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Review on concrete under combined environmental actions and possibilities for application to alkali activated materials

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Abstract

Alkali Activated Materials (AAMs), which are locally available alumino-silicate based materials, are emerging as alternative binders to Ordinary Portland Cement (OPC) due to higher performance and reduced carbon footprint. Before their implementation on a larger scale, their durability performance needs to be fully understood. The data on durability performance of AAMs under single environmental action are limited, and there are almost no data on their behaviour under two or more environmental actions. This article provides brief literature review on novel methods for determining durability of concrete under combined environmental actions, which could be utilised to determine the behaviour of AAMs under combined environmental actions.

Key words: durability; alkali activated materials; degradation mechanisms; combined environmental actions

Ponašanje betona pri kombiniranom djelovanju okoliša i mogućnosti primjene na alkalno-aktivirane materijale

Sažetak

Alkalno aktivirani materijali (AAM), koji su lokalno dostupni materijali na bazi alumino-silikata, postaju alternativa običnom portlandskom cementu (OPC) zbog poboljšanih svojstava i smanjenog ugljičnog otiska. Prije značajnije upotrebe u praksi, potrebno je u potpunosti razumjeti njihovo ponašanje u različitim okolišima. Postoje ograničeni podaci o dugotrajnom ponašanju AAM-a pod jednim djelovanjem iz okoliša i gotovo da nema podataka o njihovom ponašanju pri kombiniranom djelovanju dva ili više opterećenja iz okoliša. Ovaj rad daje kratki pregled literature o metodama za određivanje trajnosti betona pri kombiniranom djelovanju različitih opterećenja iz okoliša te osvrt na mogućnosti primjene za analizu otpornosti AAM-a.

Ključne riječi: trajnost, alkalno-aktivirani materijali, degradacijski mehanizmi, kombinirani utjecaj okoliša

1 Introduction

Cement has been the dominating binder in the construction industry since the last century, with an annual production of approximately 3 Gt [1]. To satisfy the demand of construction industry, cement has been produced at an exponential rate. The projections, based upon the current rate of cement consumption, suggest that approximately 4 Gt of cement per year will be produced in the next 40 years [2, 3]. Despite the benefits that the cement-based-concrete has provided to the humanity, it has a carbon footprint that poses serious environmental and health hazards. The production of cement releases greenhouse gases both directly and indirectly: the heating of limestone releases CO_2 directly, while the burning of fossil fuels to heat the kiln results in indirect CO_2 emissions. Around 0.9 tonnes of carbon dioxide (CO_2) are released during production of one tonne of ordinary Portland cement (OPC) [4, 5]. It has been estimated in various reports that cement industry contributes with 5% to 10% to the total global CO_2 gas emissions [6-9]. Apart from releasing contaminated gases into the atmosphere, cement industry also relies on natural resources [10]. In order to minimise CO_2 gas emissions, reduce depletion of natural resources, and achieve significant energy savings, great efforts have been invested to research and develop new cementitious materials that could potentially be used as alternatives to cement. Among the alternative materials that are currently under study a notable place is taken by alkali-activated materials (AAMs).

Alkali-activated materials (AAMs) are currently emerging low CO_2 alternative binders that could be utilized in the place of OPC. The AAMs are based on chemical reaction between an alkali metal source (solid or dissolved) and a solid (alumino-) silicate powder [11]. AAMs can be produced from a variety of aluminosilicate precursors depending upon user's demand for reactivity, cost, and value. AAMs are very versatile and can be developed using locally available materials, which is a significant advantage for countries abounding in such materials. On the other hand, any generalisation of AAMs is practically impossible due to the fact that properties of AAMs are highly dependent upon the type of precursor and activators. However, AAMs are a key aspect in the development of sustainable building materials for construction industry [12].

Since AAMs are being considered as potential alternative binding materials for concrete, and as they are used to construct large-scale structural elements, it is significant to understand their relevant durability performance under various deteriorating mechanisms. Furthermore, in real conditions, structural elements are not only subjected to a single deteriorating mechanism but also to multiple deteriorating mechanisms. Therefore, this work will shortly review the durability performance of AAMs and provide a brief overview of possible test methods that could be used for determining behaviour of AAMs under combined environmental actions.

2 Durability performance of alkali-activated materials

During their intended service life, concrete structures can be subjected to various environmental actions/loads, which have a direct effect on their service life. One of the main reasons for premature deterioration of concrete structures is that the compressive strength of concrete is given advantage over other performance qualities. There are many deteriorating processes and mechanisms that directly and indirectly influence durability of concrete structures and ultimately their service life. These deteriorating mechanisms are shown in Figure 1. Though water absorption and permeability of the matrix mostly govern the durability performance of both AAMs and OPC, it should be noted that their behaviour patterns under deterioration mechanisms are quite different. Furthermore, different reaction products of AAMs, such as C-A-S-H and N-A-S-H, formed depending upon the type of precursor and activator used, behave differently under various environmental actions. The deteriorating mechanisms that are critical for AAMs and that will be in the focus of the present paper are highlighted in green in Figure 1.

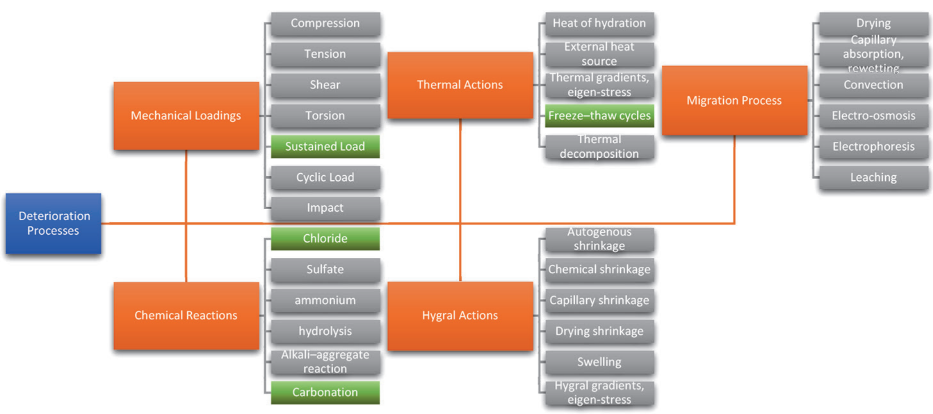

Figure 1. List of various deteriorating mechanisms [13]

2.1 Carbonation

If taken in consideration for OPC, carbonation is a chemical reaction that takes place between carbonic acid (developed in pore solution through dissociation of external CO_2 which penetrates into the matrix) and hydration products of the binder, thus producing carbonates within the paste [14]. This reaction causes a significant decrease in pH value of the paste. Both the reaction as well as its subsequential resultant cause the reinforcement within the concrete to become prone to corrosion. Carbonation is controlled by

1) diffusion through a fluid film,
2) diffusion through a solid product layer, or
3) chemical reaction at the particle surface [15].

It is significantly influenced by various factors such as relative humidity, atmospheric CO_2 concentration, pore network's tortuosity, and chemistry of binding phases and pore solution [16]. The mechanism of carbonation is quite different for AAMs, as it is highly dependent on chemical composition of materials used as binders, and the nature and concentration of activators that are to be used. Furthermore, the pH in AAMs is governed by the pore solution as compared to OPC in which the Portlandite is the controlling factor of pH. Thus, for AAMs, carbonation occurs in two stages: carbonation within the pore solution which results in pH reduction and precipitation of Na-rich carbonates, and the decalcification of gel and structure deterioration [17]. Bernal et al. [18] have established that subjecting AAM concrete to more than 1% CO_2 concentration under accelerated testing results in a significant reduction in service life, which indicates that AAMs are highly susceptible to carbonation when compared to OPC. This high carbonation has been attributed to the lack of portlandite, low Ca/Si ratio and high alkali content which, when coupled, increase the risks of carbonation through the decalcification of C-A-S-H to form calcium carbonates.

2.2 Chloride ingress

Although chlorides do not directly damage the concrete, they induce corrosion of reinforcing steel bars by damaging their passivated layer, which leads to a significant reduction in structural capability of structural elements. Chloride ions penetrate when concrete structures are in marine/coastal areas or when de-icing salts are used in cold regions. It has been reported that AAMs perform better with a reduced corrosion rate [19, 20] and that the chloride penetration depth is much lower [21] compared to OPC-based concrete. The low chloride diffusivity in AAMs has been attributed to better pore structure and enhanced chloride binding capacity of AAM concrete [22].

2.3 Freezing and thawing

In cold regions, durability of concrete structures is affected by two deteriorating mechanisms, namely, 1) damage due to repeated freezing and thawing cycles, and 2) scaling of concrete surface that is exposed to deicing salts [23]. The repeated cycles of freezing and thawing cause severe damage to concrete structures [24]. This damage is attributed to the nature of porous structure in concrete material (distribution and size of pores and capillaries and degree of saturation). AAMs have been studied for their resistance to freezing and thawing, and it has been found that AAMs have a higher resistance to frost damage due to high compactness of the paste. Better resistance of AAMs to frost damage has also been reported by Cai et al. [25] and other authors, suggesting that the utilisation of AAMs in cold regions could potentially be beneficial.

3 Combined environmental actions on concrete

Though there are numerous methods that help in predicting durability and service life of reinforced concrete structures, in most of these methods, only one deterioration process is taken into account [26, 27]. In effect, these methods do not represent the actual situation the concrete and reinforced concrete structures face in real life. In practice, these structures are generally subjected to static or dynamic mechanical loads combined with environmental actions such as carbonation and chloride penetration [26]. Micro-cracks are developed in the porous and composite structure of concrete when mechanical loads such as compressive and tensile ones are applied [26]. These micro-cracks act as a medium through which chloride and CO_2 can enter the concrete matrix. Hence the rate of carbonation and chloride penetration will be accelerated, resulting in reduction of service life of structures under the combined effect of mechanical and environmental actions [26].
Another example that may elucidate synergetic effects of combined environmental actions is that the structures in cold regions are not only subjected to freezing-thaw damage but are also influenced by erosion due to atmospheric carbon dioxide (CO_2) [28]. These combined environmental effects cause structural damage due to to freeze-thaw cycles and carbonation of concrete, resulting in complex actions that affect durability of concrete structures in cold regions [29]. Synergetic effects of combined loads on structures have been greatly neglected [26]. The earliest record on combined actions research dates back to 1986 [26, 30-33]. As shown in Figure 1, there are many possible combinations, as structures may be affected by two or more than two loads simultaneously and/or consecutively. This research aims to consider the potential synergetic effect of the combination of environmental and mechanical actions, which is a more realistic loading scenario. Although there are no standardised testing methods for determining durability performance of concrete subjected to combined environmental actions, many researchers have conducted the testing using two approaches: 1) consecutive loading, and 2) simultaneous loading.

3.1 Consecutive loading

A possible method of subjecting concrete structures to combined aggressive attacks is to apply environmental attacks alternatively or consecutively one after another. It has been observed from previous individual freezing-thawing tests that repeated cycles cause significant internal damage due to crystallisation of ice and expansion, causing cracks to develop. As cracks form, they create additional pathways for the aggressive elements such as chloride ions, sulphates, and carbonation, which penetrate to the matrix causing further damage. Previous researchers have taken this into account while testing concrete, by applying environmental attacks alternatively to determine durability performance of concrete. A summary of previous studies on alternative aggressive environmental attacks on concrete is presented in Table 1. It can be observed from Table 1 that more severe damage compared to that caused by single attack occurs when concrete is subjected to combined environmental actions in a consecutive manner. It can further be observed that the sequence in which the environmental attacks are applied is also quite significant. Though these results are encouraging and indicate that the concrete performance under combined environmental actions should be given higher priority than is presently the case, the alternative application of environmental attacks does not represent actual loads concrete structures are subjected to.

Table 1. Summary of previous studies on consecutive loading

Deterioration mechanisms and application method	Remarks	Ref
Carbonation, freezing-thawing cycles and compressive strength Single environmental attacks (C, FTC) and then compressive strength Alternative environmental attacks (FTC-C and C-FTC) and then compressive strength	Alternative environmental attacks caused severe damage compared to individual attacks. Initially, the carbonation was beneficial; however, repetitive alternative cycles generated cracks due to ice crystallisation and $CaCO_3$ expansion.	[34]
Freezing-thawing cycles, carbonation and chloride attack FTC with and without salts, C and CP Alternative C and CP	Depth of carbonation increased with an increase in the number of FTC due to internal deterioration which produced surface cracks, through which atmospheric CO_2 penetrated. Chloride migration increased with an increase in FTCs due to microcracks, but only for high w/b ratios. The presence of chlorides reduced the influence of carbonation; as a result, lower carbonation depth was observed compared to samples without chloride exposure. However, if carbonation is done first, it increased chloride depth.	[35]
Carbonation and freezing-thawing cycles and flexural strength 14 days C and 100 cycles under FTC, 100 cycles under FTC and 14 days of C	The order in which samples were subjected to attacks had significant influence, as rapid loss in flexural strength was reported when FTC was done first; this was attributed to the expansion and osmotic pressures caused by water as well as the linking of pores during FTC.	[36]
Freezing-thawing cycles, carbonation and chloride penetration Initially subjected to 0, 50 and 150 FTC, Then subjected to 0, 1, 2 weeks under C, and then CP	It was observed that coupled attacks caused service life to reduce significantly compared to single attack. Furthermore, both the amount and depth of carbonation increased when concrete was exposed to FTC. The exposure to FTC resulted in internal damage and cracking, which facilitated the ingress of carbonation; this in return caused pore size distribution to shift and thus resulted in an increase in chloride.	[37]

Deterioration mechanisms and application method	Remarks	Ref
Carbonation, freezing-thawing cycles and cyclic loading First samples subjected to five cycles of loading and unloading at different stress levels (0, 0.2, 0.4, 0.5, 0.6 and 0.8 of fc) and then subjected to alternative environmental attacks (0, 25 and 50 F or C)	The volume fraction of small pores decreases upon an increase in loading, causing the porosity of concrete to increase. The influence of porosity was observed when concrete was subjected to FTC, in which case an increase in porosity caused a decrease in resistance to FTC. The increase in stress levels also influenced the depth of carbonation, as it was observed that the carbonation depth decreased while the stress level was below the 20% peak stress, but the carbonation depth rapidly increased as the load increased beyond 20% peak stress.	[38]
Note: **FTC** = freezing and thawing Cycles, **C** = Carbonation, **CP** = Chloride Penetration		

3.2 Simultaneous loading

It can be observed from previous section that a lot of work has been conducted on alternative effects on concrete involving consecutive deteriorating mechanisms such as chloride penetration, carbonation, freezing-thawing and mechanical loadings. However, some researchers caution that application of consecutive loads still does not represent real-life scenarios concrete can be exposed to. Therefore, novel setups have been developed for simultaneous application of deterioration mechanisms. Previous studies on simultaneous loadings are summarised in Table 2, while novel setups introduced by various researchers for determining durability of concrete under combined environmental actions are presented in Figure 2.

Table 2. Summary of previous studies on simultaneous loading

Deterioration mechanisms	**Stress ratio** [s]	Remarks	Ref
Chloride penetration under compressive loading	0.3, 0.5, 0.7 fc	12% loss in strength was observed	[39]
Chloride penetration under compressive loading and curing age	NAC: 0.2, 0.4, 0.6 fc RAC: 0.2, 0.4, 0.6, 0.8 fc	The chloride diffusion coefficient of RAC and NAC decreased at different stress levels. However, 0.8fc for RAC showed an increase in chloride diffusion.	[40]
Chloride penetration under sustained compressive and tensile loading	Various Stress ratios for both compressive and tensile	An initial increase in compressive stresses resulted in a decrease in chloride diffusion; however, further increase showed an increase in chloride diffusion. The application of tensile stresses resulted in a gradual increase in chloride diffusivity.	[41]
Chloride penetration under sustained compressive loading	0, 0.25, 0.50, 0.75 fc	It was observed that lower load had little influence on the chloride ingress in concrete. However, when the load was 0.75fc, a great difference in chloride transport was observed.	[42]
Freezing and thawing under sustained flexural loading	0, 0.17, 0.50 of flexural strength	Acceleration in surface scaling of concrete was observed with an increase in stress level.	[43]

Deterioration mechanisms	Stress ratio [s]	Remarks	Ref
Sulphate attack under sustained flexural loading	0, 0.2, 0.4, 0.6 of flexural strength	It was observed that ettringite and gypsum were formed under combined loading during wet cycles, and thus the combined attack could modify microstructural properties of concrete during the drying cycle.	[44]
Freezing and thawing under sustained loading	0, 0.36, 0.54, 0.72 of flexural strength	Sustained loading had minimum effect on the mass loss and surface damage, though a higher loading level caused greater damage due to freezing-thawing cycles, and relative dynamic modulus of elasticity decreased significantly. Flexural strength decreased gradually with an increase in the number of freezing-thawing cycles.	[45]

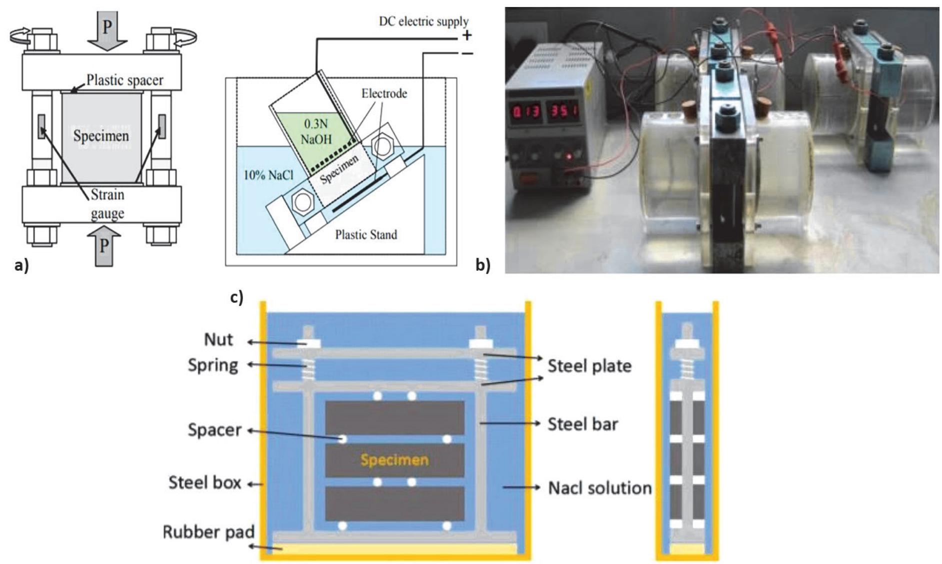

Figure 2. Illustration of setup for: a) chloride penetration under sustained compressive stresses [39]; b) modified chloride penetration under sustained compression [42]; c) freezing and thawing with de-icing salts under sustained flexural loading [45]

4 Research Outlook

Brief review presented in the paper shows that there is no standardised testing method for combined mechanical and environmental actions. However, by using specially designed test setups and loading devices, as well as the currently standardised individual testing methods for chloride, carbonation and freezing-thawing, it is possible to determine the durability of concrete that describes relatively well the actions to which concrete structures may be subjected to in real-life scenarios. The focus of future research will be on studying the influence of combined environmental actions on AAMs, taking into consideration in the first step the freezing and thawing under tensile stress. This can be achieved by prestressing the concrete, i.e. by artificially creating stresses in structural elements such that they become permanent and more favourable/efficient. The concrete will be prestressed by up to 70% of the tensile strength of prestressing cables and, after the specified curing, concrete samples will be cut into smaller specimens and subjected to a specified number of freezing and thawing cycles. After the cycles, the internal damage and surface scaling will be determined as shown in Figure 3.

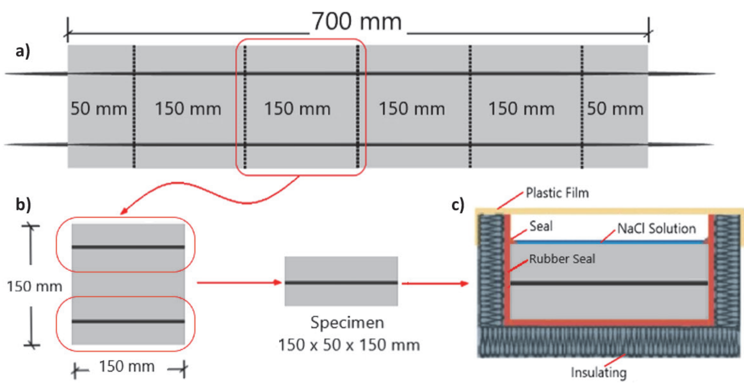

Figure 3. a) Prestressed beam; b) cutting of specimens; c) Freezing thawing test setup

AAMs are being considered as a potentially sustainable alternative to OPC due to their engineering characteristics. However, it is a relatively new material, and the data on its durability performance are limited. Furthermore, AAMs are to be utilised on a large scale, and as OPC based concrete structures are exposed to combined mechanical and environmental actions, the same will apply to AAM based structures as well. It is, therefore, necessary to determine the durability performance of AAMs subjected to combined mechanical and environmental actions.

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