Mechanisms of Alkali-Silica Reaction in Alkali-Activated High-Volume Fly Ash Mortars

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Abstract

Alkali-activation of high-volume fly ash (HVFA) is a viable approach to produce durable cementitious binders with faster and stronger strength development than its water-activated counterparts. However, the use of alkaline activator increases the risk of alkali-silica reaction (ASR) in these systems. In this work, the compressive strength and ASR susceptibility of alkali-activated fly ash-OPC mortars containing reactive aggregate are studied. The results show that in comparison to plain water-activated fly ash-OPC mixture, the alkali incorporation at a low concentration improves strength development only when the fly ash replacement ratio is higher than about 80%; however, excessive alkali has an adverse influence. Regardless of activator type and dosage, alkali-activated fly ash-OPC mortars are ASR innocent as assessed in the accelerated mortar bar test and scanning electron microscopic analysis, provided that the fly ash percentage higher than about 40%. The mechanism for the insignificant ASR expansion and damage in alkali-activated HVFA mortars is likely attributed to the low calcium content that prevents gelation of deleterious and expansive ASR products.

1. Introduction

1.1 Alkali-activated high-volume fly ash

Pulverized fly ash has been commonly used as supplementary cementitious material to partially substitute ordinary portland cement (OPC) in producing sustainable and durable cementitious materials (Khatri et al. 1995; Lothenbach et al. 2011). High-volume fly ash (HVFA) concrete with the fly ash replacement ratio larger than 50% has gained sufficient attention as an alternative to conventional OPC concrete with considerably reduced greenhouse gas emission and embodied energy consumption (Mehta 2004). In addition, HVFA concrete with 40% to 60% fly ash has been shown to pose good ultimate mechanical properties, lower drying shrinkage (Atiş 2003), alleviated thermal cracking tendency (Atiş 2002), and excellent chemical durability (Malhotra and Mehta 2002).

Alkaline activation of HVFA (denoted as AAHVFA hereafter) has been proposed as a strategy to further increase the replacement ratio of fly ash to even higher than 80% to 100%, whilst with remarkable mechanical properties at ambient temperature (Alahrache et al. 2016; Fernández-Jiménez et al. 2007; Nath and Sarker 2015; Palomo et al. 1999; Somna et al. 2011). Alkali-activation of HVFA facilitates the dissolution of reactive aluminosilicate components from fly ash particles and dissociation of various alumino-silicate species [e.g., (H₃SiO₄)⁺, (H₃AlO₄)²⁻], resulting in precipitation of cementitious hydrates (Davidovits 2005; Duxson et al. 2007; Fernández-Jiménez et al. 2005; Hardjito et al. 2004). Depending on the reactant chemistry and calcium availability, the reacted products in alkali-activated fly ash-OPC blends can be calcium-silicate-hydrates (C-S-H), calcium-aluminosilicate-hydrates (C-A-S-H), alkali-aluminosilicate-hydrates (N-A-S-H), and/or a mix of them (Fernández-Jiménez and Palomo 2005; Li et al. 2010; Oh et al. 2010). The previous studies of alkali-activated HVFA concrete in literature are mainly limited to its reaction mechanisms and some physical and mechanical properties (Donatello et al. 2013; Garcia-Lodeiro et al. 2013).

1.2 Alkali-silica reaction (ASR) in alkali-activated fly ash concrete

Alkali-silica reaction (ASR) is a concern for alkali-activated concrete due to the considerable internal alkali incorporation from mixing solution. However, the existing studies show that alkali-activated low-calcium fly ash concrete is more resistant to ASR-induced damage than OPC concrete (Garcia-Lodeiro et al. 2007; Neves 2016). The possible mechanisms for the low evidence of ASR degradation in alkali-activated fly ash concrete may be attributed to the low calcium level in the system (Garcia-Lodeiro et al. 2007; Williamson and Juenger 2016). In fact, fly ash has been well acknowledged for effective ASR mitigation in OPC concrete (Hobbs 1988; Lane and Ozyildirim 1995; McKeen et al. 2000; Pepper and Mather 1959; RajabiPour et al. 2015). The fly ash dosage necessary to mitigate ASR in OPC system ranges approximately from about 15% to 40%, depending on the fly ash composition and aggregate reactivity (Malvar and Lenke 2006; Wright et al. 2014). Based on

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the current understanding, the proposed mechanisms by which fly ash mitigates ASR in OPC concrete include: reduced pore solution alkalinity through alkali dilution and fixation, modified ASR gel composition, lowered calcium content, and readily-supplied soluble aluminum from dissolved fly ash (Hobbs 1988; Lane and Ozyildirim 1995; Malvar et al. 2002; McKeen et al. 2000; Rajabipour et al. 2015; Saha et al. 2018; Swamy 2002; Thomas 2011).

Nevertheless, the current understanding of ASR mechanisms in alkali-activated fly ash-OPC blends is still insufficient. Different from the water-activated counterparts, the internal alkali content in AAHVFA concrete can be substantially high, which results in:

a. Constantly high alkalinity of pore solution (Lloyd et al. 2010), which may promote the dissolution kinetics and the extent of aggregate particles;

b. Different types and composition of reacted products including N-A-S-H gel formation (Garcia-Lodeiro et al. 2013);

c. Altered pore structure which affects the diffusivity and permeability of concrete (Ma et al. 2013);

d. Different mechanical properties (Alahrache et al. 2016), which would affect the resistance against ASR cracking and expansion.

All of these above-mentioned factors can influence the vulnerability of alkali-activated fly ash-OPC concrete against ASR-induced damage. As such, under a given fly ash composition and replacement ratio, the fly ash dosage necessary to mitigate ASR in AAHVFA may be different from those of water-activated HVFA. In addition, activators of various types and dosages can be used in producing AAHVFA, including sodium hydroxide, sodium silicate (Palomo et al. 2007), sodium carbonate (Alahrache et al. 2016), and sodium sulfate solutions (Velandia et al. 2018). Unfortunately, little information is available regarding the influence of activator type and dosage on the ASR in AAHVFA concrete.

1.3 Research objectives
To fill the abovementioned knowledge gaps, this study examines the potential ASR occurrence in alkali-activated fly ash-OPC mortars containing reactive mineral aggregate with various fly ash percentages from 0% to 80%, activator types and dosages, and incorporation of silica fume. The ASR susceptibility of mixtures are assessed using the accelerated mortar bar test method and further confirmed by electron microscopic analysis. Investigating the alkali-activated fly ash-OPC system contributes to the general understanding of ASR reaction mechanisms in concrete and mitigation mechanisms of fly ash.

2. Materials and Methodology

2.1 Materials
Pulverized fly ash (FA) supplied by CLP Hong Kong Limited and a commercial OPC and silica fume (SF), with the oxide composition listed in Table 1, were used.

The X-ray diffraction (XRD) analysis of raw FA and OPC (see Fig. 1) suggests that the OPC contains 71.8% C3S, 3.6% C2S, 5.9% C3A, and 8.4% C4AF, while fly ash is mostly made of silicon, aluminum, and calcium, and composed of mainly vitreous aluminosilicate glass with a trace of quartz and mullite.

The fine aggregate used in preparing mortar specimens was obtained from crushing volcanic rocks into the gradation shown in Table 2. The moisture adsorption capacity of the aggregate is 0.17%, as per ASTM C128. The X-ray diffraction (XDR) analysis of raw FA and OPC (see Fig. 1) suggests that the OPC contains 71.8% C3S, 3.6% C2S, 5.9% C3A, and 8.4% C4AF, while fly ash is mostly made of silicon, aluminum, and calcium, and composed of mainly vitreous aluminosilicate glass with a trace of quartz and mullite.

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Table 1 Oxide composition of ordinary Portland cement, pulverized fly ash, silica fume, and reactive aggregate determined by X-ray fluorescence (XRF) spectrometer.

| Oxide (wt. %) | OPC  | FA   | SF   | Reactive aggregate |
|--------------|------|------|------|-------------------|
| CaO          | 66.48| 9.75 | 0.85 | 1.84              |
| SiO2         | 20.17| 52.80| 93.62| 68.68             |
| Al2O3        | 4.01 | 21.21| -    | 15.64             |
| MgO          | 0.85 | 2.81 | 0.91 | 0.62              |
| SO3          | 5.13 | 1.68 | -    | -                 |
| Fe2O3        | 2.77 | 6.44 | 3.25 | 2.81              |
| Na2O         | -    | 2.07 | -    | 4.41              |
| K2O          | 0.58 | 1.88 | 1.04 | 5.02              |
| MnO          | -    | 0.15 | 0.32 | 0.14              |
| TiO2         | -    | 1.20 | -    | 0.27              |
| Total        | 99.99| 99.99| 99.99| 99.43             |

Table 2 Gradation of fine aggregate in the mortar specimens.

| Sieve Size | Passing | Retained on |
|------------|---------|-------------|
| 4.75 mm    | 2.36 mm | 10          |
| 2.36 mm    | 1.18 mm | 30          |
| 1.18 mm    | 600 µm  | 30          |
| 600 µm     | 300 µm  | 20          |
| 300 µm     | 150 µm  | 10          |
potassium-rich feldspar, and muscovite minerals. The backscattered electron image analysis with elemental mappings (not shown) of the intact aggregate indicates that the multiple mineral constitutes are heterogeneously distributed and intimately intermixed. The reactive components in the adopted aggregate are likely to be the glassy siliceous matrix.

2.2 Mixture proportion
Following the requirements of ASTM C1567, prismatic mortar bars of 25 mm × 25 mm × 250 mm with a constant water-to-binder (w/b) ratio of 0.47 and aggregate-to-binder mass ratio of 2.25 were prepared, as shown in Table 3 and Table 4. In Series A, the mortars have various levels of fly ash replacement ratio ranging from 0% to 80% and are activated with water or 2.0 M NaOH solution. The purpose of Series A was to study the influence of alkalis on strength development of fly ash-OPC blends, as well as to identify the approximate fly ash percentage ratio to ensure ASR innocence. In Series B, the AAHVFA mortars have a constant replacement ratio of fly ash and SF at 80% and are activated by two types of activators, i.e., sodium hydroxide (NaOH) and sodium carbonate (Na₂CO₃), at either 2.0 M or 4.0 M in term of the aqueous concentration of sodium cation. The purpose of Series B was to investigate the effect of activator type and dosage, as well as SF incorporation, on their ASR susceptibility.

2.3 Compressive strength
The compressive strength of 40 mm cubic paste specimens (mixture proportion listed in Tables 3 and 4) was measured at 7 d, 14 d, 21 d, and 28 d. After casting, the specimens were sealed and cured at ambient temperature for 24 hours prior to demolding. Then, the specimens were cured in sealed bags to minimize moisture evaporation and carbonation due to high alkalinity. The compressive strength of specimens was measured under the testing condition following ASTM C109.

2.4 Accelerated mortar bar test
The ASR susceptibility of mortar specimens containing...
reactive fine aggregate was assessed using the accelerated mortar bar test (AMBT) method as per ASTM C1567. This test provides the time-dependent length expansion of specimens exposed to 1.0 M NaOH bath at 80°C. Since ASTM C1567 requires the specimens to be cured in an oven at 80°C for 24 hours before immersing into the NaOH bath, the potential subsequent shrinkage of specimens during immersion is expected to be small. Despite the reliability of AMBT as a method to evaluate the ASR susceptibility being criticized due to the extreme and unrealistic exposure condition, it is useful at least for comparative study. In addition, the accelerated testing method allows the investigation of ASR reaction mechanisms in concrete at laboratory-controlled conditions, which would provide useful thermodynamic and kinetics information and insights regarding ASR-damaged concrete in the fields. Direct application of laboratory testing results for discerning ASR in field concrete would provide misleading or even faulty judgments.

It should also be emphasized that the alkalinity in the pore solution of alkali-activated mortars may be higher than that of the NaOH bath. As such, it is of concern that if alkali leaching from alkali-activated specimens occurs during testing, it could lower the ASR development. However, the dissolution rate of amorphous silica is at the highest at an intermediate concentration of NaOH solution (at around 1.0 M) (Maraghechi et al. 2016; Tarnopol and Junge 1946). In that context, the alkali leaching, if occurring to some extent in alkali-activated mortars, does not seem to considerably alter ASR development. Also, a recent study concluded that ASTM 1567 is effective and appropriate in detecting the occurrence of ASR in alkali-activated systems (Li 2017). As such, mainly for inter-system comparison purpose, using 1.0 M NaOH is still useful in determining the ASR susceptibility of alkali-activated fly ash-OPC mortar systems.

2.5 Scanning electron microscopy
A Hitachi S-3400N scanning electron microscope equipped with X-ray energy-dispersive spectroscopy (SEM/EDS) was used for screening for the potential ASR gels formation and compositional analysis in selected specimens after the AMBT. The mortar bar specimens were cut into slices using a low-speed saw with isopropyl alcohol as the lubricating liquid to minimize dissolution and washing out of ASR gels. The sliced pieces were then immered into isopropyl alcohol for 7 d, followed by vacuum drying at 80°C for 2 d. Then, the dried specimens were impregnated with low-viscosity epoxy under vacuum and polished down to 1 µm.

3. Results and Discussion

3.1 Strength development
Figure 3(a) shows the compressive strength development of water and NaOH-activated fly ash-OPC blends with various fly ash-to-OPC ratios (Series A). Regardless of solution type, increasing fly ash replacement ratio decreases the compressive strength of hardened fly ash-OPC blends at a fixed w/b ratio. It should be noted that the HVFA concrete can have a low w/b ratio below 0.2, reaching strength comparable to OPC reference (Malhotra 2002). The use of NaOH activator clearly undermines the strength of fly ash-OPC blends until the fly ash percentage is higher than about 80% since high alkalinity inhibits OPC hydration (Mota et al. 2018). In other words, alkaline activation is merely beneficial to the strength development of fly ash-OPC mortar systems. Figure 3(b) shows the strength development of AAH-VFA pastes with a constant FA and SF replacement ratio of 80:20 or a fly ash-to-OPC-to-SF ratio of 70:20:10 activated by different types of solution (Series B).

Table 3 Mixture proportion of fly ash-OPC blends with two types of solution, including water and 2.0 M NaOH (Series A).

| Mix ID | Fly ash-to-OPC mass ratio | w/b ratio | Aggregate-to-binder mass ratio |
|--------|--------------------------|----------|-------------------------------|
| 00FA   | 0:100                    | 0.4 (paste) and 0.47 (mortar) | 2.25 |
| 20FA   | 20:80                    | 0.4 and 0.47 | 2.25 |
| 40FA   | 40:60                    | 0.4 and 0.47 | 2.25 |
| 60FA   | 60:40                    | 0.4 and 0.47 | 2.25 |
| 80FA   | 80:20                    | 0.4 and 0.47 | 2.25 |

Table 4 Mixture proportion of alkali-activated high-volume fly ash mortars with a fly ash-to-OPC ratio of 80:20 or a fly ash-to-OPC-to-SF ratio of 70:20:10 activated by different types of solution (Series B).

| Mix ID | Fly ash-to-OPC-to-SF ratio | w/b ratio | Aggregate-to-binder mass ratio | Solution |
|--------|---------------------------|----------|-------------------------------|----------|
| 80FA-W | 80:20:0                   | 0.4 (paste) and 0.47 (mortar) | 2.25 | Water |
| 80FA-2NH| 80:20:0                   | 0.4 and 0.47 | 2.25 | 2.0 M NaOH |
| 80FA-4NH| 80:20:0                   | 0.4 and 0.47 | 2.25 | 4.0 M NaOH |
| 80FA-1Nc| 80:20:0                   | 0.4 and 0.47 | 2.25 | 1.0 M Na₂CO₃ |
| 80FA-2Nc| 80:20:0                   | 0.4 and 0.47 | 2.25 | 2.0 M Na₂CO₃ |
| 70FA10SF-W| 70:20:10                 | 0.4 and 0.47 | 2.25 | Water |
| 70FA10SF-2NH| 70:20:10                | 0.4 and 0.47 | 2.25 | 2.0 M NaOH |
| 70FA10SF-1Nc| 70:20:10                 | 0.4 and 0.47 | 2.25 | 1.0 M Na₂CO₃ |

Note: In the nomenclature, W:Water, NH: NaOH solution, Nc: Na₂CO₃ solution.
HVFA samples, the addition of NaOH or Na\(_2\)CO\(_3\) solution as the activating solution at 2.0 M sodium concentration considerably benefits the strength development; however, excessive alkali addition tends to adversely impact the strength development. For instance, the 28 d compressive strength of 4.0 M NaOH or 2.0 M Na\(_2\)CO\(_3\)-activated HVFA is about 40% or 20% lower than that of 2.0 M NaOH-activated or 1.0 M Na\(_2\)CO\(_3\)-activated counterparts. The negative influence of highly concentrated alkaline solution on the strength of HVFA can also be attributed to the inhibition of OPC hydration at high alkalinity (Mota et al. 2018). With the SF addition, the strength of AAHVFA is considerably increased, regardless of activator composition. In particular, adding 10% SF results in about 40% to 50% enhancement of 28 d strength of AAHVFA mixtures. In contrast, little strength improvement is observed for water-activated HVFA due to SF addition, implying that a synergic effect between alkalis and SF exists on the strength development of AAHVFA system.

At the same alkali concentration, the Na\(_2\)CO\(_3\)-activated HVFA tends to have a slightly higher strength than the NaOH-counterparts. The high strength of carbonate-activated HVFA may be attributed to the formation of pore-filling calcium carbonate as a result of reactions between carbonate anions and dissolved calcium from hydrating OPC and/or fly ash.

3.2 ASR-induced expansion

**Figure 4(a)** shows the expansion of alkali-activated mortars with various proportions of fly ash and OPC (Series A). The AMBT results are in general agreement with those of conventional water-activated fly ash-OPC blended mortars reported in the literature (Shehata and Thomas 2002). In particular, increasing fly ash percentage in alkali-activated fly ash-OPC mortars reduces the...
ASR-induced length expansion, despite the high alkalinity. It can be seen that when the fly ash replacement ratio is higher than 40%, the 14-day expansion is less than 0.1%. The 40% replacement ratio for controlling the ASR-induced expansion in alkali-activated fly ash-OPC mortars may not be a universal value and likely vary with the fly ash composition and nature of aggregate tested (Shehata and Thomas 2000).

Figure 4(b) shows the length change of AAHVFA mortar specimens (Series B) during AMBT. Regardless of activator type and dosage and SF incorporation, the expansion of all AAHVFA mixtures is within 0.1%, which is the ASR-innocuous threshold based on ASTM C1567. This observation suggests that despite the significant incorporation of internal alkalis in AAHVFA system, little ASR-induced expansion is generated.

3.3 SEM/EDS analysis

Figures 5(a) to 5(c) show the SEM images of the alkali-activated fly ash-OPC mortars with various fly ash replacement ratios after AMBT. It can be seen that for mixture with the fly ash percentage higher than 40%, little internal through cracks are observed within the aggregate or at the paste-aggregate interface, which correlates well with the AMBT results. However, in reference OPC mortars, ASR-induced cracks occur almost within the interior of aggregate particles, rather than at the paste or aggregate-paste interface. It may suggest that the development of aggregate distress onsets within the particles at the beginning of gel formation, then extend the cracks to the cement paste (Swamy 2002).

As shown in Figs. 5(e) and 5(f), the aggregate particles in the water-activated and alkali-activated HVFA mortars show some signs of surface degradation after AMBT. The elemental mapping in Fig. 6 suggests little
conspicuous ASR gels formation in HVFA, despite some surface cracking of aggregate. On the contrary, ASR gels are unambiguously confirmed in reference OPC mortars, as shown in Fig. 7. The chemical compositions of the ASR gels formed in OPC mortars and degraded aggregate surfaces in HVFA mortars are shown in Table 5. It can be seen that the Ca/Si molar ratio of analyzed ASR gels is higher than the typical value of ASR gels reported in the literature [Ca/Si molar ratio of ASR gels ranges from 1/2~1/6 to 1.3-1.8 (Katayama 2010)]. According to Katayama (2006, 2010), the composition of ASR gels varies according to the distance

| Location in Samples                  | Na/Si       | K/Si       | Ca/Si       | Al/Si       |
|--------------------------------------|-------------|------------|-------------|-------------|
| Degraded aggregate surface in Fig. 6 | 0.09 (0.05) | 0.15 (0.08)| 0.09 (0.04) | 0.20 (0.06) |
| ASR gels in Fig. 7                   | 0.21 (0.04) | 0.09 (0.05)| 0.26 (0.04) | 0.08 (0.08) |

Table 5 Chemical composition of ASR gels and degraded aggregate surface.

Fig. 5 Representative backscattered electron microscopy images of alkali-activated fly ash-OPC mortars (a) 00FA-2NH (reference OPC mortar); (b) 20FA-2NH; (c) 40FA-2NH; (d) 60FA-2NH; (e) 80FA-2NH; (f) 80FA-W (Note: W: Water, NH: NaOH solution, Nc: Na2CO3 solution).
3.4 ASR mechanisms
(1) The role of alkalis
Some studies argue that the main mechanisms by which fly ash controls ASR expansion of conventional OPC concrete is to reduce the pore solution alkalinity through extensive alkalis binding in C-A-S-H with a low Ca/Si ratio (Kawabata and Yamada 2015). However, differing from water-activated HVFA, the pore solution alkalinity of AAHVFA can be consistently high; the pH of pore solution can remain beyond 13 for alkali-activated fly ash or OPC system even at the later stage of reaction (Nedeljkovic et al. 2016; Ye et al. 2017). In addition, the increase of alkalinity in the activating solution by doubling the alkali dosage does not seem to induce any noticeable expansion in the mortar specimens, which probably rules out the mechanisms of alkali dilution and alkali binding. It should be noted that for AAHVFA systems, the alkali works as catalysis and structural forming agents in the formed N-A-S-H gel products. Although at the beginning of reaction, a significant amount of alkalis is bound to the structure of N-A-S-H, the interaction of N-A-S-H with dissolving calcium from hydrating OPC partially converts the N-A-S-H into C-A-S-H (Garcia-Lodeiro et al. 2013; Ye and Radlińska 2017), resulting in ‘alkali recycling’ and maintaining high alkalinity (Thomas 2001). As such, the

Fig. 6 SEM/EDS elemental mapping of degraded aggregate in HVFA mixture 80FA-W mortar. The cracks observed at the surface of aggregates are likely due to the degradation of aggregate particles in high alkalinity environments. The composition of degraded aggregate surface is listed in Table 5.
alkali shortage does not seem to be the major reason for the absence of ASR-induced expansion and damage in AAHVFA. In addition, external alkalis are readily supplemented to the specimens in the AMBT.

(2) The role of calcium
The low calcium content in the AAHVFA systems can reasonably explain the little ASR-induced expansion. The limited amount of calcium in the AAHVFA systems, sourced mainly from OPC hydration and some from fly ash, is likely to be fully incorporated into the formation of C-A-S-H products. As such, with little amount of calcium available in the pore solution, the alkali-silica gels, if gelation occurs, are highly fluid (Vayghan et al. 2016), and the swelling of gels pushes them into pores, during which confining stress would be alleviated, causing insignificant expansive pressure. This mechanism implies that silica dissolution still takes place, as long as the pore solution alkalinity remains high enough to dissolve reactive components of aggregate. However, under the circumstance of low calcium availability, the dissolved silicate and alkalis would probably remain in the solution (Diamond 1989; Rajabipour et al. 2015) or precipitate out in a form of highly viscous gels with less deleterious effect than calcium-rich ASR gels. The ASR gels with a higher calcium content are stiffer and less viscous, and tend to generate higher internal stress upon moisture absorption (Bleszynski and Thomas 1998; Vayghan et al. 2016). The observed degradation of aggregate surface but little ASR expansion may favor this mechanism.

Fig. 7 SEM/EDS elemental mapping of degraded aggregate in 00FA-W (OPC reference mortar) with ASR gels formation.

The composition of formed ASR gels at the surface of aggregate is listed in Table 5.
(3) The role of aluminum
Another possible mechanism is that the high aluminum content in the AAHVFA system prevents the silica dissolution of aggregate even though the pH level keeps high. Although aluminum contributed by fly ash does not reduce the pore solution alkalinity, it largely reduces the dissolution kinetics and extent of silica in aggregate (Chappex and Scrivener 2012), probably due to adsorption of aluminum ions on silicate surface (Iler 1973). Different from the mechanism that the low calcium in the system inhibits the formation of deleterious calcium-rich ASR gels, this mechanism suggests inhibited dissolution of silica at the beginning and therefore the impeded gel formation. As demonstrated in Fig. 8, the OPC mortars with nano-Al$_2$O$_3$ particles addition even at 5% can show about half ASR expansion of reference mixture. As such, it is reasonable to deduce that the high aluminum content in AAHVFA may also contribute to the low ASR damage. Nevertheless, further investigation should be conducted to further elucidate this mechanism in AAHVFA.

4. Conclusions
In this paper, the compressive strength and ASR susceptibility of alkali-activated fly ash-OPC mortars are studied. Based on the experimental findings, the following conclusions can be drawn:
(1) The addition of activating alkalis in the form of sodium hydroxide or sodium carbonate at a relatively low concentration considerably improves the mechanical properties of HVFA cementitious systems; however, a high concentration of alkaline activator is unfavorable and has an adverse impact, which is perhaps due to the inhibited dissolution of OPC at high alkalinity.
(2) The addition of a small percentage of silica fume in the water-activated HVFA system does not substantially affect its strength development; in contrast, jointly added with alkaline activation, silica fume improves significantly the mechanical properties of AAHVFA system.
(3) Despite the high alkali content in AAHVFA, it is not susceptible to ASR-induced expansion in AMBT. The SEM/EDS examination of samples confirms the absence of ASR-induced damage in AAHVFA systems provided that the fly ash replacement ratio is higher than 40%; however, the value may vary depending on the fly ash composition and nature of aggregate tested.
(4) Although some cracks, which may be the sign of aggregate degradation, are detected at the outer surfaces of aggregate particles in AAHVFA mortar systems, little ASR-induced expansion is observed. The potential mechanism of the absence of ASR-induced expansion in AAHVFA mortars is due to the low calcium content that prevents gelation of deleterious calcium-enriched ASR gels. In addition, the high aluminum content in AAHVFA system may also contribute to the low ASR expansion by inhibiting aggregate dissolution.

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![Fig. 8](image-url)

**Fig. 8** The length expansion of OPC mortar specimens with nano-Al$_2$O$_3$ addition assessed using AMBT method with testing duration extended to 28 d. The amount of nano-Al$_2$O$_3$ addition is 5% or 10% with respect to the OPC mass. The other testing conditions and mixture parameters are the same as those mentioned in the Materials and Methodology section. (three replicates for each test; the error bar indicates the standard deviation).
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