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A mechanistic study on mitigation of alkali-silica reaction by fine lightweight aggregates

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ABSTRACT

Previous studies have shown that fine lightweight aggregate (FLWAs) may be a possible solution for ASR mitigation. However, the mechanisms of mitigation have not yet been fully elucidated. This study investigated how three commonly used FLWAs, expanded slate, shale, and clay can mitigate ASR in concrete using the accelerated mortar bar test (AMBT), concrete prism test (CPT), pore solution analysis and scanning electron microscope (SEM) analysis. The AMBT and CPT results showed that expanded clay was the most effective in reducing the expansion caused by ASR. Pore solution analysis showed that FLWAs, especially expanded shale and clay can reduce the alkalinity as well as increase aluminum content in the pore solution. SEM analysis revealed that infilling reaction products formed in the pores of the FLWAs, whose composition was closer to C-A-S-H, rather than alkali-silica reaction product.

1. Introduction

Lightweight aggregates (LWAs) can be manufactured in different ways, and one commonly used method is to heat raw materials under high temperature (over 1100 °C), where the raw materials liquefy and air bubbles are released out of the aggregates which results in expansion and "bloating" of the aggregate [1]. LWAs have been used as both fine and coarse aggregates in concrete construction for many decades. In many cases, they are used to reduce the overall density of a concrete or mortar mixture, thus reducing dead loads as well as loading associated with transportation of large pre-stressed concrete members [2]. Furthermore, LWAs are frequently used in thermally-insulating mortars and grouts. Due to their inherently high silica and alumina contents, many fine lightweight aggregates (FLWAs) can be ground finely to function as active pozzolanic materials as well [3,4]. In the past 15–20 years, research focused on mixing pre-wetted fine lightweight aggregate into high performance concrete to serve as moisture reservoirs for internal curing [1,5–9]. In spite of the increased interest in using FLWAs for internal curing, limited information exists as to the benefits these types of aggregates may provide in terms of durability, specifically resistance to alkali-silica reaction (ASR).

For concrete susceptible to ASR, certain types of aggregate containing reactive silica, may be easily attacked by the hydroxyl ions available in the pore solution of concrete. The attack can cause the formation of a hygroscopic reaction product containing silica, sodium, potassium and calcium ions. This product has a high affinity for water and can swell and expand. Then expansion, cracking and further deterioration of concrete can result [10–12]. Damage due to ASR can lead to other significant concrete durability issues and reduce the life span of concrete structures.

Research on mitigation of ASR has been going on for over 70 years. The four necessary components for ASR are aggregate with reactive silica, available alkalis, calcium, and moisture [13–15]. If any one of these can be removed, ASR can be limited or even eliminated. However, eliminating even one of these components is often not practical. Therefore, various ASR mitigation strategies can be envisioned before the concrete is mixed. Based on current research, recommended ASR mitigation methods include limiting alkali content, using non-reactive aggregate, using supplementary cementitious materials (SCMs), and using lithium nitrate [16–19]. However, not all mitigation methods will be available to construction projects due to the constraints of locally available resources and transportation costs. Furthermore, certain highly and very highly reactive aggregates may require several different mitigation strategies used synergistically to reduce the risk of deleterious ASR. Compared to portland cement, SCMs such as blast furnace slag and fly ash are produced in a smaller quantities [20]. Other feasible ASR mitigation methods are still in great need.

Previous research found that the use of FLWAs to mitigate ASR is

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promising [1,16,21–23]. However, due to a lack of comprehensive supporting data and inconclusive evidence for mitigation mechanisms, the use of the FLWAs to mitigate ASR has not been widely accepted or utilized. The aim of this research project is to determine whether FLWAs can mitigate ASR in concrete and to elucidate the mechanisms.

2. Background information

2.1. Mitigation theories

Existing research found that incorporating FLWAs could be a potential strategy to control the expansion caused by ASR. Although mechanisms for ASR mitigation by incorporating FLWAs have been proposed, there is a lack of agreement among various researchers. According to these studies, the proposed mitigation mechanisms can be categorized into the following theories:

2.1.1. Dilution of reactive aggregate

Shin et al. showed that by using expanded slate, expanded shale and expanded clay to partially replace the fine alkali-silica reactive aggregate in the accelerated mortar bar test (AMBT), less expansion of the mortar bars was observed [23]. Therefore, they showed that by using FLWAs to replace the reactive aggregates, less reactive components are available to be attacked by the alkali and less amorphous reaction products were expected to form. However, the impact of incorporating FLWAs on the pessimum effect (balance of reactive silica and available alkali which produces the highest expansion) was not investigated.

2.1.2. Dilution of pore solution

Collins assumed that incorporating lightweight aggregates (coarse) could result in a dilution of the pore solution as the internal curing water residing in the pores of pre-wetted LWAs may be released into pore solution [24]. However, this assumption is possibly invalid, since the internal water in FLWAs will not start releasing until 7 hr after mixing [25]. Therefore, this influence is more likely to be partial, i.e., the ITZ of the FLWAs.

2.1.3. Refined microstructure

FLWAs were reported to influence the durability of concrete by refining its microstructure. Elsharief and co-workers showed that a refinement of the interfacial transition zone (ITZ) was observed in mortars prepared with both oven-dried and pre-wetted expanded shale [26]. Other researchers found that by using FLWAs for internal curing, the overall porosity of concrete was decreased so that the rate of fluid ingress could be reduced [23,26–28]. As discussed above, when the microstructure was refined by incorporating FLWAs, less moisture intrusion to the mixture can be expected. With less moisture available for the ASR reaction product to absorb, the expansion was reduced. It is likely that this mechanism would impact the rate of reaction rather than the ultimate extent of reaction and resulting expansion.

2.1.4. ASR product accommodation

Boyd and Bremner found that deposits were observed in the pores of the FLWAs, which were claimed to be ASR product [21,29]. Due to the porous structures of FLWAs, some other researchers also assumed that the FLWAs could provide space for ASR product to deposit and thus the expansion could be suppressed [21–23,30].

2.1.5. Pozzolanic activity

Urhan found that expanded perlite showed pozzolanic activity in concrete through the ISO R 863 test (pozzolanicity test for pozzolanic cements) [3]. Bekta found that both ground expanded perlite and natural perlite were effective in ASR mitigation. However, the expanded perlite showed superiority in limiting expansions [31]. Furthermore, Dahl et al. showed that when a micro expanded clay (5–10 μm in diameter) was used to replace the cement in concrete, the expansion caused by ASR was significantly reduced with increasing micro expanded clay replacement [32]. Other researchers investigated the durability of concrete when FLWAs were incorporated and showed a localized pozzolanic activity due to a high content of amorphous silica and alumina in FLWAs [22,23,33].

2.2. Concerns about current assumptions

While several potential theories were proposed by researchers, inconsistencies were still found among these theories. Through reviewing current literature, we found that the theory of ITZ refinement and the ASR product deposit theories are contradictory. According to Elsharief's study, when ITZ was refined, the microstructure of mortar mixtures became denser [26]. In this case, with a refined ITZ and a denser microstructure, ASR product would be less likely to be deposited into FLWAs due to a reduction in transport properties.

Lightweight aggregates (LWAs) were found to be pozzolanically reactive when they were ground finely (usually smaller than 100 μm) [34,35]. Due to the large surface area of the ground LWAs, they tend to react with available alkalis in concrete to initiate a localized pozzolanic reaction. However when using as a fine aggregate, the average particle size is significantly larger, in comparision to pozzolans. It is questionable if a FLWA is still pozzolanically reactive when being used as a fine aggregate in concrete.

In addition, despite the findings that FLWAs were effective in reducing expansion caused by ASR, Ceukelaire reported that a concrete bridge in Kotich, Belgium, still suffered from ASR and DEF (as well as other mineral precipitates) even when FLWAs were incorporated into the concrete [36]. The ASR was found to be caused by the reactive aggregates and an extensively high alkali content in concrete. Besides the alkalis from cement, alkalis leached from FLWAs could be another factor accelerating the reactions [36]. This indicates that in concrete with a high alkali content, using FLWAs as the sole mitigation strategy may not be effective.

The type of FLWAs can largely influence its efficacy on ASR mitigation. Mladenovic et al. showed that not all FLWAs were effective in mitigating ASR in mortar mixtures [5]. FLWAs containing a glassy phase, such as expanded glass and perlite, showed reactivity according to the ASTM C289 test [5]. Moons et al. found that expanded glass reacted with alkalis in concrete, which may be a concern for long-term durability [37]. Ducman found that FLWA based on waste glass can be deleterious according to the ASTM C289 test [38]. The authors of these studies all indicated that very rapid tests including ASTM C289 and ASTM C227 were not reliable in determining the reactivity of FLWAs, and the use of the concrete prism test was strongly suggested [5,37,38]. These studies all indicate further comprehensive investigations into the efficacy of FLWA for mitigating ASR is necessary.

2.3. ASR product composition

In previous research, reaction products were found in the pores of FLWAs, and these reaction products were also named as alkali-silica gel in some studies. In general, ASR product contains Si, Na, K, Ca and sometimes Mg. Typically, the molar ratio of $(Na_2O + K_2O)/SiO_2$ ranges from 0.05 to 0.6, and $(CaO + MgO)/SiO_2$ ranges from 0 to 0.2 [11,39,40]. In addition, it was found that the composition of ASR product can vary significantly depending on its location in the concrete [39,41,42]. Knudsen and Thaulow noted that the ASR product residing in cracks far from reaction site had about 20% CaO in it, whereas the ASR product in aggregates showed a lower CaO content [39]. Diamond also noted that ASR product had a variable Ca/Si due to its complicated mechanisms while forming [43]. Thomas reported that in a seven-year-old concrete, the ASR product in the aggregates had a Ca/Si of 0.25 and the Ca/Si was observed to be up to 1.30 for the ASR product within the paste [44]. Furthermore, the content of Ca in ASR product can influence the expansive properties of the ASR product. Thomas reported that ASR