

A review on the role of moisture and temperature in alkali silica reaction (ASR)

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Abstract

Alkali silica reaction (ASR) is a widely known chemical reaction in concrete that can cause premature distress and leads to loss of serviceability of affected structures. Since its identification in the late 1930s, extensive research has been carried out for a better understanding of the mechanisms involved in the reaction, while also developing ways to prevent it and manage already affected structures. However, few intensive discussions have been made in the literature regarding the influence of moisture content and temperature on ASR. Moisture plays an important role in the initiation and progress of the reaction and has been predominantly quantified by the internal relative humidity (RH), an RH threshold of 80% has been widely referenced to be required to initiate the reaction but this might be dependent on other factors like temperature, siliceous material or reactive aggregate type (coarse or fine). The RH is popularly measured with the aid of RH sensors, these have been reviewed to be less suitable at high humidity due to their susceptibility to damages resulting from condensation. The mobility of moisture and ions in the concrete microstructure can be affected by the exposure temperature, an increase in this condition has been adopted in recent performance tests to accelerate the rate of expansion and reduce the duration of the test. The side effects of this increase are lower viscosity of the ASR gel and increased alkali leaching, an already lingering issue affecting most prism and cylindrical based performance tests. Mathematical modeling of ASR in various scales incorporating the influence of temperature and moisture is discussed. Most multi-scale models ensure a robust simulation that captures other phenomena like creep, shrinkage, porosity, crack distribution and pattern.

Keywords: alkali-silica reaction; moisture; temperature

1. INTRODUCTION

Without underestimating the influence of other constituents of concrete like water, cement, chemical and mineral admixtures, aggregates can be considered as one of the most important components as they constitute about three-quarters of the volume of concrete and contributes important characteristics like stability and rigidity to name a few. For this reason, it is important to ensure good quality of aggregates used in concrete works. Concrete can be degraded by various deterioration mechanisms like corrosion, sulfate attack, freezing and thawing, with the occurrence of one leading to high susceptibility to another. From all the various deterioration mechanisms, alkali silica reactions (ASR) is the most prominent in regards to the aggregates [1–3]. ASR is a chemical reaction that is initiated by the exposure of amorphous, disordered, or poorly crystallized silica in the aggregate to alkali in the pore solution of concrete in the presence of an ample amount of water [4, 5]. Upon the reaction of the silica-based aggregates with alkalis in the presence of water, a hygroscopic gel is formed. There exist several analogies in the literature in regarding to the ASR gel swelling mechanism [6, 7]. However, it is generally believed that the ASR gel imbibes water, expands and exerts pressure on the surrounding paste. ASR can be manifested in several ways including cracking, displacement of structural members, gel pop-out [8, 9]. The cracks can initiate other durability problems like corrosion as a result of the ingress of chloride, carbonation, sulfate attack (external). Thus, the eventual inevitable loss of serviceability of the affected structure.

Since the discovery of ASR over 7 decades ago, several research studies have been ongoing to understand the mechanism of the reaction, develop standardized performance tests in a bid to determine the necessary factors required to be implemented for either the prevention or the control of the reaction [10]. The main measures that can help prevent the reaction include the use of low alkali

cement, nonreactive aggregates, and reducing the presence of water. The availability of water is the easiest to control among the trident of factors responsible for ASR at the construction stage through the reduction of w/c [11]. Water is required for dissolving and transporting ions in the pore solution and it is also needed for imbibition by the ASR gel for swelling to occur. Its availability in concrete has been prominently quantified with the internal relative humidity (RH). Temperature plays an important role in the durability of concrete structures. Thus, unquestionably why it is pivotal in initiating and sustaining the ASR. The dissolution of silica in the concrete pore solution is highly dependent on the temperature. The effect of an increment in temperature leading to the accelerated dissolution of silica was reported by Helmuth et al. [12], the authors recorded an increase in the rate of dissolution from 71%, 8%, and 7% to 100%, 66%, and 31%, respectively when the temperature of storage of three silica particle types in 3M NaOH solution was increased from 25°C to 80°C. Inclusively, the increase in temperature boosts the diffusion of ions, both adequate moisture and temperature are necessary for the increase in the rate of expansion and leads to a reduction in testing durations as employed in the accelerated performance tests. Temperature is known to have the highest impact on the internal moisture state and the transport properties in concrete [10]. As stated by Zhang et al. [13], the increase in temperature leads to the reduced internal relative humidity in concrete. It is therefore imperative to study the individual and the interactive influences of these two exposure conditions on the reaction. There are several mathematical models that incorporate the influence of the moisture condition and temperature in predicting the rate and total ASR expansion in concrete/mortar to determine the progress of the reaction and ultimately the mechanical degradation of affected structures. This review discusses the use of relative humidity in quantifying internal moisture in concrete, the interrelationship between moisture, and temperature and their unique role in the reaction and also reviews some of the available mathematical models.

2. THE INFLUENCE OF WATER IN ASR

2.1 Water in concrete; Relative humidity (RH) as an indicator

Water is an important parameter in the various degradation processes of concrete [13], about 80% moisture content is required for significant damage due to freeze and thaw [14], 55% to 65% is needed for the initiation of carbonation [15]. The general consensus is that an RH greater than 80% is necessary to initiate ASR [16]. The moisture in concrete is made up of water vapor and liquid water [17], Several researchers have quantified available water in concrete using the pore water saturation technique [17], degree of capillary saturation [18], the gravimetric technique, microwave radars, synthetic aperture radar (SAR) imaging [19]. However, the most prominent is the internal relative humidity but despite its use, it is not the accurate measure of the available moisture in concrete microstructure, since it is the ratio of water vapor present in the air to the amount the air can hold at a particular temperature. The relationship between the RH and moisture can best be explained with the aid of a sorption isotherm which varies depending on the aggregate/concrete properties. However, it is generally accepted that the RH is at 100% at complete saturation. After the casting of concrete, the voids are filled with liquid water and the concrete is in a liquid-like state called the saturated condition. In this state, a continuous liquid network exists and the relative humidity in the concrete pores is known to be close to (or at) 100% [20]. This stage is referred to as the water-vapour saturated phase [21] and its duration before the internal relative humidity begins to drop due to evaporation or cement hydration is called the critical time. According to Leech et al. [22], the critical time may be influenced by the water-cementitious ratio (w/c) of the concrete or the depth from the drying surface. The critical time is longer for concrete with a high w/c ratio as a result of the availability of sufficient water to support both evaporation and cement hydration. When the hydration of the cement begins, the water content in the concrete reduces as the surface area of the cement particles increases. As the reaction continues, the previously continuous liquid network breaks, isolating the pore water which leads to the decrease in the internal RH in concrete. Furthermore, as the concrete ages, the rate of hydration greatly reduces and the water present in hydrated cement paste can either be bound in the reaction products or available in pores which includes the interlayer and the capillary pores. The interlayer water is strongly held and can only be dried by an RH below 11% [23]. According to Nilsson [24], there exists a low pore water pressure (PWP) in the water contained in the capillary voids which are of diameter 50nm and above. As a result of the relationship between the PWP and the relative humidity in the air above a water level which can be related using the Kelvin-Laplace-Young equations [25], the relative humidity has been used to quantify the available moisture in concrete [24].

The RH in concrete can be monitored using embedded sensors which have increasingly been available and easy to use. A saturated concrete has an RH close to 100% and decreases with the loss of moisture either to evaporation or cement hydration or both. There exists an interrelationship between the RH and cement hydration. As the loss of moisture due to cement hydration/evaporation leads to a decrease in RH, also, the rate of cement hydration diminishes when RH reduces. Stressing this relationship, Parrott [26] reported the rate of cement hydration at 90% RH is about half of its rate at complete saturation. The temperature plays a major role in the RH in concrete, it has an inverse relationship with the RH as the increase in the temperature upturns the capacity of the air to take more moisture, thus, reducing the RH. Despite the reduction in RH, the moisture content in the concrete may be sufficient for the initiation or progress of the reaction. Furthermore, the increase in temperature improves the movement of moisture and ions to the reaction site.

The use of humidity sensors has been productive over the years, however, they have been reported to be unreliable at high values (RH > 90%) as a result of condensation. At high relative humidity, a slight decrease in temperature as low as 2°C would lead to the saturation of the air referred to as the dew point and condensation occurs. The accumulation of water droplets on the surface of the sensors often leads to their malfunction [25]. Furthermore, the long time it takes for them to stabilize at high RH is also a well-known challenge of most sensors [27]. Therefore, it is imperative to overcome these problems for improved assessment of internal RH in concrete. Wilson and Weiss [25] assessed the use of cyclically and constantly heated sensors to dry accumulated droplets on sensors in a bid to improve their reliability in quantifying available moisture in the concrete. Improved but yet unfavorable readings were recorded in the cyclically heated sensors, as most of the sensors were affected by the condensed water. However, the constantly heated sensors which ensure a temperature high enough to instantly dry the accumulated water proved to be effective in improving the reliability of the sensors. Another factor that could affect the use of sensors in concrete is the direct exposure to alkaline environment [28].

2.2 Role of water in the reaction

Water as one of the trio factors required to trigger ASR in concrete/mortar is needed in sufficient quantity for the transfer of alkali cations and hydroxyl ions to the reaction site, and the subsequent imbibition by the resulting gel to induce adequate stress through expansion enough to cause cracking of the surrounding paste. Water is available for the reaction through the casting water and any external water to which the structure is exposed during its service life. The quantity of water available during casting is dependent on the water to cementitious ratio (w/c) which in itself is an important parameter that influences the durability of concrete. The increase in w/c ratio constitutes more voids in hardened concrete due to the presence of more water between the solid particles while in the fresh state [29]. Relating the w/c to ASR expansion, reducing the w/c ratio leads to lower expansion since the low w/c ratio produces a concrete/mortar with low permeability, hence, limiting the migration of alkali ions and reducing available water for sorption by the gel if any [30]. According to Kim and Lee [31], self-desiccation is prominent in concrete with low w/c as a result of the loss of moisture during hydration of cement leading to the emptying of pores and a reduction in the RH. This phenomenon increases as the w/c decreases [18], thus, a w/c of 0.3 and lower can mitigate the ASR reaction [32]. However, in cases where low w/c is used, reactive aggregates might be classified as non-reactive due to the availability of low RH, and considering this effect, a moderate w/c would be required for the initiation of ASR. In another case, reducing the w/c may not sufficiently reduce the initiation of the reaction as moisture could be available from other sources like an external supply of water and even the moisture content of the aggregate used. In a research work carried out by Beauchemin et al. [33] on concrete prisms with different types of recycled concrete aggregate (RCA) using the concrete prism test (CPT) to determine the efficiency of the performance test in assessing the reactivity potentials of RCA collected from demolished ASR-affected structures, different testing series with varying RCA types and saturation conditions were prepared and conditioned at ASR environment. Under similar exposure conditions, high expansion was recorded in prisms made with aggregates in saturated surface dry (SSD) condition as compared to those made with dry aggregates.

The effect of permeable concrete on ASR and the influence of the constituted voids in easing transport of ions has been well documented. The reduction of the voids can help in mitigating or delay the initiation of the reaction. Beyene et al. [34] studied the effect of internal curing as a mitigative measure for ASR in concrete. The petrographic analysis was conducted on cylinders made of two mixtures including plain concrete and lightweight aggregate (LWA) concrete with a portion of the fine aggregate replaced with pre-wetted LWA coarse sand. The internally cured concrete samples were characterized with less ASR induced cracks and distresses compared to the plain concrete samples. This is as a result of the extra

water supplied by the LWA which increased cement hydration. Thus, making the microstructure denser (less permeable) and reducing the migration of ions required for the reaction. In a related work by Shin et al. [35], experimental results show that mortars cast and tested in accordance to the accelerated mortar bar test with a partial replacement of the reactive sand with LWA exhibited a low expansion rate compared to plain mortar based samples. Expansion in the plain mortar progressed significantly after 10 days but not before, probably because the pressure exerted by the ASR gel does not exceed the tensile strength of the mortar. While the dense microstructure of the LWA based mortar could only delay the expansion into later ages and reduce the rate but not halt the strain produced completely. This is as a result of the availability of minimum required amount of water in the mortar microstructure environment for the slow but ensured progress of the reaction.

As discussed in section 2.1, the RH has been used to quantify available water in the concrete microstructure. To investigate the effect of RH on ASR expansion, Larive [36] cast and monitored expansion in four concrete prisms stored in four different conditions and reported the specimens stored in the highest RH condition experienced the highest expansion. Thus, buttressing the need for a humid environment for the reaction. However, at high RH, the experiment could be prone to alkali leaching [10]. Furthermore, upon the confirmation of water as a crux for the reaction and the sufficiency in its quantity, the availability of an external supply of water may not be compulsory for the initiation of the reaction since the water added during the casting of concrete ensures the availability of minimum internal humidity needed for the reaction even as hydration progresses [37]. In a research work by Poyet et al. [38], the cylindrical mortar specimens conditioned at 82% RH and a temperature of 60°C had a constant mean mass throughout the experiment which indicates the initial RH in the specimen after casting was 82%, slightly greater than the minimum required RH for the initiation of the reaction. However, the dissolution and the reaction products might be limited and the swelling resulting from such reaction might not be sufficient to produce a swelling pressure that exceeds the available internal stress of the surrounding concrete paste. If the internal RH is increased, the dissolution of remaining silica, the reaction of the products, and swelling of the gel will be greatly altered leading to large expansions. The scenario is also applicable to the temporary loss of water which might put the reaction on hold and continues upon the re-exposure to water. As stated by Multon and Toutlemonde [39], in situations where the ASR expansion has been halted by lack of water, subsequent re-exposure can lead to the formation of new ASR gels along with the rapid swelling of already existing ASR gels. The authors cast concrete specimens 32 cm high, 16 cm in diameter (casting direction), and 28cm high, 14cm in diameter (perpendicular) which were exposed to 38°C temperature for 676 days either in the air (100%RH) or under watertight aluminum. The ASR expansion stabilized before the addition of water. However, upon the late supply of water, supplementary expansion was recorded in both specimens. Large and increasing deformation were recorded upon the addition of late water, deformation did not stabilize until 300 days after the new addition. This proves that the ASR expansion could have been stopped without reaching its maximal potential due to lack of water and the reactivity was re-initiated by the late supply of water [39, 40]. In a similar finding by Larive [36], expansion up to 0.1% can be attained with the water remaining in the concrete/mortar after hydration. The late supply of water could result in a significant increase in expansion provided the initial swelling of the ASR gel occurred before the loss of water. If otherwise, the expansion might take a little longer and the reinitiation is also dependent on the availability of enough alkali and silica.

The influence of moisture on ASR might be greatly affected by temperature [24]. In a capillary porous medium like concrete, the increase in temperature results in a decrease in the internal relative humidity and consequently affects expansion. At high moisture content and moderately high temperature, the rate of the reaction is high so is the imbibition of water by the gel. However, at an outrageously high temperature, the viscosity of the gel reduces, leading to the loss of its degrading expansive properties and the flow of the gel into surrounding cracks. Literature has reported various RH humidity thresholds for the initiation of ASR. Olafsson [41] reported a threshold of 80% at 23°C which falls to 75% at 38°C. A few years later Ludwig [42] stated an 80 – 85% RH at 20°C. Thereafter, Tomosawa et al. [11] and Kurihara and Katawaki [43] worked at a high temperature of 40°C and reported a threshold of 75%. However, the inconsistencies in the type of reactive aggregates used (either coarse or fine aggregates) might hinder the easy comparisons of these results. As shown in Table 2.1, the type of reactive content of the mixture may affect the initiation of the reaction. Furthermore, since the ASR expansion is greatly dependent on the type of aggregate being tested; a coarse aggregate has been known to have a different effect on expansion compared to the fine aggregate [44]. Cracks are initiated in the aggregates and extended to the concrete paste if the coarse aggregate is reactive. However, if the fine aggregate

is reactive but not the coarse, cracks forms in the concrete paste without affecting the coarse aggregates [45].

Table 2.1: Influence of reactive content in concrete/mortar on relative humidity threshold

Reference	Reactive content	Sample type	Relative humidity threshold
Tomosawa et al. [11]	Reactive coarse	Concrete prism	75% RH at 40°C
Deschenes et al. [32]	Reactive fine	Concrete prism	75.5-85.8% RH at 21°C
Poyet et al. [38]	Reactive fine	Cylindrical mortar	<59% RH at 60°C
Olafsson [41]	Reactive fine	Mortar bar	80% RH at 23°C, 75% RH at 38°C
Ludwig [42]	Reactive fine	Mortar bar	80 – 85% RH at 20°C
Kurihara and Katawaki [43]	Reactive fine	Mortar bar	75% RH at 40°C

3. THE INFLUENCE OF TEMPERATURE IN ASR

Temperature plays an important role in the durability of concrete structures. Causes of durability problems like corrosion of embedded steels, freezing and thawing among others are all dependent on temperature [46], same can be said of its importance in ASR. The increase in temperature has been the most efficient factor in accelerating the reaction [47], as it can increase the rate of expansion by 1.7 times when the temperature is increased from 38°C to 50°C [5]. Furthermore, in a research carried out by Fournier et al. [48] illustrating the importance of temperature to the reaction, concrete blocks of sizes 0.4 by 0.4 by 0.7m made with reactive aggregates, cast in Ottawa and Austin and exposed to outdoor conditions were monitored, change in length measured in the summer through fall and all year long, respectively. A higher average yearly temperature was reported in Austin compared to Ottawa having a slightly varying amount of precipitation throughout the year. The experimental result shows that field expansion of structures incorporating certain reactive aggregates is about 4-5 times faster in warmer exposure conditions when compared to cooler conditions. In most countries in North America, Central and Eastern Europe where severe climatic conditions are experienced, most importantly in the winter when structures could be subjected to over 100 freezing cycles [49], the exposure of concrete to extreme cyclic temperatures may be important for a better understanding of the combined influence of varying exposure condition on the reaction. Several researchers have reported the combined influence of these exposure conditions on the deterioration associated with the ASR and the pertinent influence of the temperature as the driving force [5, 47, 51].

The increase in temperature increases the solubility of silica and enforces an increment in expansion due to ASR. However, there have been several reports that expansion decreases beyond a temperature of 40°C [50]; few others indicate a maximum increase of 38°C [2]. Nevertheless, it is well known that a temperature as high as 70-90°C helps improve the crystallization of the CSH, as rapid hydration occurs which reduces the porosity of the microstructure and thereby limiting the movement of ions required for the reaction. As stated by Larive [36], the temperature has little effect on the final expansion but plays a great role in its rate. The author exposed concrete cylinders to temperatures of 23°C, 38°C, and 60°C but no linear relationship exists in the expansion as the temperature increases. Similarly, in a research carried out by Kawabata et al. [8], highly reactive aggregate-based concrete prisms wrapped with a wet polypropylene non-woven cloth containing 50g of 0.73 mol/L NaOH solution were exposed to a temperature of 20°C, 40°C, and 60°C. The alkaline cloth was used as a measure to reduce alkaline leaching in a newly proposed alkali wrapped concrete prism test (AW-CPT) [51]. The early expansion rate was hugely affected by the increase in temperature, the highest early expansion was recorded at 60°C while the temperature had a slight effect on the late expansion. Also, the late expansion at 40°C increased significantly beyond that at 60°C which is only slightly higher than expansion at 20°C. As a result of the low expansion at late ages, fewer cracks were observed at 60°C using the scanning electron microscope (SEM). Previous researchers have attributed the low late expansion at high temperature to excessive alkali leaching but since this method makes a provision for the prevention of this lingering problem of most concrete prism tests and accelerated concrete prism tests, it could be hypothesized that the cement paste provides adequate restraint to the expansive pressure induced by the ASR gel or the likelihood of the ASR gel already exceeded its swelling potentials. Furthermore, exudation of the gel was observed in the SEM analysis in prisms conditioned at 60°C buttressing research made by Lindgård

[10] that the viscosity of ASR gel decreases at high temperature. The consequent flow of such gel through the cracks reduces its expansive pressure on the cement paste. The effect of temperature could be dependent on other factors like the form of silica; amorphous silica will have a higher solubility than quartz at the same temperature, availability of moisture, alkalinity level.

As a result of the severity of accelerated mortar bar tests (AMBT) and the long duration of concrete prism tests (CPT) which can take as long as 2 years to determine the efficacy of supplementary cementitious materials (SCMs), there has been an urgent need to develop a faster and efficient performance test to determine the reactivity of aggregates. Several researchers have been working on the accelerated concrete prism test (ACPT) and it is gaining popularity over the past 2 decades. Some of the popular yet unstandardized tests are shown in Table 3.1. The referenced tests can be compared with the standardized concrete prism tests (CPT) having an expansion threshold of 0.04% after one year when conditioned in 38°C and a relative humidity close to 100%.

Table 3.1: Final expansion of some accelerated concrete prism tests

Reference	Concrete/mortar properties	Testing conditions	Expansion (end of test)
Gautam & Panesar [5]	Spratt reactive aggregate from Ontario	>95% RH, 50°C	0.25% at 187 days
Poyet et al. [38]	Reactive limestone	100% RH, 60°C	0.24% at 200 days
Fournier et al. [52]	Highly reactive Spratt aggregate from Ontario	100% RH, 60°C	0.15% at 91 days
Ideker et al. [53]	Seven reactive aggregates	100% RH, 60°C	0.045 – 0.239% at 91 days
Drolet et al. [54]	Spratt reactive aggregate from Ontario	100% RH, 60°C	0.059% at 91 days
Sanchez et al. [55]	Spratt reactive aggregate from Ontario	100% RH, 60°C	0.19% at 120 days

Ideker et al. [53] developed a test similar to the CPT and increased the temperature from 38°C to 60°C. The increase in temperature reduces the testing duration to 3 months and 6 months when the efficacy of SCMs is determined. Comparing to the CPT, expansions recorded in the ACPT at 13 weeks is about 53% lower than the 52 weeks expansion for coarse aggregates. Discrepancies may be attributed to an increase in alkali leaching, gel exudation, or other factors earlier discussed. Although, an additional factor; an effect of non-reactive fine aggregate used was declared by the authors to be responsible for the difference in expansion. Similar ACPTs has been developed by increasing the temperature to 60°C, which reduces the testing duration but all prone to reduced late expansion [38, 52, 54–56]. However, a similar test but conditioned at 50°C has been reported to experience a low reduction in total expansion [5] probably because the sulfate ions that develops as a result of the high temperature have no effect on the pH of the pore solution as in 60°C. Although, similar modulus of rupture and dynamic modulus of elasticity was observed, however, the extents of damage were different. Since the research was carried out using reactive Spratt aggregates, expansion properties might differ in other aggregates [5].

An important factor to be considered while increasing the testing temperature is alkali leaching which has been a perpetual occurrence even in normal CPT with a temperature of 38°C. The phenomenon is prominent in concrete stored over water in a sealed container for a long period of time. As a result of a slight change in temperature, condensed water falls on the concrete specimens which lead to the diffusion of alkali from the concrete reducing the alkali content. In wrapped concrete prisms with similar constituents exposed to temperatures of 38°C and 60°C by Lindgård et al. [18], it was observed that 14-37% of total alkaline content was leached out after 39 weeks upon exposure to 60°C as against the 10-49% leached out from the prisms subjected to a 38°C temperature after 112 weeks. Although the expansion experienced in the early ages of the prisms subjected to 60°C are higher than those subjected to 38°C, the opposite was experienced at late ages. Thus, the increase in temperature accelerates early expansion and reduces the late expansion [42, 54]. Based on the reviewed research works, it can be noted that initial expansion can be accelerated, and the testing duration can be reduced through increased temperature. However, it should also be noted that the increase of testing temperature to as high as 65°C can promote the formation of delayed ettringite formation which can contribute to the swelling effect on the mortar/concrete sample, thus, hindering the determination of the accurate

expansion potential of the aggregate. This explains why most performance tests are carried at a temperature below this critical limit [57]. The exposure of concrete specimens to high temperature affects the solubility of ettringite leading to an increase in the concentration of sulfates. Thus, the OH^- concentration and the pH in the pore solution will be reduced. An increase in the curing days from 1 to 7 days at an approximate temperature of 20°C will ensure low dissolution of ettringite when there is an elevated temperature [10].

4. MATHEMATICAL MODELLING OF INFLUENCE OF WATER AND TEMPERATURE ON ASR

ASR occurs in the mesoscopic level of concrete where reactive silica, alkalis, and water are all combined to form an expansive gel which increases by taking in water [58]. The expansion due to ASR initiates micro-cracking in concrete which then progresses to macro cracks that can be easily observed in the field. The macro cracks can take a long time to manifest in affected structures. Several mathematical models have been produced to simulate the reaction in order to provide a better understanding of the kinetics and the mechanism for expansion. The numerical model which has been extensively used in the literature for this role is discussed in this review. Modeling of ASR on different scales and comparing such simulations will aid the easy understanding of the effects of the reaction [59]. There exists vast ASR models spread over various scales including the micro [38, 60], meso [61–63], macro [4, 64], and the multi-scale [9, 59, 65, 66]. The micro-scale models used to predict damages in ASR materials is based on the representative volume element (RVE) and the models simulated in this scale can be a chemical model that simulates diffusion, the mechanical model that simulates only expansion, or chemo-mechanical models which simulates both diffusion and expansion [67]. The mesoscopic scale involves modeling as an aggregate strain or gel expansion scattered in the aggregate [58] while the macro models combine the kinetics of the reaction with the constitutive mechanics with reference to the experimentally gathered expansion results. The multi-scale models combine these scales with other factors that affect expansion as seen in recently developed models. These models help to provide a robust simulation that captures other phenomenon like creep and shrinkage, porosity.

As explained in this review, the exposure conditions are vital for the initiation of the reaction, its rate, and sustainability. Thus, the incorporation of these conditions in the mathematical models is imperative for a successful and complete simulation of its behavior. Several authors have included the temperature or moisture or the influence of the two conditions in their proposed model, few of which are reported in Table 4.1. Itam and Husain [61] proposed a mesoscale model to assess the effect of varying environmental conditions on the degradation produced in ASR conditioned concrete prisms. The model is focused on the chemical reaction while omitting the mechanical loading, thus limiting the simulation to study the chemoelastic properties of affected structures. A similar damage pattern was experienced in the model calibrated with varying RH. However, the time required to attain such damage was longer for lower RH. Also, from the results of the simulations, a low RH of 60% could initiate the reaction although less damage could be developed as a result. Comi et al. [9] developed a two-phase macro model that considers the influence of temperature and humidity on the mechanical degradation caused by ASR; kinetics of the reaction and the total expansion. The model was an extension from an earlier work carried out by Comi and Pignatelli [4] to simulate the effect of moisture gradient on ASR degradation in concrete. The authors dipped the bottom half of a beam in water and the upper half conditioned at an RH of 30% for 14 months before immersing in water for 9 months. The lower half having been completely saturated remains in a saturated state while the upper half experienced a change in moisture state throughout the 9 months. Thus, creating a moisture gradient in the beam. The effect of this gradient on the reaction and consequential role in the mechanical degradation of ASR-affected structures was therefore simulated. In the more recent work which includes the effect of temperature, the water in the concrete is quantified with the aid of degree of saturation while the possible effect of moisture gradient in the concrete is accounted for using the moisture diffusion analysis. The reaction is assumed to be caused as a result of two-phase heterogeneous materials; the concrete and wet gel. The constitutive model was derived using the free energy equation with characteristic parameters adapted from experimental data and implemented with finite elements. The proposed model was calibrated and validated using experimental data obtained from the literature. From the results, the huge dependence of ASR on water saturation was confirmed. Likewise, the effect of the late supply of water leading to a significant increase in expansion while a correlative experimental and simulated delay in expansion was observed in specimens experiencing moisture gradient.

Table 4.1: ASR mathematical models

Reference	Model Scale	Testing conditions
Comi and Pignatelli [4]	Macro	Influence of moisture gradient and temperature
Comi et al. [9]	Macro	Influence of humidity and temperature
Esposito and Hendriks [59]	Multi	Influence of water supply
Puatatsananon and Saouma [67]	Micro	Influence of internal moisture
Itam and Husain [61]	Meso	Influence of humidity and temperature
Cusatis et al. [65]	Multi	Influence of humidity and temperature
Timothy et al. [66]	Multi	Influence of water transport
Grymin et al. [68]	Micro and Meso scale	Influence of humidity and temperature

A multi-scale model was developed by Esposito and Hendriks [59] involving the micro and macro mechanical relationship. The micro-mechanical simulation uses the representative volume element concept to appraise the properties of the concrete. An elastic concrete is assumed with the aggregates modeled as spheres from which the chemical process is initiated and ASR gel formed as a result of the reaction. The increase in the volume of the gel coupled with its flow into the voids generated in the aggregates leads to the damage of the system. The model was able to account for the mechanical degradation caused by mechanical and chemical loading. It could also be used to simulate the effect of water supply on concrete degradation. Furthermore, the influence of water transport on ASR damage in concrete was simulated using a multi-scale model by Timothy et al. [66], fully saturated condition was modeled using the Darcy's law while Richard's equation was employed for unsaturated conditions. From the simulation which was verified with experimental results, it was observed that microcracks formed by the ASR gel increase water transport. Thus, increasing the availability of water for imbibition by the gel, as the gel increases in volume, the empty pores are filled leading to the generation of swelling pressure that causes macro cracks in the concrete specimens. Also, in a multi-scale model developed by Cusatis et al. [65], the proposed model was based on the earlier developed ASR Lattice Discrete Particle Model (LDPM) by Alnaggar et. al [69], a superior model to most reported in the literature due to its incorporation of the effect of crack pattern and distribution on expansion. The extended model includes the influence of the distribution of humidity and temperature in concrete on the degradation caused by the reaction. The model divided the development of the reaction into two phases namely the gel formation and the imbibition of water by the gel with both phases a function of temperature and moisture. The model verified with experimental data gathered from concrete cylinders and beams gave matching ASR expansion results coupled with and without shrinkage and creep expansions. Also, comparing the expansion results in samples conditioned at 30% RH, 100% RH, and sealed, similar experimental and simulated results were recorded with expansion greatest at 100% RH and greater at 30% RH.

The mathematical modeling of ASR has moved dramatically from simple simulations to more sophisticated ones which reproduce ASR and its behavior in varying environmental conditions with accompanying structural defects like creep, shrinkage, and even the crack pattern and its distribution in both mortar and concrete. However, limited models are available to simulate varying environmental conditions on large scale problems.

5. CONCLUSION

This review unearths the key roles of water and temperature in ASR and also provides a lucid understanding of the relationship between the exposure conditions. Water is required for dissolving ions and for the transportation of dissolved ions. These movements can be accelerated with an increase in temperature. Thus, the more moisture available and the higher the temperature, the more the expansion and degradation caused by ASR. The increase in temperature has been employed in the accelerated concrete prism tests (ACPT) to increase early expansion and reduce the test duration. Even so, most of these accelerated performance tests are prone to reduced gel viscosity and increased alkali leaching.

The quantification of moisture in concrete has been mostly done with the aid of relative humidity which is not the ideal measure of water in the concrete. Nevertheless, the reduction of moisture in concrete may depict a reduction in the RH. There exists an RH threshold below which little or no expansion occurs. This limit has been widely claimed to be 80% but it may be greatly affected by temperature, the degree of reactivity of the aggregate or the reactive aggregate type used; fine or coarse aggregate, a piece of key information found missing in the literature. Furthermore, the increase in temperature increases the capacity of air to take more moisture, leading to a reduction in RH but expansion might be initiated or sustained even at this low RH if there exists sufficient moisture in the concrete. The RH in concrete has been broadly measured via humidity sensors which have been reported to have low reliability at high humidity due to condensation. Thus, their readings in humid conditions could be questionable. Several mathematical models have been developed to simulate ASR to monitor the kinetics and the mechanism for expansion. Such models can be used as a predictive tool to determine the rate of expansion to ascertain the remaining service life of affected structures and the periodicity of mitigative actions. The most versatile is the multi-scale models that incorporate the influence of moisture condition and temperature with other physical properties of concrete.

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