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The study of relationship between compressive strength and expansion of alkali silica reaction and/or delayed ettringite formation with the use of fly ash

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ABSTRACT

Mass concrete structures that have been deteriorated are typically attributed to shrinkage or thermal deformation. However, there is another type of cracking that has been found whose crack patterns have been considered to be the result of alkali-silica reaction (ASR) and/or delayed ettringite formation (DEF) that occurred in heat-steam cured in massive concrete structures when the initial temperature during the hydration process exceeds 70 °C. It is generally believed that fly ash has played an important role in increasing the durability in concrete. This study investigates the effects of fly ash on the compressive strength and expansion of mortar specimens subjected to ASR and/or DEF and water absorption in mortar specimens. Mortar samples were prepared using Portland cement Type III with 20% replacement of Class F fly ash, some specimens contained reactive aggregates as silica sand through a replacement of 30 wt% of river sand. Sodium sulfate was added (4%wt SO_3 addition). Some specimens were exposed to an elevated temperature curing at early age to induce ASR and accelerate DEF. Compressive strength and length change were measured over 200 days. Results indicate that fly ash effectively mitigated ASR expansion but had a limited impact on DEF. Samples exposed to both ASR and DEF conditions exhibited essential expansion and rapid reduction of compressive strength when reactive aggregate and sodium sulfate were used. This research provides insights into the complex interactions between fly ash, ASR, and DEF in cementitious systems, with implications for improving concrete durability in aggressive environments.

Keywords: Fly ash, Alkali-silica reaction, Delayed ettringite formation, Compressive strength, Expansion

INTRODUCTION

Concrete is one of the most widely used construction materials worldwide due to its versatility, strength, and relatively low cost. However, the long-term durability of concrete structures can be compromised by various degradation mechanisms, including alkali-silica reaction (ASR) and delayed ettringite formation (DEF) as shown in the bridge foundation in Thailand shown in Figure 1. These phenomena can lead to expansive reactions within the concrete matrix, resulting in cracking, loss of strength, and ultimately, reduced service life of structures [1].

ASR is a complex chemical process between reactive silica in aggregates and alkali hydroxides in the concrete pore solution. The reaction produces an expansive gel that can lead to cracking and deterioration of concrete structures[2]. The mechanism of ASR involves the dissolution of silica by hydroxyl ions, followed by the formation of an alkali-silica gel that absorbs water and expands [3]. Recent studies have focused on the role of calcium in the ASR mechanism. Gaboriaud et al. (1999) proposed that calcium plays a crucial role in forming expansive products, suggesting that the interaction between calcium and the alkali-silica gel is essential for understanding ASR kinetics [4]. This finding has implications for using supplementary cementitious materials like fly ash, which can modify the calcium content in the pore solution. Various factors, including the reactivity of aggregates, alkali content of cement, environmental conditions, and the presence of supplementary cementitious materials influence the progression of ASR. Lindgard et al. (2012) conducted a comprehensive review of factors affecting ASR in concrete, highlighting the complex interplay between material properties and environmental conditions [5].

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Figure 1 Cracking of the bridge foundation in Thailand.

DEF, conversely, is associated with the decomposition and subsequent reformation of ettringite in concrete subjected to high curing temperatures, leading to expansion and cracking in mature concrete [6]. The mechanism of DEF involves the decomposition of ettringite at temperatures higher than 70 °C, the incorporation of sulfate ions into the C-S-H gel, and the gradual release of these sulfates over time, leading to the delayed formation of ettringite in the hardened concrete matrix [7]. Recent research by Brunetaud et al. (2007) has provided insights into the kinetics of DEF, demonstrating that the expansion process occurs in three phases: induction, acceleration, and stabilization [8]. The factors influencing DEF include curing temperature, cement composition (particularly C_3A and sulfate content), and exposure conditions. Ramlochan et al. (2003) investigated the effect of supplementary cementing materials on DEF, finding that their effectiveness depends on both chemical and physical factors [9].

However, ASR and DEF have been extensively studied individually, their potential interaction in concrete systems is less well understood. Bérubé et al. (2002) investigated the combined effects of ASR and DEF, suggesting that the presence of one mechanism may influence the development of the other [10]. They observed that concrete affected by both ASR and DEF exhibited more severe deterioration than concrete affected by either mechanism alone. Recent work by Sriprasong et al. (2020) has shed light on the synergistic effects of ASR and DEF, demonstrating that the presence of ASR can accelerate the onset of DEF expansion [11]. This finding highlights the importance of considering multiple degradation mechanisms when assessing concrete durability.

Using supplementary cementitious materials (SCMs) such as fly ash has been widely recognized as an effective method to mitigate ASR in concrete [12]. Fly ash, a by-product of coal combustion in power plants, is known to reduce the available alkalis in the pore solution and modify the composition of the calcium silicate hydrate (C-S-H) gel, thereby limiting the potential for expansive reactions [13]. While the effects of fly ash on ASR have been extensively studied, its impact on DEF and the potential interaction between ASR and DEF in the presence of fly ash are less well understood. This knowledge gap is particularly significant given that concrete structures may be simultaneously exposed to conditions that promote both ASR and DEF, such as in mass concrete elements or precast concrete products subjected to heat treatment [9]. Recent research by Owsiak (2010) has explored the combined effects of fly ash on both ASR and DEF, suggesting that the optimal fly ash content for mitigating both mechanisms may differ from that required for ASR alone[14]. This finding underscores the need for further investigation into the role of fly ash in complex degradation scenarios.

The present study aims to investigate the relationship between compressive strength and expansion in mortar specimens subjected to conditions promoting ASR and/or DEF, focusing on the mitigating effects of fly ash. By examining various combinations of reactive aggregates, sulfate addition, and high-temperature curing, this research provides a comprehensive understanding of the complex interactions between these degradation mechanisms and the role of fly ash in enhancing concrete durability. The significance of this study lies in its potential to inform the development of more resilient concrete mixtures capable of withstanding multiple degradation mechanisms. As infrastructure ages and environmental conditions become more aggressive due to climate change, the need for durable concrete that can resist both ASR and DEF becomes increasingly critical [15].

This research addresses the effect of fly ash in mitigating ASR and DEF and its combination in different situations on expansion and attendant damage in mortar, focusing on the influence of SO_3 with chemicals to add sulphate ions to the pore solution. Fine reactive aggregates (silica sand) were used to initiate ASR. The internal damage due to the expansion was characterized by correlation with the compressive strength. Hence, ASR and DEF are consistently examined, combining high temperature at early ages, addition of alkali sulphates, and reactive aggregate. In this study, High-early-strength Portland cement type III (HPC) is used, which is often used in laboratory test because it has a higher C_3A, which could accelerate ASR due to a higher alkali, while high SO_3 in HPC has an effect to DEF. It is generally believed that using fly ash reduces the alkalies in cement, which means it can inhibit the risk of ASR and possibly also the risk of DEF.

MATERIALS AND METHODS

Research design

This study employs a quantitative experimental design to investigate the effects of fly ash on the compressive strength and expansion of mortar specimens subjected to conditions promoting alkali-silica reaction (ASR) and/or delayed ettringite formation

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(DEF). The research design allows for systematically manipulating key variables, including aggregate reactivity, sulfate content, and curing temperature, to isolate and examine the individual and combined effects of ASR and DEF.

Materials

Porland Cement: Type III (HPC) conforming to ASTM C150 was used as the primary binder. The chemical composition of HPC is given in Table1. Type III cement was chosen due to its higher early strength and heat of hydration, which can accelerate ASR and DEF processes, allowing for the observation of these phenomena within the study timeframe.

Table1 The chemical composition of the Portland Cement type III used in this study.

Chemical composition	%by weight
Calcium Oxide (CaO)	65.07
Silicon Dioxide (SiO_2)	20.74
Aluminum Oxide (Al_2O_3)	5.03
Iron Oxide (Fe_2O_3)	3.02
Magnesium Oxide (MgO)	2.78
Titanium Dioxide (TiO_2)	0.18
Sulphur Trioxide (SO_3)	1.95
Potassium Oxide (K_2O)	0.18
Sodium Oxide (Na_2O)	0.35
Loss on Ignition (ig. loss)	0.7

Fly Ash: Shehata and Thomas (2000) suggested that fly ash could mitigate ASR, especially fly ash with class F [12]. Thus, fly ash from the BLCP Power Plant in Rayong, Thailand, which was class F, similar to the report of Shehata and Thomas (2000) was used as a partial replacement for cement.

Aggregates: This study used two types of fine aggregates: 1) Natural river sand passing through a No.50 sieve (0.30 mm opening) as the non-reactive aggregate. 2) Reactive silica sand passing through a No.60 sieve (0.25 mm opening) was used to promote ASR.

Chemical Admixtures: Sodium sulfate (Na_2SO_4) was used to increase the sulfate content in selected mixtures, promoting DEF as per the methodology described [9]. In a previous study, Escadeillas et al. (2007) [16] and Zhang et al. (2002a) [17] suggested that high SO_3 content in cement and SO_3/Al_2O_3 molar ratio could be a significant factor for DEF. In the absence of SO_3, there can be no ettringite. However, ettringite (not monosulphate) can be present at the end of the heat treatment in the presence of much SO_3. On the other hand, in the absence of Al_2O_3, ettringite is not present again. However, if Al_2O_3 is higher, monosulphate (not ettringite) can be present. Taylor et al. (2001) indicated that the pessimum of SO_3 is trending to increase with the content of Al_2O_3; thus, this will suggest a pessimum of the SO_3 / Al_2O_3 ratio [7]. Zhang et al. (2002b) have studied the expansions for the mortar specimens made from SO_3 / Al_2O_3 molar ratios in the range between 0.80-1.40 [18]. The results indicate that the maximum expansion occurs with the molar ratio of about 1.00, and no expansion was observed when the molar ratio is lower 0.80. Zhang et al. (2002b)'s also defined a DEF Index for the expansion as shown in Eqn. 1-1 and suggested that there is no expansion when DEF index (calculated from Eqn. 1-1) is lower than 1.1 while the expansion can be observed when DEF index is above 1.1 [18].

Eqn.1-1

$$\mathbf{DEFIndex} = \left(\frac{\mathbf{SO_3}}{\mathbf{Al_2O_3}}\right)_{\mathbf{a}} \times \left[\frac{\mathbf{(SO_3+C_3A)_b}}{\mathbf{10}}\right] \times \sqrt{\mathbf{Na_2O_{eq}}}$$

where; $(SO_3 / Al_2O_3)_a$ is the molar ratio of SO_3 to Al_2O_3 of the cement,

$(SO_3 + C_3A)_b$ is the combination of SO_3 and C_3A %wt in the cement

$\sqrt{Na_2O_{eq}}$ is the square root of Na_2O_{eq} %wt in the cement.

Mixture proportions

The amount of water can be found according to the flow table test method (ASTM C230/C230M). The flow test result suggests the water-to-cement ratio is equal to 0.83 Six mortar mixtures were prepared with a water-to-binder (cement + fly ash) ratio of 0.83. The mixture proportions are detailed in Table 2. The mixture IDs are interpreted as follows: FA contains fly ash, NS is no sulfate addition, S is sulfate addition, NR is no reactive aggregate, R contains reactive aggregate (silica sand), T cured at room temperature, and 90 subjected to 90°C heat treatment.

Table 2 Mortar Mixture Proportions.

Mixture ID	Cement (%)	Fly Ash (%)	River Sand (%)	Silica sand (%)	Na_2SO_4 (% of cement weight)
FA_NSR_T	80	20	70	30	0
FA_NSR_90	80	20	70	30	0
FA_SNR_T	80	20	100	0	4
FA_SNR_90	80	20	100	0	4
FA_SR_T	80	20	70	30	4
FA_SR_90	80	20	70	30	4

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Specimen preparation

Mortar specimens were prepared according to ASTM C109 for compressive strength testing (50 mm cubes) and ASTM C1260 for expansion testing (25x25x285 mm prisms). The mixing procedure followed ASTM C305.

Curing regimes

In order to accelerate the DEF effectively, the temperature history was adapted based on the work of Famy (1999) and Famy et al. (2001) as shown in Figure 2. A set of specimens suffixed by_90 were cured for four hours under sealed conditions at 30 °C soon after casting, and then exposed to 90 C for twelve hours with a temperature gradient of 30 °C/hr. Subsequently, the temperature was gradually reduced to 30 °C over four hours, the specimens were kept at 30 °C for another two hours, and finally the seal and mould of the specimens were removed. Another set of specimens, suffixed by _T, were cured at 30±2 °C (room temperature) for twenty-four hours under sealed conditions.

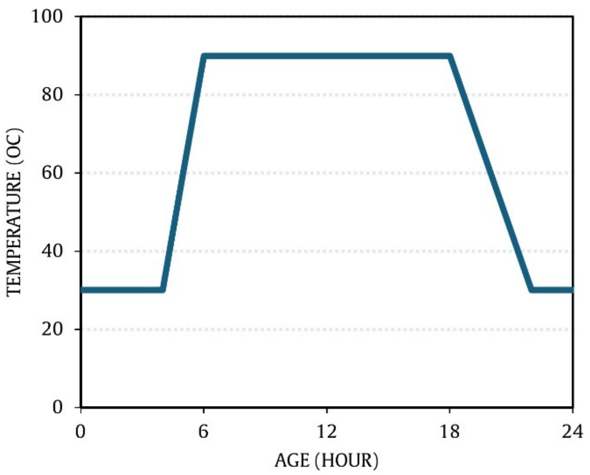

Figure 2 Curing regimes at early age to accelerate DEF.

After the initial curing period, all specimens were submerged in water at 30 ± 2°C, As the DEF expansion rate may be retarded when the pH in the pore solution rises due to leaching [19, 20] the water used to submerge the specimens needs to be changed every four weeks.

Testing procedures

Expansion measurements: length change measurements were conducted on mortar prisms at 7, 14, 28, 56, 100, 150, and 200 days using a digital length comparator with a precision of 0.001 mm, following the procedure outlined in ASTM C1260.

Compressive strength testing: compressive strength tests were performed on mortar cubes at 7, 14, 28, 56, 100, 150, and 200 days using a hydraulic press under ASTM C109.

Data analysis: The results are reported by averaging the measured values of three specimens for each type of mix proportion and curing condition. The expansion and compressive strength data were analyzed using descriptive statistics and graphical methods to identify trends and relationships. The effects of fly ash, sulfate addition, reactive aggregates, and curing temperature on expansion and strength development were evaluated by comparing the different mixture designs. The relationship between expansion and compressive strength was examined using regression analysis to test the hypothesis of a non-linear relationship and to identify potential threshold values for critical expansion related to the higher expansion that might occur when the compressive strength is suddenly reduced.

RESULTS AND DISCUSSION

1. Results

1.1 Expansion measurements

The expansion measurements for all mortar mixtures over the 200-day test period are presented in Figure 3.

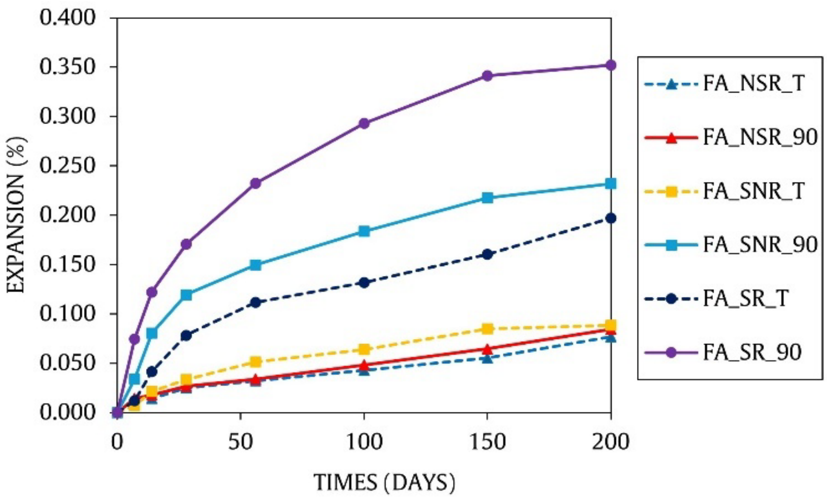

Figure 3 Expansion of mortar specimens over time.

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The expansion results reveal several key trends as follows: 1) mixtures subjected to high-temperature curing (90°C) consistently showed higher expansion compared to their room-temperature counterparts, 2) the addition of sodium sulfate resulted in increased expansion, particularly when combined with high-temperature curing, 3) mixtures containing reactive aggregates (R) exhibited higher expansion than those without, indicating the occurrence of ASR, 4) the combination of reactive aggregates, sulfate addition, and high-temperature curing (FA_SR_90) produced the highest expansion, reaching 0.352% at 200 days, and 5) mixtures without reactive aggregates or sulfate addition (FA_NSR_T and FA_NSR_90) showed the lowest expansion, suggesting that fly ash was effective in mitigating ASR when other promoting factors were absent.

1.2 Compressive strength results

The compressive strength results for all mortar mixtures over the 200-day test period are presented in Figure 4.

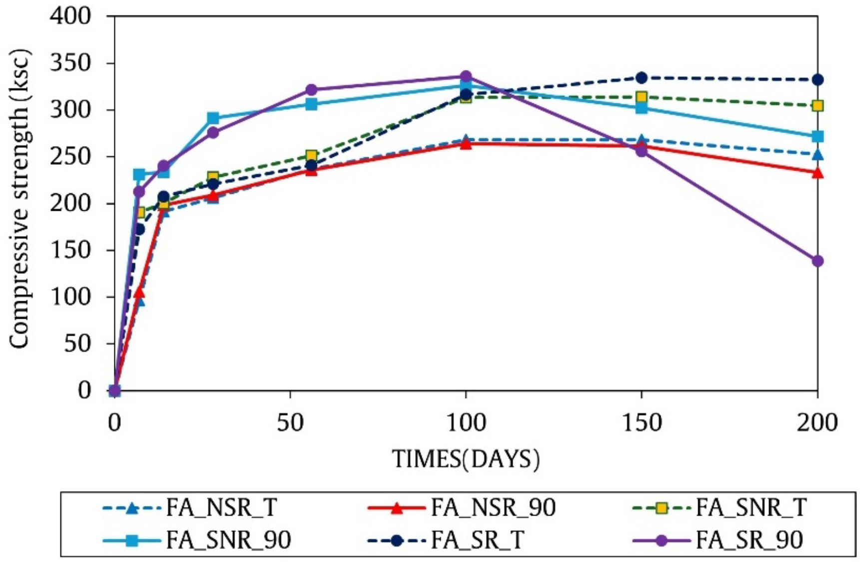

Figure 4 Compressive strength of mortar specimens over time.

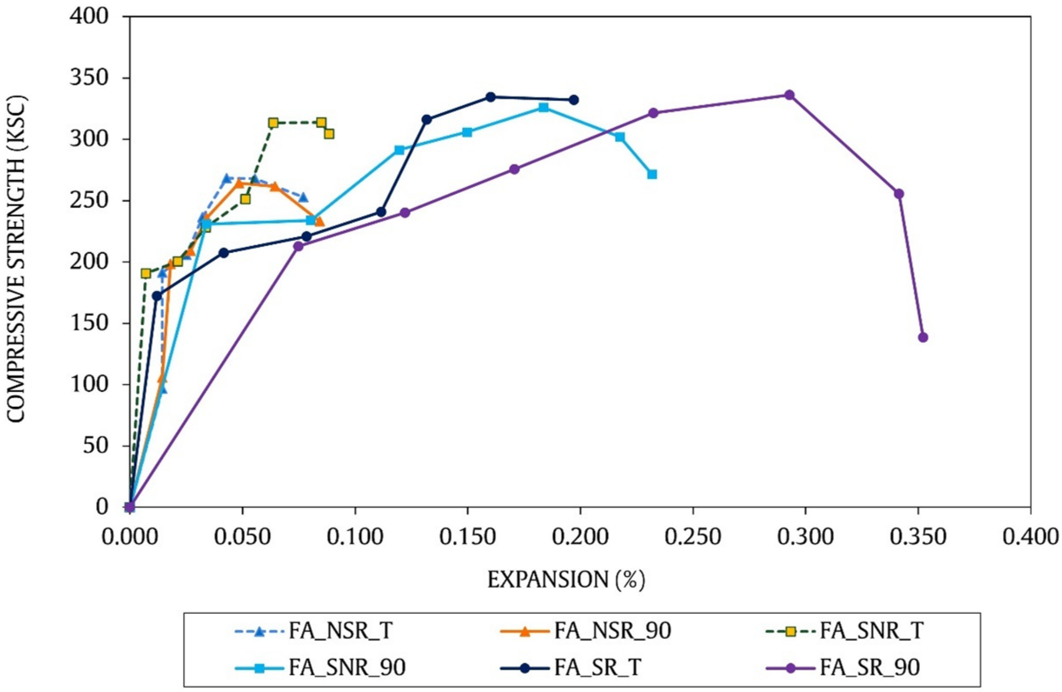

Figure 5 Relationship between expansion and compressive strength.

The compressive strength results reveal the following trends: 1) most mixtures showed an increase in strength up to 100 days, followed by a plateau or decline, 2) mixtures subjected to high- temperature curing initially developed higher strengths but showed more pronounced strength loss at later ages, 3) the addition of sodium sulfate (S) resulted in higher early-age strength but led to more significant strength loss

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over time, particularly when combined with high-temperature curing, 4) the mixture with both ASR and DEF promoting factors (FA_SR_90) exhibited the most dramatic strength loss, dropping from a peak of 32.94 MPa at 100 days to 13.60 MPa at 200 days, and 5) mixtures without reactive aggregates or sulfate addition (FA_NSR_T and FA_NSR_90) maintained relatively stable strength throughout the test period.

1.2 Relationship Between Expansion and Compressive Strength

The relationship between expansion and compressive strength for all mixtures is illustrated in Figure 5 Key observations from this analysis include:

- A general inverse relationship between expansion and compressive strength is evident, with higher expansion associated with lower strength.
- The relationship appears non-linear, with a more rapid decline in strength observed beyond an expansion threshold of approximately 0.10%.
- Mixtures subjected to both ASR and DEF-promoting conditions (FA_SR_90) show the most pronounced negative correlation between expansion and strength loss.
- Mixtures with only fly ash and no promoting factors for ASR or DEF (FA_NSR_T and FA_NSR_90) exhibit minimal expansion and maintain relatively stable strength.

These results provide insights into the complex interactions between fly ash, ASR, and DEF, and their combined effects on mortar expansion and strength development. These findings have implications for understanding the durability of cementitious systems exposed to multiple degradation mechanisms and the role of fly ash in mitigating these effects.

2. Discussion

The results of this study provide valuable insights into the complex interactions between fly ash, alkali-silica reaction (ASR), and delayed ettringite formation (DEF) in cementitious systems. The following discussion interprets these findings in the context of the research questions and existing literature.

2.1 Effectiveness of Fly Ash in Mitigating ASR and DEF

The expansion results demonstrate that fly ash effectively mitigated ASR expansion, particularly without other promoting factors. This is evident in the low expansion values observed for mixtures FA_NSR_T and FA_NSR_90, which contained fly ash but no reactive aggregates or added sulfates. This finding is consistent with previous research [12]. who reported significant reductions in ASR expansion with fly ash. The ASR detection via ASR detection kit, as shown in Figure 6, suggests a tiny amount of ASR gel (green gel) around the reactive aggregate (red aggregate).

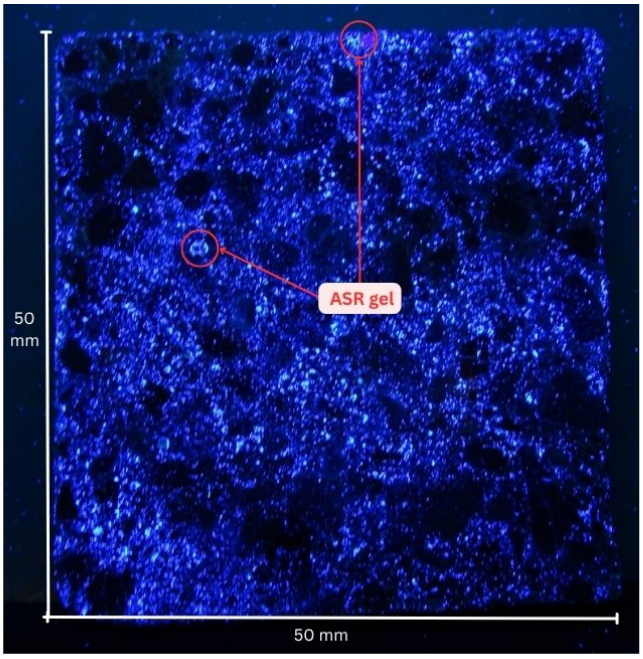

Figure 6 ASR Detection of mortar specimens.

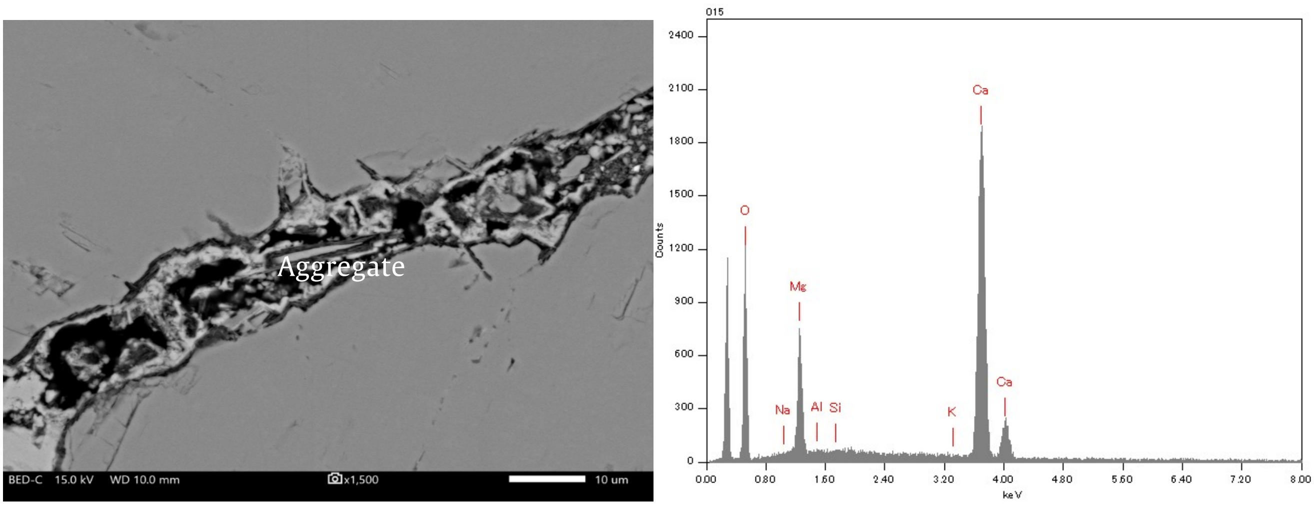

Figure 7 Left: Backscattered electron image (cracks inside aggregate) Right: Results of qualitative analysis using EDS.

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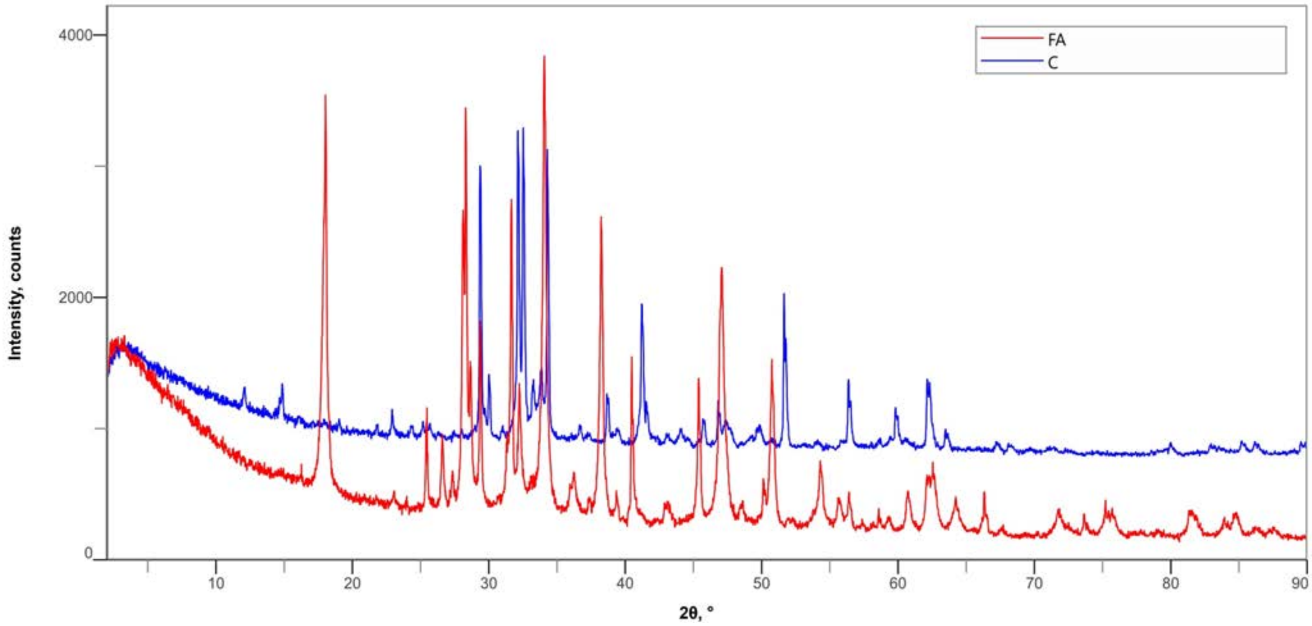

Figure 8 XRD Analysis.

However, the effectiveness of fly ash in mitigating DEF-induced expansion appears to be more limited. Despite fly ash, mixtures containing added sulfates (FA_SNR_T and FA_SNR_90) exhibited higher expansion than their non-sulfate counterparts. This observation aligns with Ramlochan et al. (2003) [9], who noted that higher quantities of fly ash might be necessary to mitigate DEF compared to ASR effectively. The results suggest that while the 20% fly ash replacement used in this study was beneficial in reducing ASR expansion, it may not have significantly mitigated DEF under the aggressive conditions created by sulfate addition and high-temperature curing. This highlights the importance of considering the specific degradation mechanisms and exposure conditions when determining optimal fly ash content for durability.

Moreover, there is no gaps around the aggregate which it possibly suggests to ettringite or cracks in the cement paste. At the same time, the EDS analysis also indicated that there is low silica (Si) in the specimens, which can ensure that fly ash could reduce the occurrence of ASR according to Figure 7 that were observed by polarizing microscope by SEM-EDS analysis. Figure 8 shows a specimen containing fly ash (red line) and a specimen without the replacement of fly ash (blue line). The position (2θ angles) and intensities of the peak provide information about the spacing between the lattice planes and the abundance of different crystallographic forms present in the sample, which means the specimens that contain fly ash could have a higher percent crystallinity and also a higher crystal perfection according to a peak width. From this perspective, it can be suggested that the higher compressive strength and lower expansion have occurred due to fly ash, which led to a gap fulfillment before the occurrence of ASR.

2.2 Relative Contributions of ASR and DEF to Expansion and Strength Loss

The expansion and strength data reveal distinct patterns for specimens subjected to conditions promoting ASR, DEF, or both mechanisms simultaneously. Mixtures containing reactive aggregates (FA_SR_T and FA_SR_90) showed higher expansion than those without, indicating the occurrence of ASR. However, the addition of sulfates and high-temperature curing (FA_SNR_90 and FA_SR_90) resulted in even greater expansion, suggesting a significant contribution from DEF.

The expansion was higher in the presence of a reactive aggregate and added sulphate (FA_SR_90), which might be due to the high curing temperature initiating ASR, while the subsequent reaction occurs later in moist curing conditions [21]. Without a reactive aggregate, the larger expansion of FA_SNR_90 than FA_SNR_T at 200 days was likely due to ettringite formation at a later age. Usually, when sulphate is added, alkali content is exposed to a high temperature (over 70 °C) at an early stage, DEF is more likely to occur [7]. Even at 200 days, a continued expansion is evident from the DEF requiring more time to complete the reaction [22].

In the specimens that exhibited a significant expansion, there was a steeper slope from a gradual degradation of compressive strength in FA_SR_T compared to the slope of FA_SNR_90 and FA_SR_90, which gradually increased at the beginning and rapidly reduced at a later age. The gradual degradation in FA_SR_T indicates that K_2SO_4 and reactive aggregate cause ASR expansion and subsequent damage at the initial stage due to ASR gel that produces an internal tensile strength and easily affects ASR as a reduction of the modulus [23].

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In the specimens coupled with ASR and DEF (FA_SR_90), the ASR acceleration at the initial stage from the elevated temperature can immediately reduce compressive strength development and early expansion. The subsequent damage and rapid expansion at later stages might be caused by DEF, which likely results from a lowered pH by ASR occurrence.

Alternatively, the increased slope for FA_SNR_90 at the initial stage might be due to the accelerated hydration from an increased curing temperature [24]. At later stages, the slope of FA_SNR_90 starts to fall sharply when the expansion reaches approximately 0.18%, which might be due to the occurrence of DEF leading to a rapid reduction of the compressive strength.

2.3 Expansion and Strength Development Patterns

This study's expansion and strength development patterns reveal complex interactions between ASR, DEF, and fly ash over time. The non-linear relationship between expansion and compressive strength, particularly evident in mixtures subjected to both ASR and DEF conditions (FA_SR_90), supports this study's fourth hypothesis (H4). This non-linear relationship suggests the existence of a threshold expansion value beyond which strength loss accelerates rapidly.

For the FA_SR_90 mixture, this threshold appears to be around 0.2% expansion, corresponding to the 56-day measurement. After this point, the rate of strength loss increased dramatically, with compressive strength dropping from 31.51 MPa at 56 days to 13.60 MPa at 200 days. This observation is consistent with the findings of Bérubé et al. (2002), who reported accelerated strength loss in concrete affected by both ASR and DEF once a critical level of expansion was reached.

The time-dependent nature of ASR and DEF development is also evident in the results. In mixtures prone to both mechanisms (FA_SR_90), expansion occurred more rapidly in the early stages (up to 56 days) compared to DEF-only mixtures (FA_SNR_90). This suggests that ASR may have dominated the early expansion, with DEF contributing more significantly to later stages. This observation supports the fifth hypothesis (H5) and aligns with the work of Biangam et al.(2012), [25] who noted that the relative contributions of ASR and DEF to concrete deterioration can vary over time.

2.4 Implications for Concrete Durability

The findings of this study have several important implications for concrete durability in environments where both ASR and DEF are potential concerns:

1) Fly ash effectiveness: While 20% fly ash replacement effectively mitigated ASR expansion, controlling DEF under aggressive conditions may not be sufficient. This suggests higher fly ash contents or combinations with other supplementary cementitious materials may be necessary for comprehensive durability enhancement.

2) Synergistic effects: The severe deterioration observed in specimens subjected to both ASR and DEF highlights the need to consider potential synergistic effects when assessing concrete durability. Designing for resistance to a single degradation mechanism may not be sufficient in complex exposure environments.

3) Early-age thermal management: The significant impact of high-temperature curing on DEF development underscores the importance of careful thermal management in precast concrete production and mass concrete placement. Limiting maximum curing temperatures and controlling cooling rates may be critical for long-term durability.

4) Long-term monitoring: The delayed nature of DEF-induced expansion and strength loss emphasizes the need for extended monitoring periods in durability studies and in-service structures. Standard 28-day tests may not capture the full extent of potential deterioration in systems prone to DEF.

5) Mixture optimization: The complex interactions between fly ash, ASR, and DEF observed in this study suggest that optimizing concrete mixtures for durability may require a more nuanced approach. Balancing the mitigation of multiple degradation mechanisms while maintaining desired early-age properties presents a significant challenge for concrete technologists.

2.4 Limitations and Future Research Directions

While this study provides valuable insights into the interactions between fly ash, ASR, and DEF, several limitations should be acknowledged:

1) Limited fly ash content: Only one fly ash replacement level (20%) was investigated. Future studies should explore a range of fly ash contents to determine optimal levels for mitigating both ASR and DEF.

2) Single fly ash source: The study used Class F fly ash from a single source. Different fly ash compositions may yield varying results, warranting further investigation.

3) Mortar vs. concrete: The use of mortar specimens, while allowing for accelerated testing, may not fully represent the behavior of concrete under field conditions. Validation studies using concrete specimens are recommended.

4) Laboratory conditions: The controlled laboratory environment may not accurately reflect the variability of field exposure conditions. Long-term field studies would provide valuable complementary data.

5) Limited duration: While the 200-day test period captured significant deterioration, even longer-term studies may reveal additional insights into the progression of ASR and DEF.

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Based on these limitations and the findings of this study, several directions for future research are proposed:

1) Investigate the effectiveness of higher fly ash contents and combinations with other supplementary cementitious materials in mitigating combined ASR-DEF deterioration.

2) Explore alternative test methods that can differentiate between ASR and DEF-induced expansion, such as microstructural analysis techniques.

3) Conduct parallel studies using concrete specimens to validate the mortar bar results and assess the impact of coarse aggregates on ASR-DEF interactions.

4) Develop and validate numerical models to predict long-term concrete performance under combined ASR-DEF conditions, incorporating the effects of fly ash and other mitigation strategies.

5) Investigate the potential for developing performance-based specifications that address multiple degradation mechanisms simultaneously, moving beyond single-parameter durability criteria.

CONCLUSIONS

This study investigated the effects of fly ash on the compressive strength and expansion of mortar specimens subjected to conditions promoting alkali-silica reaction (ASR) and/or delayed ettringite formation (DEF). The key findings can be summarized as follows:

1) The 20% fly ash replacement used in this study effectively mitigated ASR-induced expansion but showed limited efficacy in controlling DEF under aggressive conditions.

2) Specimens subjected to conditions promoting both ASR and DEF exhibited the highest expansion and most severe strength loss, supporting the hypothesis of synergistic effects between these degradation mechanisms.

3) A non-linear relationship between expansion and compressive strength was observed, with accelerated strength loss occurring beyond a threshold expansion value of approximately 0.2%.

4) The relative contributions of ASR and DEF to overall deterioration varied over time, with ASR appearing to dominate early expansion and DEF becoming more significant in later stages.

5) High-temperature curing significantly exacerbated both ASR and DEF-induced deterioration, highlighting the importance of thermal management in concrete production and placement.

These findings contribute to the broader understanding of concrete durability under complex exposure conditions and have important implications for designing durable cementitious systems. The study underscores the need for a more comprehensive approach to durability enhancement that considers multiple degradation mechanisms and their potential interactions. Future research should optimize fly ash content and explore combinations with other supplementary cementitious materials to effectively mitigate ASR and DEF. Additionally, long-term field studies and the development of advanced predictive models will be crucial for translating these laboratory findings into practical guidelines for durable concrete design and construction.

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