



## Review

## Durability of alkali-activated materials in aggressive environments: A review on recent studies

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## HIGHLIGHTS

- Recent studies on durability of AAMs in aggressive environments.
- Permeability, carbonation, chloride penetration and sulfate resistance.
- Durability of AAMs is compared with that of OPC.
- Perspectives on testing methods and suggestions in future research are drawn.

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## ABSTRACT

Corrosion of reinforcement and concrete deterioration induced by aggressive media could severely reduce the bearing capacity of structures. The durability of alkali-activated materials (AAMs) in aggressive environments, such as carbonation, chloride penetration and sulfate attack, have been a research focus worldwide. Reaction products and microstructures of AAMs are different from ordinary Portland cement (OPC), therefore the corrosion mechanisms and assessments are different. This paper reviews factors influencing water absorption and permeability of AAMs, effect of gel composition and exposure environments on carbonation, chloride penetration and chloride migration test methods, and sulfate resistance in high-calcium and low-calcium alkali-activated systems. There remains a large space in these aspects to completely understand the deterioration of AAMs, as pointed out in the end. The perspectives suggested in this paper will be useful for future study on long-term durability of AAMs.

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## 1. Introduction

The production of Portland cement is consuming a large amount of resources and energy, bringing out significant emissions of CO<sub>2</sub>, thus the building materials with low carbon footprint are gaining more and more concerns worldwide [1]. Alkali-activated materials (AAMs), prepared with aluminosilicates and alkaline activators, have been studied extensively in the past few decades due to the friendly environment impact and excellent performances, such as high early strength, acid and alkali resistance and freeze-thaw resistance [2–7]. Granulated blast furnace slag [8,9], fly ash [10] and metakaolin [11] are the major aluminosilicates used as precursors, and the activators include caustic alkali, silicate, carbonate and sulfate, etc. [12]. The reaction mechanisms of AAMs are different from Portland cement [13–15]. In order to facilitate the study, AAMs are normally classified into two kinds of gel systems [3,16], one is high-calcium system, dominated by calcium alumina silicate hydrate (C-A-S-H) gels with tobermorite-like structure, such as alkali-activated slag; the other is low-calcium system, also named 'geopolymers', in which alkali aluminosilicate (N-A-S-H) gels with pseudo-zeolitic structure are the main products, like alkali-activated fly ash and other low-calcium binders. The C-A-S-H and N-A-S-H gels could coexist in alkali-activated blended systems [17,18], and the main reaction products could change from N-A-S-H to C-A-S-H gel with the increase of calcium content, which is beneficial to the composition design of AAMs [19].

AAMs have shown satisfactory performances in building structures, road paving and waste solidification [12]; however, problems still exist in wide application [20], such as the cost of raw materials [21,22] and unknown performance of long-term durability [23]. Carbonation, chloride penetration and sulfate attack are the three critical durability factors because of their adverse effect under aggressive environments [24,25], and these factors are related to water absorption and permeability of materials.

There are controversies on performances of AAMs versus Portland cement concretes in terms of water absorption and permeability. Shi et al. [8,9,26] claimed that the water permeability of sodium silicate-activated slag mortar and concrete was lower than that of OPC. However, Bernal et al. [27,28] reported that the water absorption and permeability of alkali-activated slag concrete (AASC) were higher than ordinary Portland cement concrete (OPCC). And Albitar et al. [29] also found that the OPCC has lower water absorption and sorptivity rate than alkali-activated fly ash and slag concretes. In fact, without a standard manufacturing specification, the comparison between AAMs and OPC systems may lead to confusion, even though it is on equivalent strength grade. The water absorption and permeability of AAMs are influenced by many factors, including precursors, activators, specimen maturity and test methods [30].

Although the durability of both AAMs and OPC are affected by their water absorption and permeability of the matrix, their deterioration mechanisms are different. For example, in terms of carbonation, the dissolved CO<sub>2</sub> in pore solution could also react with reaction products of AAMs, reducing the pH of pore solution and increasing the corrosion risk of reinforcing steel due to the depas-

sivation [31]. But owing to the absence of Ca(OH)<sub>2</sub>, Byfors and Bakharev et al. [32–34] found that carbonation rate of alkali-activated slag (AAS) was faster than Portland cement as evaluated by accelerated carbonation tests; while accelerated carbonation tests may be not applicable as it differs largely to the actual condition (0.03–0.04% CO<sub>2</sub>) [12]. It was reported that the natural carbonation rate of AASC is just slightly faster than that of OPCC [34,35]. Therefore, the accelerated carbonation tests used for Portland cement cannot perfectly represent natural carbonation behavior of AAMs [36–40].

Chloride ingress is a main factor responsible for rebar corrosion [41–45]. Reinforced concretes exposed to marine environments and de-icing salts are suffered to chloride attack. In spite of the chlorides usually do not significantly harm the concrete matrix, this attack causes steel corrosion by a depassivation process, finally reduces the bearing capacity of structures. Compared to OPC, the formation of Friedel's salt (Ca<sub>2</sub>Al(OH)<sub>6</sub>Cl·2H<sub>2</sub>O) in the chloride binding is not detected in alkali-activated slag/fly ash mortars, which could retard the chloride penetration [30]. However, AAMs generally have lower chloride diffusion coefficient than OPC [26,46], and exhibit better chloride resistance [47,48], due to their special gel compositions [30,43] and pore structures [10,49]. In terms of the chloride migration tests, the rapid chloride penetration test (RCPT) [50] used for Portland cement is now believed unsuitable for AAMs, because of different pore solution chemistry [9,51]; by contrast, non-steady-state chloride migration test (NSSM) [52] seems more reliable [30,53], but it needs further verification [54].

Sulfate attack is also an important factor that induces degradation of concrete structures. Besides physical effect of salt crystallization, sulfates exist in seawater, ground water and soil can react with calcium hydroxide and calcium aluminate in Portland cement [55,56], and the resulting gypsum and ettringite cause volume expansion of concrete. The integrity and stability of concrete structures may suffer serious problems subsequently. In comparison, in AAMs, there is no Ca(OH)<sub>2</sub> and the Ca/Si of C-(N)-A-S-H is lower, the mechanisms of sulfate attack are different. The sulfate resistance of AAMs is not only related to sulfate concentration and type of cations but also depends on gel compositions [26,57–61], which deserves re-examination for the purpose of clarifying the real resistance and the perspectives that must be considered in application.

In this paper, water absorption and permeability of AAMs, as the most critical parameters governing their durability, are re-examined according to the manufacturing differences. The durability performances of AAMs, including carbonation, chloride penetration and sulfate resistance, are reviewed and discussed in relation to water absorption and permeability. In the end, the perspectives on testing specification/standards and the cautions in future study are drawn.

## 2. Water absorption and permeability

### 2.1. Effect of precursors

Water absorption and permeability of AAMs are related to many factors, such as content and type of precursors. In

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