This research investigated the synergistic effects of fly ash and aggregate reactivity on chloride transport and time to corrosion. Specimens containing fly ash replacement levels of 0, 20, and 40% by weight with and without reactive aggregate were exposed to wetting/drying cycles. Expansion, corrosion potential, and macrocell current were measured monthly until corrosion of the embedded reinforcement initiated. The results indicate that inclusion of fly ash in specimens containing non-reactive aggregate results in lower apparent diffusion coefficient values (D_a) and lower critical chloride threshold values (C_T) in concrete. The benefits from the lower D_a values are more significant than the disbenefits from the reduction in C_T when assessing time to corrosion initiation. Specimens containing reactive aggregate and 20% fly ash exhibited longer times to corrosion initiation than specimens containing 40% fly ash. Results indicate that the ASR gel resists the transport of chlorides and the formation of small amounts of ASR gel in the specimens containing 20% fly ash reactive aggregate results in slower transport rates and longer times to corrosion initiation.

Published by Elsevier Ltd.

1. Introduction

Concrete deterioration such as ASR and corrosion of the steel reinforcement can significantly influence the service life of reinforced concrete (RC) structures. Significant research has been performed on preventing corrosion and ASR in RC structures. However, research on the topic has mostly been reported independently. The use of supplementary cementitious materials (SCMs) in concrete in partial replacement of the portland cement is a common method to lower transport rates and reduce ASR damage in concrete. However, the synergistic effects of both SCMs and ASR on transport rates and time to corrosion initiation has not been well researched. Research is needed to better understand the synergistic effects of SCMs and ASR on chloride transport rates and time to corrosion.

ASR is the reaction between reactive silica in aggregate and alkalis in the pore solution of the concrete. The presence of reactive aggregate, sufficient alkalis, and sufficient moisture is necessary for ASR to occur. The product of this reaction is an ASR gel. This gel forms in and around the aggregates and in the pores of concrete, and in the presence of water, draws this water from the pore solution (or external sources) and expands. The expansion of this ASR gel can then result in expansion and cracking of the concrete structure.

Reactive aggregates are aggregates that tend to breakdown in highly alkaline pore solution. The solubility of the amorphous silica is higher by several orders of magnitude in high pH environments when compared to lower pH environments [1]. As a result, amorphous or poorly crystalline silica aggregates are more susceptible to dissolution in high pH concrete pore solutions. The majority of

alkalis required for the ASR reaction are provided by the portland cement. Dissolved silica ions ($H_3SiO_4^-$ and $H_2SiO_4^{2-}$) can form from the reaction between the hydroxyl ions (OH^-) and the reactive silica (SiO_2) components of a reactive aggregate [2]. The negatively dissolved silica ions attract the cations of Na^+ and K^+ in the pore solution and form ASR gel. Hansen [3] reported that because of the high surface area and porous structure of the ASR gel, the gel can then draw water from the pore solution or from external sources, causing expansion of the gel, resulting in cracking of the concrete structure.

Mitigating ASR in concrete has been studied by many researchers [4–6]. Eliminating one or more of the required components of the ASR can prevent or reduce the damage caused by ASR. However, it is not always practical or economical to eliminate some of these required components for ASR (e.g., the aggregate source). Because of limited availability of truly non-reactive aggregates in some locations, the use of non-reactive aggregate may not be an economical method to mitigate ASR.

SCMs, particularly fly ash, is a commonly used constituent material for mitigating ASR in concrete and this has been widely reported in the literature [5,7–10]. Fly ash is primarily composed of silica glass, which is composed mostly of aluminum, calcium, iron, and silicon. Depending on the calcium content of the fly ash, it can be divided into different classifications. Class F, or low-calcium fly ash, typically contains less than 15% calcium (CaO) and Class C, or high-calcium fly ash, contains more than 15% CaO. Fly ash reacts with the calcium hydroxide ($Ca(OH)_2$) formed from the hydration of portland cement and this reaction results in the formation of calcium-silicate hydrates (CSH). The CSH forms in the void spaces within in the hydration products and can improve the mechanical properties and can reduce the transport rates of moisture in concrete. The reduction in moisture transport rate can limit the availability of water and swelling the ASR gel [9]. Replacing portland cement with fly ash can also mitigate ASR by reducing the alkalinity of the pore solution, referred to as the dilution effect [10]. Fly ash can also reduce the alkalis available for ASR through alkali binding. The additional CSH from the reaction of fly ash could bind alkalis and hydroxyl ions, which can also limit the ASR gel formation [9].

Shehata and Thomas [6] reported that the CaO content of the fly ash is the most important parameter that effects the ability of the fly ash to control ASR expansion. In general, as the amount of CaO increases in fly ash, the efficiency (at a constant mass replacement of cement) decreases. The calcium to silica ratio (C/S) in the CSH structure is lower in concretes containing Class F fly ash, which can increase the alkali binding ability of the fly ash concrete. In addition, Diamond [11] reported that the alkalis in concrete containing Class C fly ash are more readily available to participate in the ASR than concretes containing Class F fly ash. As a result, the effectiveness of Class F fly ash in controlling ASR is reported to be better than Class C fly ash.

In addition to reducing the damage caused by ASR, the addition of fly ash can also decrease the transport rate of chlorides. Significant research has been performed on how SCMs, and specifically fly ash, reduce the transport rate of chlorides in concrete, which should increase the time to corrosion. This may result in a concrete that is more durable and more resistant to reinforcement corrosion. Although the effect of fly ash on ASR and the effect of fly ash on chloride transport rates in concrete has been researched significantly, little research has been performed to quantify the synergistic effects of both fly ash and ASR on transport rates and time to corrosion. Research is needed.

Because of the high alkalinity of the pore solution in concrete, a protective passive layer typically forms on the steel surface; which protects the steel from corrosion. However, this passive layer can be destroyed by two mechanisms; (1) carbonation, and (2) chloride induced corrosion. Carbonation can reduce the pH of the concrete pore solution and as a result the metal loses its passivity, which results in initiation of corrosion in the concrete [12]. When chlorides are transported into the concrete and the chloride concentration at the steel reinforcement surface reaches a certain critical threshold concentration (C_T), the passive film on the steel is destroyed and corrosion occurs. The time it takes for sufficient chlorides to reach the C_T at the steel reinforcement surface is referred to as time to initiation of corrosion (T_i). The chloride transport rate through the concrete has a significant influence on T_i. The effect of fly ash on chloride transport rates in concrete has been studied by many researchers and the benefits are well reported [13–16]. However, the chloride transport rate is not the only variable that influences the time to corrosion. It is the combined effect of several variables, including chloride transport rate and C_T that influence the time to corrosion. Angst et al. [15] reported that the C_T is dependent on several variables, one being pore solution pH at the steel reinforcement-concrete interface. Byfors [16] reported that although SCMs (silica fume and fly ash) can significantly reduce the chloride transport rate through the concrete, the pH of the pore solution is reduced when SCMs are used in concrete, which could reduce the C_T.

The passive state of the steel reinforcement in concrete is more stable at higher pH values. In addition, the presence of chlorides in the pore solution can increase the probability of corrosion initiation. Relating chloride concentration to the pH of the pore solution (hydroxyl concentration) is a common way to express C_T, which is presented as $[Cl^-]/[OH^-]$ Hausmann [17] reported that a $[Cl^-]/[OH^-]$ of 0.6 or more is necessary for corrosion initiation. ACI 222 [18] reports that the maximum value of $[Cl^-]/[OH^-]$ that can be tolerated without breakdown of the passive film is 0.29 at a pH of 12.6 and 0.30 at a pH of 13.3.

Recently, Trejo and Tibbits [19] and Presuel-Moreno and Moreno [20] reported that SCMs can influence the C_T value. The presence of SCMs can reduce the hydroxyl ions in the concrete pore solution and increase the $[Cl^-]/[OH^-]$ value [16]. As a result, SCMs may negatively influence the time to corrosion initiation in RC structures. Trejo and Tibbits [19] reported that addition of Class F fly ash resulted in a decrease in diffusivity and a decrease in C_T. The results from the research indicated that the mixtures containing the fly ash had a mean C_T of approximately 12% of the mean C_T for mixtures containing no fly ash. In addition, when the fly ash replacement level increased from 20 to 40%, little reduction was observed in the C_T. Presuel-Moreno and Moreno [20] also reported that replacing portland cement with fly ash resulted in lower C_T values. The researchers reported that the C_T values for the specimens containing 35% fly ash are lower than the control specimens but higher than specimens containing 20 and 55% fly ash.

The chloride transport rate through the concrete plays a significant role in the time to corrosion initiation in RC structures. External chlorides must penetrate the concrete system and reach the surface of the steel reinforcement insufficient quantities to initiate corrosion. Concrete consists of aggregate, hydrated cement paste (hcp), and interfacial transition zones (ITZ). The ITZ forms at the aggregate-hcp and steel-hcp interfaces and generally has a higher porosity than the bulk cement paste. The porous structure of the ITZ is believed to be caused by the wall effect, which prevents cement particles from packing together in the vicinity of an aggregate surface [21].

Due to the dense structure of many aggregates, the transport rate of the chlorides through the aggregate is generally very low. However, the ITZ has a higher porosity than the bulk cement paste, and as a result of these pores being interconnected, the chloride transport rate through the ITZ would be expected to be higher than