



# Article Improved Alkali–Silica Reaction Forecast in Concrete Infrastructures through Stochastic Climate Change Impact Analysis

Md Asif Rahman and Yang Lu \*

Department of Civil Engineering, Boise State University, Boise, ID 83725-2060, USA; mdasifrahman@u.boisestate.edu

\* Correspondence: yanglufrank@boisestate.edu; Tel.: +1-(208)-426-3783

Abstract: The assessment of concrete infrastructures' functionality during natural hazards is fundamental in evaluating their performance and emergency response. In this work, the alkali–silica reaction (ASR) in concrete is evaluated under the climate change impact. The ASR is greatly influenced by the weather parameters, such as temperature and humidity. Climate change has led the quickening of global warming and has caused extreme weather events in recent years. These events can create anomalies in weather and thus convey potential threats to the concrete infrastructures affected by the ASR. Capturing these extreme events is the key prerequisite for the precise quantification of the ASR chemophysics. This work develops a novel stochastic approach to understand the influence of stochastic temperature and humidity on ASR expansion. To assess the stochastic weather impacts on concrete, a physics-informed domain is developed by capturing the variably saturated porous medium of concrete. This is an effort to analyze ASR kinetics that integrates chemo-physical damage under extreme weather events. Results elucidate that the ASR-affected concrete would experience 83.33% more damage in 10 years than from seasonal change due to the stochastic weather impacts from climate change. This improved predictive model will guide the durable infrastructure materials design practices and enhance the resiliency of concrete infrastructures.

Keywords: concrete infrastructure; alkali-silica reaction; climate change; stochastic analysis; resilience

# 1. Introduction

The Alkali-silica reaction is a common source of deterioration in Portland cement concrete. It is a set of undesirable chemical reactions that initiate expansion and subsequent damage in concrete. The ASR is considered a critical problem after its first identification in 1940 [1]. In the ASR, alkalis (Na<sub>2</sub>O and  $K_2O$ ) from the cement paste react with certain amorphous silica available in the surrounding aggregates. This reaction results in a hydrophilic alkali-silicate gel (ASR gel) that absorbs water from the surrounding environment and increases in volume. The volume increase exerts pressure on the surrounding matrix, causing expansion and internal stress in concrete. This ASR expansion can cause damage to the concrete by reducing its strength and stiffness with the progression of time. Hence, the alkali-silica reaction has attracted significant research efforts to understand the fundamental mechanisms of damage growth [2–5]. ASR expansion is greatly affected by its surrounding environment and local weather condition. Weather parameters, such as temperature and humidity influence the chemical reaction between alkalis and silica, and the subsequent expansion. The driving effect of ambient temperature and humidity on ASR expansion has already been explained previously [6,7]. Increased temperature accelerates the alkali-silica reaction to create ASR gel. Humidity supplies moisture to the concrete domain. This facilitates the micro-structural flow of moisture in concrete and induces hygroscopic swelling of available alkali-silica gel. Researchers suggest a critical value of 80% for the relative humidity to produce a significant expansion of the gel [7]. Thus, the trajectory is clear—the higher the temperature, the higher the humidity, and the



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**Copyright:** © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). more severe the ASR damage is. There is a significant amount of research to develop a numerical model that can assess constitutive properties accurately and can quantify the damage in ASR-induced concrete [8–13]. However, the ASR expansion and damage under the impact of climate change are yet to be evaluated.

Climate change is an emerging problem for the entire world. Climate change describes the overall change in the mean temperature and humidity or in the moisture condition. The previous findings confirm that our climate and its extremes are changing [14]. Climate change has led to the progression of global warming and initiated extreme weather events in recent years. Extreme weather can be defined as a sudden increase or decrease in temperature or humidity. This is an emerging problem for the entire world. Researchers have found that climate change gives a boost to the frequency or intensity of extreme events, such as heat waves, rainfall, humidity, air vapor, as well as snowfall during the winter. Human-induced climate change has recently increased the chances of heat waves [15,16]. Even a small change in global warming can boost the frequency of extreme weather events, especially heat waves, and rainfall [17]. These events have warmed the United States faster than the global rate since the late 1970s [18]. Warmer air produced through heat waves may contain more water vapor than cooler air. It is also evident that human-induced warming has increased the amount of available water vapor in the atmosphere [19,20]. There is also an increase in heavy snowfall in some regions during the winter season. Researchers have found that the intensity of snowstorms has increased since the 1950s [21] and has become more frequent across the northern part of the United States [22,23]. Thus, climate change has initiated extreme weather events with an increase in prolonged periods of extreme temperature and humidity. These events supply extra moisture and temperature to the infrastructure. It may also be found in many cases that the maximum temperature gets maximized and the minimum temperature gets minimized. Thus, climate extremes pose potential threats and risks [24]. This intrinsic randomness from climate-change-induced extreme events can adversely affect cement-based materials, especially, impacting the chemo-physical behavior of concrete infrastructures [25–28]. Particularly, the frequent changes in weather conditions can create anomalies in the chemical kinetics of ASR gel production and subsequent expansion. Favorable weather (high temperature or humidity) initiates the ASR expansion after accelerating ASR kinetics, whereas unfavorable weather (low temperature or humidity) prevents further expansion.

Extreme weather has also triggered sharp changes to the degree of saturation in porous concrete media. Aggregates containing amorphous silica are more porous, providing a large surface area and thus are more susceptible to deleterious alkali–silica reactions [29]. The moisture-absorption-induced volume expansion depends on the saturation status of this porous material. The effects of moisture on the ASR mechanism and relevant drying shrinkage of the partially saturated porous media have been evaluated [30–32]. With frequent changes in temperature and the random evaporation of the moisture content, the tiny pores inside the porous concrete may feel an increase or decrease in the internal vapor. This situation may generate a pressure gap inside the pores. This pressure drop between unsaturated and saturated media may pose internal shrinkage stress and can cause further damage. Thus, expansion and shrinkage in the pore spaces produce more stress in concrete and can potentially lead to much faster crack development in the concrete structure. A robust modeling platform incorporating the weather extremes under climate change and ASR expansion is necessary in this regard. While there is little research on the alkali–silica reaction under variable environmental conditions available [33–35], evaluating the ASR mechanism under the impact of climate change and extreme weather events has yet to be established. Current lab practices with constant temperature and humidity also disregard the random weather change and thus cannot capture the ASR damage accurately. Moreover, existing saturated porous media and the highest alkali-silica reaction assumptions (high temperature or humidity) lead to an over-conservative design, which is not cost-effective. Thus, there exists a critical research gap in the field of ASR expansion prediction. From an

engineering point of view, the effects of these extreme weather events on the performance of concrete infrastructures should be evaluated accurately.

Within the context discussed above, an alkali-silica reaction model is proposed in this work to bridge the existing research gap in the field of ASR modeling. It is critical to identify suitable strategies to incorporate climate change and extreme weather events in the model. There lies a trade-off between new and old design paradigms while adapting infrastructures for climate change [36]. Risk-based approaches are ideal for adapting infrastructure to a changing climate while optimizing climate adaptation strategies for built infrastructure [37]. From these perspectives, this work proposes strategies to adapt concrete infrastructure to climate change, including (1) identifying weather parameters and generating extreme weather data through stochastic analysis, (2) developing a modeling framework incorporating stochastic weather data, (3) addressing and developing the relevant chemo-physical system in the model, and (4) conducting a risk and long-termdamage assessment of concrete mesostructures under the influence of ASR expansion and climate change impact. To facilitate the implementation of these strategies, a twodimensional concrete mesostructure is generated as a representative of the ASTM prism test. The model relies on several partial differential equations (PDE)-based governing equation sets, which represent relevant chemo-physical phenomena during ASR expansion. Richards' equation is adopted to capture the unsaturated or partially saturated porous media of concrete. Uncertainties involved in the transport of the chemical species in the porous media are assessed through regression analysis based on the relevant unknown parameters. Stochastic processes are adopted to address the extreme weather conditions of climate change. An analysis is performed on a case-by-case basis, in which the effects of the weather parameters under different cases are incorporated into the model through the rate constants of the ASR kinetics and suitable boundary conditions. The finite element method (FEM) is applied to solve the PDE-based governing equations. The solution to ASR expansion and damage predictions account for the risk associated with climate change. The developed ASR model is validated by emulating the weather and material properties stated in the ASTM C1293 standard [38].

It is noteworthy that, ASR expansion cracks the concrete surface, which can further initiate corrosion to the reinforced concrete structures. However, the cracking behavior and fracture mechanics are not considered in this work for simplicity. Ideally, the developed model in this work integrates climate-change-induced weather data and its stochastic representation as input and provides a novel approach from the mesoscale perspective to predict ASR expansion and its evaluation with time. This comprehensive approach introduces a physics-informed domain by accounting for seasonal variations and variably saturated porous media, effectively capturing uncertain moisture access in the concrete. The results from the validated model identify that the evolution of ASR expansion varies a lot depending on the weather conditions and can be more destructive under the influence of stochastic weather change. The developed ASR model will help to achieve better resiliency in concrete infrastructures through improved material design.

#### 2. Computational Methods

The complex mechanisms of the ASR under climate change and extreme events require a precise quantitative assessment to guide the durable infrastructure-material design practices. As such, the current work combines the following steps in the ASR modeling framework based on the strategies stated above:

- A stochastic analysis of the weather parameters to account for the extreme events of climate change;
- ASR chemophysics in a partially or variably saturated porous media to account for the uncertain moisture access;
- Thermal equation development to account for the annual seasonal variation and global warming impact;

Numerical analysis with finite element method (FEM) for long-term-damage assessment of concrete mesostructures under the influence of ASR expansion.

#### 2.1. ASR Chemophysics

The reaction between the hydroxyl ions (ROH) in the pore solution of concrete and the siliceous components of the reactive aggregates produces ASR gel. Moreover, the byproduct, weak silanol groups, further react with hydroxyl ions to generate more alkali–silicate gel. This gel does not cause any damage to the concrete structure. Rather, hydrophilic ASR gel absorbs available water or moisture from the surroundings and thus gets converted to an expansive gel with a noticeable volume expansion. The chemical species involved in this gel production are depicted through the chemical reactions in Equations (1)–(3) [12,39].

$$\equiv Si - O - Si \equiv + R^+ + OH^- \rightarrow \equiv Si - O - R + H - O - Si \equiv$$
(1)

Siloxane	ROH	ASR gel	Silanol	
H–O–Si	$\equiv + R^+ + OH^-$	$\rightarrow \equiv Si - O^- R^+$	$+ H_2O$	(2)
Silanol	ROH	ASR gel	Water	
$\equiv Si-O-D$	$R + nH_2O \rightarrow$	$\equiv Si-O^- + (H_2O)$	$(n)_{n} + R^{+}$	(3)

ASR gel Water Expanded ASR gel

where  $R^+$  denotes an alkali ion ( $K^+$  or  $Na^+$ ).

## 2.1.1. Mass and Momentum Balance Equation

Due to chemical reactions, there is continuous migration and diffusion of chemical species through the moisture or pore water available in the concrete matrix. Thus, along with mass transfer, there is fluid flow in the matrix. These mass-transfer and flow-velocity impacts need to be included in the model to capture the transport mechanism and production of the chemical process. This is accomplished based on the principles of mass balance and momentum balance [40]. Equation (4) represents the mass and momentum balance equation for chemical species transport in the porous media [12]. It shows the coupled mass balance and momentum balance equation, which models chemical species transport through the diffusion and convection of each chemical species. This balance equation considers the two primary transport mechanisms: diffusion transport and diluted species transport. Fick's law governs the diffusion of chemical species, and the fluid body governs the migration of diluted species. Instead of the individual masses, the concentration of each species is considered a dependent variable in the equation, while balancing the mass transport in the cement-aggregate interactive media. In this case, changes in the molar mass or concentration of each chemical species are considered as mass transport, which is quantified by balancing the production and consumption of each species in the ASR reaction. The rate change of concentration is proportional to the diffusivity and instantaneous rate of change of the concentration of each species.

$$\frac{\partial}{\partial t}(c_i) + \nabla \cdot (-D_i \nabla c_i) + \mathbf{u} \cdot \nabla c_i = R_i$$
(4)

where  $c_i$  is the concentration of each species i (mole/m<sup>3</sup>);  $D_i$  denotes the diffusion coefficient of species i (m<sup>2</sup>/s); u is the fluid velocity vector (m/s) with components in x, y, and z direction, respectively; and  $R_i$  is a source term, which is defined as the rate change of the concentrations of species i (mole/(m<sup>3</sup>/s)). The rate change of the concentration of the species involved in the ASR can be expressed through Equation (5) [12].

$$\frac{d[Siloxane]}{dt} = -k_1[Siloxane][ROH] 
\frac{d[ROH]}{dt} = -k_1[Siloxane][ROH] - k_2[Silanol][ROH] 
\frac{d[ASR gel]}{dt} = k_1[Siloxane][ROH] + k_2[Silanol][ROH] - k_3[ASR gel][H_2O] 
\frac{d[Silonol]}{dt} = k_1[Siloxane][ROH] - k_2[Silanol][ROH] 
\frac{d[H_2O]}{dt} = k_2[Silanol][ROH] - k_3[ASR gel][H_2O] 
\frac{d[Expanded ASR gel]}{dt} = k_3[ASR gel][H_2O]$$
(5)

where [*Siloxane*], [*ROH*], [*ASR gel*], [*Silano*], [*H*<sub>2</sub>*O*], and [*Expanded ASR gel*] represent the concentration of each species, respectively. The rate constants  $k_1$ ,  $k_2$ , and  $k_3$  represent the three stages of the chemical reaction in Equations (1)–(3). Here, rate constants are calculated assuming that  $k_1 = k$ ,  $k_2 = 30 k_1$ , and  $k_3 = 60 k_1$  [12].

#### 2.1.2. Richards' Equation

Richards' equation can capture the fluid flow in partially or variably saturated porous media. The first publication of Richards' equation is by the English mathematician and physicist Lewis Fry Richardson to develop empirical methods for weather forecasting [41]. Later, the equation was attributed to Richards, who described the fluid as capillary conduction through porous media [42]. Many attempts have been made to simplify Richards' equation while simulating fluid flow in porous media. A very general form of Richards' equation is used in this work, as shown in Equation (6) [43,44]. Unsaturated or fully saturated porous media cannot account for the variable moisture supply generated by extreme weather conditions. On the other hand, Richards' equation provides an added benefit to incorporating the variable moisture transport into the ASR model compared to Darcy's law, which is limited to fully saturated conditions only. Thus, Richards' equation acts as an improvement over Darcy's law. It is a nonlinear partial differential equation, in which the pressure gradient is the major driving force and hence considered the dependent variable.

$$\rho\left(\frac{C_m}{\rho g} + S_e S\right) \frac{\partial p}{\partial t} + \nabla \cdot \left(\rho \mathbf{u}\right) = Q_m \tag{6}$$

where  $\rho$  is the fluid density (kg/m<sup>3</sup>),  $C_m$  denotes the specific moisture capacity (1/m), g is the acceleration due to gravity (m/s<sup>2</sup>),  $S_e$  represents the effective saturation (1), S represents the storage coefficient (1/Pa), p is the pressure (Pa),  $\mathbf{u}$  is the fluid velocity vector (m/s), and  $Q_m$  is the fluid source (kg/(m<sup>3</sup>.s)).

The fluid velocity vector across the faces of an infinitesimally small surface can be defined as Equation (7).

$$\mathbf{u} = -\frac{\kappa_s}{\mu}\kappa_r(\nabla p + \rho g \nabla D) \tag{7}$$

where  $\kappa_s$  defines the hydraulic permeability (m<sup>2</sup>),  $\mu$  is the fluid dynamic viscosity (Pa. s),  $k_r$  represents the relative permeability (1), and *D* is the elevation (m).

In this work, the effect of elevation, *D*, is not considered and assumed to be zero. The initial pressure level and reference pressure level are kept the same to avoid any pressure gradient at the initial stage. If hydraulic conductivity is related to hydraulic permeability, Richards' equation can be formulated as Equation (8). Thus, this work implements hydraulic conductivity for the fluid permeability analysis in the model.

$$\rho\left(\frac{C_m}{\rho g} + S_e S\right) \frac{\partial p}{\partial t} + \nabla \cdot \rho(-K_s \kappa_r \nabla p) = Q_m \tag{8}$$

where  $K_s$  is the hydraulic conductivity (m/s).

The compressibility of fluid or cement–concrete matrix is not considered in this work, and thus, the value of storage coefficient *S* is simply defined as 1 (1/Pa). The fluid source term is calculated as  $Q_m = R_{H2O} * 0.018$  [kg/mole] [31].

#### 2.1.3. Retention Model

Richards' equation provides a platform under variably saturated media to input the weather randomness in the ASR model. However, a mathematical process is needed to add these inputs to the model. The retention model can complete this job by capturing the moisture content of the partially saturated media. The idea for the concrete-water retention model has come from the established soil–water retention model, as discussed in [45]. It defines how saturated or unsaturated conditions may vary depending on the pressure head. In this work, the van Genuchten retention model is used to calculate the unsaturated hydraulic properties of the flow medium, i.e., liquid volume fraction  $\theta$ , effective saturation  $S_e$ , specific moisture capacity  $C_m$ , and relative permeability  $k_r$  [45]. The liquid fraction in concrete can be related to the pressure head. Variably saturated media work through the liquid volume fraction, which may range from a residual value  $\theta_r$  to a saturated value  $\theta_s$ (total porosity), depending on the available moisture content in the media [43]. According to the van Genuchten model, the unsaturated condition occurs when the pressure head in the media becomes negative, and it reaches saturation level when the pressure head is equal to or greater than zero [45]. In general, concrete in the field condition is mostly unsaturated. However, it absorbs moisture from the surrounding environment, and thus, the pressure head becomes positive, and the concrete gets saturated. Equation (9) describes the van Genuchten equations.

Unsaturated Condition ( $H_p < 0$ ): Saturated Condition ( $H_p \ge 0$ ):

where the pressure head,  $H_p = p/\rho g$ , m = 1 - 1/n,  $\alpha$ , m, and n are the van Genuchten coefficients. Values of  $\theta_s$ ,  $\theta_r$ ,  $\alpha$ , and n are determined based on the water retention curve for mortar and aggregate phases (weathered granite) [46,47].

It is noteworthy that Equations (4) and (8) are simulated concurrently in this work to quantify the concentration of expansive ASR gel in the variably saturated porous media of concrete. Richards' equation takes care of Darcy's velocity field of the moisture flow.

#### 2.2. Thermal Equation Development

A change in temperature from weather extremes and global warming impacts the reaction mechanism involved in ASR kinetics. To quantify this change, heat transfer in the porous media of concrete is simulated using Equation (10), which corresponds to the differential form of Fourier's law.

$$\rho C_p \frac{\partial T}{\partial t} + \nabla \cdot (\mathbf{q}) = Q_s$$

$$q = -k \nabla T$$
(10)

where  $\rho$  is the density of the solid (kg/m<sup>3</sup>),  $C_p$  denotes the specific heat capacity at constant pressure (J/(kg.K)), *T* is the temperature (K), *k* is the thermal conductivity of concrete (W/(m.K)), and  $Q_s$  is the heat source or sink (W/m<sup>3</sup>).

The heat source  $Q_s$  is usually considered for early-age concrete under cement hydration. This is ignored for hardened concrete in the case of ASR degradation in this work. Initial and reference temperatures are kept the same to avoid any temperature gradient at the initial stage.

The temperature change produced by global warming can be modeled by assuming a linear variation of the mean temperature [48]. In this work, the Representative Concentration pathway (RCP) climate model is used to visualize how ASR can evolve under the impact of global warming [49]. The global mean temperature can potentially be increased by 4.5 °C within 100 years (2000–2100), based on the projection of RCP 8.5 [49]. As such, the effect of global warming is modeled for the upcoming years by a linear time-variant function as shown in Equation (11).

$$T_{mean}(t) = T + \left(\frac{T_a - T_{a0}}{t_a}\right)t \tag{11}$$

where  $T_{mean}$  is the mean temperature that includes the global warming impact. *T* is the annual seasonal temperature (°C),  $T_{a0}$  denotes the annual average temperature at the beginning of the analysis period (°C) (t = 0 years),  $T_a$  denotes the annual average temperature at the end of the analysis period (°C) ( $t = t_a$  years),  $t_a$  is the total analysis period, and t is the time (years). Here, global warming is not spatially homogenous, and the ASR model is not simulating any specific location.

According to RCP 8.5, global surface warming can be increased by 3.6 °C within the next 80 years (2020–2100) [49,50]. Figure 1a shows this temperature increase from the projection of climate model RCP 8.5. This temperature change can also be captured by a polynomial variation of temperature with time, as shown in Equation (12).

$$\Delta T = -3\exp(-6)t^3 + 0.0005t^2 + 0.0257t - 0.003; 0 \le t \le 80$$
<sup>(12)</sup>

where  $\Delta T$  is the temperature increase (°C), and *t* is the time (years).



**Figure 1.** Temperature increase: (**a**) projected future global surface temperature increase, (**b**) effect of temperature increase on the saturation vapor pressure.

A temperature increase also raises the saturation vapor pressure significantly [51]. The saturation vapor pressure can be described as the amount of water vapor required to make the air saturated at any given temperature. From the relationship between temperature and water vapor pressure [51], saturated vapor pressure can be defined by the temperature rise as shown in Figure 1b.

#### 2.3. Stochastic Analysis

Extreme weather events add randomness to the seasonal variations of weather parameters. To address this situation, a stochastic approach is needed to synthesize the random nature of weather and the associated uncertainty in the ASR-induced damage prediction of concrete mesostructures. As such, the Karhunen–Loève (KL) expansion is implemented to account for the stochastic approach in this work. KL expansion is a popular approach to series expansion, where the stochastic process is represented as a truncated finite series [52]. Thus, it is adopted to explicitly represent the weather anomaly in the predictive model. The Karhunen–Loève expansion of a zero-mean random process  $X(t,\theta)$  is based on the spectral decomposition of its covariance function [52]. If the covariance function is bounded, symmetric, and defined by the orthogonal Eigen decomposition, the KL expansion of random process  $X(t,\theta)$  over the stochastic domain, Dcan be expressed by Equation (13) [52].

$$X(t,\theta) = \sum_{n=1}^{m} \sqrt{\lambda_n} \varphi_n(t) \xi_n(\theta)$$
(13)

where  $\varphi_n$  and  $\lambda_n$  are the orthogonal deterministic Eigen functions and Eigenvalues of the covariance function, respectively.  $\xi_n(\theta)$  is a set of uncorrelated random variables. This series is approximated by a finite number of terms m for solving practical problems. The deterministic set of Eigen functions is used to represent the stochastic process in weather parameters.

The values of  $\varphi_n$  and  $\lambda_n$  can be determined from the analytical solution of the covariance kernel, as shown in Equation (14).

$$\int_{D} C_X(t_i, t_j) \varphi_n(t_j) dt_j = \lambda_n \varphi_n(t_i)$$
(14)

where  $C_X(t_i,t_j)$  is the covariance function, and  $t_i$ , and  $t_j$  are the coordinates of point *i* and *j*, respectively.

In this work, an exponential covariance kernel is implemented in the symmetrical domain D = [-1, 1], to solve the integral problem. The exponential function is considered to simulate the randomness of extreme weather events. This function consists of only two parameters ( $\sigma^2$  and *b*):

$$C_X(t_i, t_j) = \sigma^2 \exp\left(\frac{|t_i - t_j|}{b}\right)$$
(15)

where  $\sigma^2$  is the variance, and *b* is a correlation length parameter. The variance is a scaling factor that determines how far function values can vary from the mean. The length parameter defines the smoothness of the function, i.e., how frequently the value can change. In this work, variance  $\sigma^2$  is assumed to be 1 so that the function stays close to its mean values, and the correlation length parameter b is assumed as 0.1 so that the function value can change quickly to imitate random changes in temperature or humidity due to the extreme events.

Thus, for a certain mean  $\mu$  for the process, the KL expansion of random process  $X(t,\theta)$  can be further derived as Equation (16).

$$X(t,\theta) = \mu + \sum_{n=1}^{m} \sqrt{\lambda_n} \varphi_n(t) \xi_n(\theta)$$
(16)

The random variable set  $\xi_n(\theta)$  is assumed to be a Gaussian process. Details of the derivation for the Eigenvalues and Eigenvectors estimation can be found in [52].

Stochastic Temperature and Humidity

The derived KL expansion is used to consider the time-dependent stochasticity of both temperature and relative humidity. The stochastic process is combined with the mean temperature and humidity, in reproducing the stochastic temperature and humidity. This is an effort to imitate the real-world weather condition under climate change and extreme weather events. Equation (16) can be expressed as Equation (17) to calculate the stochastic temperature of the surrounding environments.

$$T(t,\theta) = T_{mean} + \sum_{n=1}^{m} \sqrt{\lambda_n} \varphi_n(t) \xi_n(\theta)$$
(17)

where  $T(t,\theta)$  represents the stochastic temperature.

From here, the stochastic relative humidity can be quantified. The relative humidity and dew-point temperature indicate the amount of available moisture in the air. Global warming increases the dew-point temperature, and thus, relative humidity also increases with it. To process the stochastic humidity, Equations (18)–(19) is derived based on the relation between temperature and humidity [53].

$$T_d = T - \left(\frac{100 - RH}{5}\right) \tag{18}$$

$$RH(t,\theta) = 100 - 5(T(t,\theta) - T_d)$$
<sup>(19)</sup>

where  $T_d$  is the dew-point temperature (°C), *RH* is the annual seasonal relative humidity, and *RH*(*t*, $\theta$ ) is the stochastic humidity (%), at any certain time.

The generated stochastic temperature and humidity are implemented in the developed ASR model in this work. The stochastic temperature  $T(t,\theta)$  is utilized to calculate the rate constants in the ASR kinetics. The relationship between the rate constants and temperature is defined through the Arrhenius equation, as given by Equation (20) [54].

$$k = A \exp\left(-\frac{E_a}{R_g T(t,\theta)}\right)$$
(20)

where *k* is the rate constant, *A* is the pre-exponential factor (frequency factor),  $E_a$  is the activation energy, and  $R_g$  is the universal gas constant. Thus, the stochastic temperature accounts for the impacts of weather extremes in the ASR kinetics.

The stochastic temperature  $T(t,\theta)$  is also applied as a boundary condition on the top surface of the concrete domain. On the other hand, the stochastic relative humidity  $RH(t,\theta)$ is fed into the model by incorporating ambient vapor pressure at the concrete boundary. Ambient vapor pressure is a function of relative humidity and can be calculated from the saturation vapor pressure using Equation (21).

$$P_{amb} = RH(t,\theta).P_{sat} \tag{21}$$

where  $P_{sat}$  is the temperature-dependent saturation vapor pressure, and  $P_{amb}$  is the ambient vapor pressure due to relative humidity. From here, vapor concentration at the boundary can be calculated by Equation (22).

$$C_v = \frac{P_{amb}}{R_g T(t,\theta)} \tag{22}$$

where  $C_v$  is the vapor concentration (mole/m<sup>3</sup>) at the boundary. Vapor concentration,  $C_v$ , is applied as an inflow boundary condition at the concrete's top surface. The influx of these boundary conditions through the concrete surface is shown in Figure 2a.

#### 2.4. Numerical Analysis

In this work, a mesoscale model is developed to accommodate the non-linear evolution of ASR damage in both space and time. Mixed mineralogy gravel C8 is considered for validation purposes [55]. The developed model is simulated initially for 1 year to conduct parameter estimation and model validation. The developed model is simulated for another 10 years to extrapolate the ASR expansion data and to predict the service life of the concrete under ASR damage.



Figure 2. Concrete mesoscale: (a) a two-dimensional domain, and (b) meshed geometry.

#### 2.4.1. Mesoscopic Geometry

This work captures concrete mesoscale geometry in a two-dimensional computational framework to predict concrete damage propagation under ASR expansion. A mesoscale concrete prism with a cross-section of 75 mm  $\times$  75 mm is created according to the ASTM C 1293 concrete prism test [38]. This concrete prism consists of two phases, mortar and aggregate, as shown in Figure 2a. In this mesoscale geometry, each element size is 1 mm, and the maximum particle size is 20 mm. A packing density of 0.7 is calculated from the relation between particle packing density and particle size distribution [56]. The considered mesoscale domain meshes use quadrilateral elements, as shown in Figure 2b. An in-house MATLAB code is developed to convert each pixel of concrete geometry into a quadrilateral element. The meshed geometry is further processed to make it readable in the NASTRAN bulk data format, a common format for importing generated meshes into the finite element solver. The developed model is then analyzed by the finite element method to simulate ASR expansion in this complex concrete matrix.

In this concrete mesoscale development, material properties are selected so that they align with the model validation [55]. A 28-day compressive strength of 34MPa is used to represent the concrete density under a cement content of 420 kg/m<sup>3</sup> based on the relationship between strength and cement content in lightweight aggregate concrete [57]. An increased alkali content is used to boost the chemical reaction as an ASTM test [38]. An alkali content of 1.25% Na<sub>2</sub>O<sub>eq</sub> (by mass of cement) is considered to represent the hydroxyl ion concentration in concrete [55]. From here, the initial concentration of ROH in the mortar phase is calculated as 875 mole/m<sup>3</sup>, based on the relationship between ROH concentration and % equivalent Alkali Na<sub>2</sub>O<sub>eq</sub> [7]. A case study of the effects of ROH concentration on ASR gel production can be found in [58]. The initial concentration of H<sub>2</sub>O is assumed to be 1000 mole/m<sup>3</sup> to ensure there is enough water available in the concrete domain to initiate ASR expansion. Thus, the initial concentration of ROH and H<sub>2</sub>O considered in this work provides an elevated environment for ASR expansion to happen.

Furthermore, an in-house MATLAB code is developed to account for the uncertainties involved in the transport of the chemical species in the ASR-affected porous concrete media. The uncertainties in the transport mechanism may rise from unknown parameters, such as the diffusion coefficient and the initial concentration of the chemical species. This is addressed in the model through a rigorous process that starts with an initial guess as a trial basis to estimate the unknown parameters from the regression analysis. Based on those initial guesses, a probability density function (PDF) considers the range of possible values as a uniform random function. This work utilizes the accept-and-reject method, in which a calibrated threshold value is assumed to limit the parameter values. After calibration,

a threshold value of 0.001 is selected to find the suitable parameter values, for which the simulated results represent the experimental data. This ensures the reliability of the estimated parameters in the developed ASR Model. An error calculation and estimations are completed through the following algorithm:

Error =  $(Y_2 - Y_1)^2$ ; If Error  $\leq 0.001$ : Accept the sample Proposal PDF = @(mu) unifrnd (x<sub>1</sub>, x<sub>2</sub>, x<sub>3</sub>,...); Else: Reject the sample

The algorithm compares the experimental data  $(Y_1)$  with the simulated data  $(Y_2)$  using potential parameter values  $(x_1, x_2, x_3)$ . It iteratively finds the possible value of the parameter from the listed ranges in the probability density function if the error is below the threshold. Otherwise, the algorithm continues the loop to find the unknown parameter value.

Based on the parameter estimation, the diffusion coefficient of ROH in mortar has been found to be  $5 \times 10^{-14}$  m<sup>2</sup>/s. The initial concentration of siloxane has been found to be 710 mole/m<sup>3</sup> in aggregate. Pre-exponential factor A has been calculated as 0.00014 m<sup>3</sup>/(mol s). A detailed summary of the relevant material properties in the mortar and aggregate phases of concrete is presented in Table 1.

Table 1. Material properties used in the developed ASR Model.

	Mortar	Aggregate	Source	
Diffusion coefficient of ASR gel (m <sup>2</sup> /s)	$1  imes 10^{-10}$	$1  imes 10^{-12}$	[13]	
Diffusion coefficient of $H_2O(m^2/s)$	$5 imes 10^{-10}$	0	[54]	
Initial concentration of $H_2O$ (mole/m <sup>3</sup> )	1000	0	Calibrated	
Initial concentration of Silanol (mole/m <sup>3</sup> )	0	0		
Initial concentration of ASR gel (mole/m <sup>3</sup> )	0	0	[58]	
Initial concentration of expanded ASR gel (mole/m <sup>3</sup> )	0	0		
Activation energy, $E_a$ (J/mole)	43,000	43,000	[59]	
Universal gas constant, $R_g$ (J/(mole. K))	8.3144598	8.3144598	Constant	
Initial pressure (atm)	1	1	Calibrated	
Reference pressure (atm)	1	1	Calibrated	
Residual water content, $\theta_r$	0	0.08		
Saturated water content, $\theta_s$	0.185	0.308	[46.47]	
van Genuchten coefficient, $\alpha$ (1/m)	$3.23 \times 10^{-4}$	15.3		
van Genuchten coefficient, n	1.217	1.406		
Hydraulic conductivity, $K_s$ (m/s)	$6  imes 10^{-13}$	$5.35  imes 10^{-11}$		
Heat capacity (J/(kg K))	1548	850	[60]	
Thermal conductivity (W/(m-K))	1.73	2.9		
Initial temperature (K)	293.15	293.15	Calibrated	
Reference temperature (K)	293.15	293.15	Calibrated	
Young's modulus (Pa)	$5 imes 10^6$	$60  imes 10^6$		
Poisson's ratio	0.2	0.25	[60]	
Density $(kg/m^3)$	3150	2600		

#### 2.4.2. Parametric Study

There is a critical question to answer: how will ASR expansion evolve under different weather conditions? As an effort to address this question, this work implements a parametric study of temperature and relative humidity to assess the weather events in the model. Several benchmark problems have been proposed in the case studies to account for the evolution of the ASR under different weather conditions.

#### Seasonal Variations

There exists a correlation between temperature and humidity. In this work, this correlation is considered by considering the effect of water vapor on relative humidity. The water vapor required to saturate air during cooler seasons is lower, and therefore, the

relative humidity is larger for these seasons. On the contrary, the relative humidity has lower values for warmer seasons.

In this work, the seasonal variations of temperature and humidity are incorporated in the model in terms of the four seasons of equal duration—winter, spring, summer, and fall. The sinusoidal functions, as shown in Equations (23)–(26), are developed to represent randomness in the daily weather due to the seasonal variation. These numbers do not represent any specific region. Here, temperature and humidity data are picked in different ranges to represent random changes in the daily weather parameters. Figure 3 shows the daily temperature, and Figure 4 shows the daily relative humidity.



Figure 3. Daily temperature variations: (a) winter, (b) spring, (c) summer, (d) fall.

Winter:

T (°C) = 5 + 10 sin (2 
$$\pi$$
t/24) 0 ≤ t ≤ 24 h (1 day)

RH (%) = 82.5 + 12.5 sin (2 
$$\pi$$
t/24) 0  $\leq$  t  $\leq$  24 h (1 day) (23)

Spring:

T (°C) = 25 + 10 sin (2 
$$\pi$$
t/24) 0 ≤ t ≤ 24 h (1 day)

RH (%) = 70 + 15 sin (2 
$$\pi t/24$$
) 0  $\leq t \leq 24$  h (1 day) (24)

Summer:

RH (%) = 65 + 15 sin (2 
$$\pi t/24$$
) 0  $\leq t \leq 24$  h (1 day) (25)

Fall:

T (°C) = 
$$12.5 + 12.5 \sin(2\pi t/24) 0 \le t \le 24 h (1 day)$$

T (°C) = 35 + 10 sin (2  $\pi$ t/24) 0  $\leq$  t  $\leq$  24 h (1 day)

RH (%) = 80 + 15 sin (2  $\pi t/24$ ) 0  $\leq t \leq 24$  h (1 day) (26)



Figure 4. Daily relative humidity variations: (a) winter, (b) spring, (c) summer, (d) fall.

A piecewise function was generated to capture all the seasons together in a 1-year timeframe for both temperature and relative humidity. Figure 5 shows these piecewise functions with time (months). Seasonal variation is denoted by  $T_1$  and  $RH_1$  for annual temperature and relative humidity, respectively. It has been found from the past 30 years of climate data that a mean daily temperature anomaly follows a half-sine distribution around the year [61]. Keeping that in mind, the daily temperature and humidity are processed in such a way that they also produce half-sine distributions at the end of a complete year.



**Figure 5.** Seasonal variation: (**a**) annual temperature variations (T<sub>1</sub>), (**b**) annual relative humidity variations (RH<sub>1</sub>).

## Stochastic Distributions

To represent the annual seasonal temperature and humidity distribution, as shown above, the half-sine functions produced by Equations (27)–(28) are formulated, which periodically repeat each year throughout the simulation period. Figure 6 visualizes these functions for temperature and relative humidity, within a 1-year timeframe.

$$T(^{\circ}C) = \frac{T_{max} + T_{min}}{2} - \frac{T_{max} - T_{min}}{2} * \sin(2\pi t - f\pi)$$
(27)

$$RH(\%) = \frac{RH_{max} + RH_{min}}{2} - \frac{RH_{max} - RH_{min}}{2} * \sin(2\pi t - f\pi)$$
(28)

where  $T_{max}$  and  $T_{min}$  are the maximum and minimum temperatures in a year, which are assumed as 45 °C and -5 °C, respectively. This represents an average temperature of 20 °C. RH<sub>max</sub> and RH<sub>min</sub> are the maximum and minimum relative humidity in a year, which are assumed as 95% and 50%, respectively. The term t represents the simulation time (years), and f is a frequency factor. A value of 0.5 is assigned to the frequency factor, f.



Figure 6. Seasonal variations in 1 year: (a) temperature, (b) relative humidity.

The temperature from Equation (27) is used in Equation (11) to account for the temperature change with time. In this case, the annual average temperature at the beginning of the analysis period  $T_{a0}$  is taken as 20 °C, and the annual average temperature at the end of the analysis period  $T_a$  is taken as 23.6 °C, following the 3.6 °C temperature rise for the next 80 years [49]. The analysis period  $t_a$  is 80 years. This helps to calculate the mean temperature T<sub>mean</sub> considering the global warming impact. From here, the mean temperature T<sub>mean</sub> from Equation (11) and relative humidity RH from Equation (28) are used in the stochastic analysis to generate their stochastic distributions. Stochasticity captures the temperature and relative humidity for the next 80 years as shown in Figure 7. Here, the random field realization of the KL expansion represents the randomness in the nature due to the extreme events caused by climate change. This later updates the temperature and humidity values accordingly. The stochastic distribution is denoted by  $T_2$  and  $RH_2$  for stochastic temperature and relative humidity, respectively. It is obvious from Figure 7a that the temperature tends to increase gradually due to global warming. It is also noticeable that the temperature and humidity are decreasing at some points and increasing at later points. These stochastic distributions have the potential to randomize the ASR expansion.

Finally, based on these temperature and humidity data, case studies are conducted to visualize weather impacts on alkali–silica expansion. Table 2 presents a summary of the 10 weather cases studied in this work. Here, insulated means the concrete structure is wrapped up in such a way that the external humidity cannot supply any moisture to the structure. On the other hand, humidity can impact the concrete if it is open to the environment. A relative humidity of 30% is considered to indicate a drying stage since it cannot be zero, technically. Among these 10 weather cases, case 1 is considered a validation case to represent the ASTM C 1293 concrete prism test [38].

#### 2.4.3. ASR Damage

ASR-induced volumetric strain ( $\varepsilon_{gel}$ ) can be expressed in terms of a relationship between concrete density in damaged and non-damaged states [13]:

$$\varepsilon_{gel} = \frac{\rho_{gel}}{\rho_{gel} + \rho_c} \tag{29}$$

where  $\varepsilon_{gel}$  is the volumetric strain from ASR expansion, and  $\rho_{gel}$  and  $\rho_c$  represent the mass density of alkali-silica gel and concrete, respectively. The concrete density  $\rho_c$  after 90 days is calculated as 2475.5 kg/m<sup>3</sup>. The density of ASR gel can be calculated from Equation (30) [58].

$$\rho_{gel} = [Expanded \ ASR \ gel] \times M_{gel} \tag{30}$$

Here, [*Expanded ASR gel*] denotes the concentration of expansive *ASR gel*, and  $M_{gel}$  denotes the molar mass of the expanded ASR gel. Based on the atomic mass of the chemical elements that form the expanded ASR gel, the molar mass of the ASR gel is calculated as 119 gm/mole (0.119 kg/mole).

Finally, the ASR damage due to ASR expansion under extreme weather events is calculated from Equation (31). Damage is considered when the volumetric strain or percent expansion is greater than 0.1%.

$$D_{gel} = 2.021 \times \varepsilon_{gel} - 0.195; \varepsilon_{gel} > 0.1\%$$
(31)

where  $D_{gel}$  represents the damage due to ASR expansion.

Thus, based on the facts discussed so far, the developed ASR model accounts for the climate change impact on ASR expansion under a variably saturated porous media. This is a new development from the authors' previous work [58].



**Figure 7.** Stochastic distribution: (**a**) stochastic temperature, T<sub>2</sub> (2020–2100), (**b**) stochastic relative humidity, RH<sub>2</sub> (2020–2100).

Case ID	Ambient Temperature (°C)	Ambient Humidity (%)	Representing Conditions
Case 1	38	100	Used in the model validation [55].
Case 2	38	30	Fully insulated.
Case 3	60	30	High temperature,
			Fully insulated.
Case 4	60	100	High temperature,
			Maximum saturation.
Case 5	20	100	Low temperature, Maximum saturation.
Case 6	25	70	Room temperature and humidity.
Case 7	38	100, 30	100% humidity for the first half of the year and then
			late drying to 30% over the last half of the year.
			Drying at 30% humidity for the first half of the year
Case 8	38	30, 100	and then late water supply to 100% over the last half
			of the year.
Case 9	$RH_1$	T <sub>1</sub>	Seasonal variation.
Case 10	RH <sub>2</sub>	T <sub>2</sub>	Stochastic distribution.

Table 2. Case studies for the weather parameters.

## 3. Results and Discussion

The analysis has been performed based on the case studies and input parameters discussed in the previous sections. Accumulated results represent the average value over the whole concrete domain, i.e., the average of both the mortar and aggregate phases.

#### 3.1. Validation of the Developed Model

To ensure the accuracy of the extrapolated data, a deterministic analysis is needed to check the compatibility of the simulation results with the governing equation sets and associated environmental conditions. As such, model validation is accomplished by comparing the simulation data to the 1-year experimental data of aggregate type C8 [55]. In this case, concrete is analyzed assuming a free ASR expansion without any external loads on it. The goodness of fit of the model is estimated using the Root Mean Square Error (*RMSE*) method through the following equation:

$$RMSE = \sum_{i=1}^{N} \sqrt{\frac{(Z_i - Z_0)^2}{N}}$$
(32)

where  $(Z_i - Z_0)^2$  is the differences in squared, and *N* is the sample size.

The validation model shows a slight discrepancy in the expansion with the experimental data from a certain point at the beginning. However, simulation results intersect with it eventually at a later stage, which ensures better extrapolation beyond the validation period, as shown in Figure 8a. This model also shows a latency period at the beginning stage, which is more logical for the ASR kinetics to manifest. The RMSE values lie close to zero  $(1 \times 10^{-3} \sim 0.1 \times 10^{-3})$ , which identifies the goodness of fit, and ensure the accuracy of the estimated unknown parameters. Moreover, to verify the validated model's predictions, the same environmental conditions and model setup were applied to 14 different types of aggregates from various locations across North America [55]. The model predictions closely align with the experimental data of the 1-year ASR expansion (correlation R = 0.98). Thus, the developed model can predict the expansion behavior of concrete under an alkali–silica reaction.

This validated model will perform based on the following considerations:

- NaOH and KOH are interchangeable in the model.
- This work focuses on ASR gel production and its evolution over time. Thus, the production of non-expansive calcium silicate gel (CSH), which limits ASR expansion through a reaction between the available calcium and ASR gel, is kept out of the consideration.

- ASR-induced volumetric expansion is not unidirectional, i.e., values may change depending on the boundary conditions applied to the concrete domain.
- This model represents the stationary boundaries, i.e., the geometry is not changing with time or expansion.



**Figure 8.** Validation of the developed model: (**a**) ASR expansion in type C8 aggregate, and (**b**) experiment and model prediction for type C1-C14 aggregates.

#### 3.2. ASR Expansion Analysis

The analysis is performed on a 1-year expansion of type C8 aggregate for the first eight cases of the weather parameters, as shown in Figure 9. Case 1 is the validation case that represents the ASTM concrete prism test condition, and shows an expansion of 0.15%. Maximum expansion happens for case 4 (0.32%) after 1 year. Case 4 represents a temperature of 60 °C and maximum saturation. Unlike case 4, case 3 represents concrete with no or little saturation. It can represent concrete in a fully insulated condition. Thus, an expansion for case 3 is less than that of case 4 (0.28%). Case 2 has a temperature of 38 °C and thus, less expansion than case 3 (0.10%). Case 5 represents a low temperature but a high saturation condition. The low temperature of 20 °C highly reduces its ASR expansion (0.03%). Case 6 is for room environment condition and has a slightly higher expansion than case 5 (0.04%).



Figure 9. Expansion of ASR gel in concrete for different cases: (a) cases 1-6, (b) cases 7-8.

Case 7 considers a highly saturated state initially, and then it goes through drying during the last half of the year. With a high supply of humidity, ASR expansion continues to increase initially and reaches a value of 0.07%. When the drying stage is applied to the concrete after half of the year, expansion does not stop, but rather, it continues increasing in a decreasing manner. This can relate to concrete under late drying. Finally, after the 1-year expansion, it reaches a value of 0.12%. On the other hand, case 8 represents an opposite

phenomenon to case 7. Here, drying occurs for the first half of the year. However, expansion is bumped up significantly with an application of high humidity, and expansion reaches a value of 0.13% after 1 year. This case can relate to concrete with a late water supply.

A sensitivity check for ASR expansion is performed based on the temperature and humidity values. Figure 10 visualizes the 1-year-simulation of type C8 aggregate with different temperature values at a constant relative humidity of 100% and with different humidity values at a constant temperature of 38 °C (311.15 K). Polynomial functions are included to estimate these relations in terms of ASR expansion. High temperature and humidity provide the most favorable condition for ASR kinetics, which increases the ASR expansion. Expansion is significant when the temperature is above 26.85 °C (300 K) and the relative humidity is above 80%. These findings are consistent with earlier studies [6,7].



Figure 10. Evolution of ASR expansion: (a) ambient temperature, (b) ambient humidity.

# 3.3. Long-Term ASR Forecasts

An extended ASR analysis is performed for 10 years to represent the real-world scenario of existing concrete infrastructures. Seasonal variation, case 9, and stochastic events, case 10, are simulated on type C8 aggregate in this analysis.

Figure 11a shows that the concentration of the relevant chemical species changes as time progresses. It is obvious that the concentration of ASR gel increases initially and then keeps decreasing with the progression of time. This happens due to the presence of available water. ASR gel absorbs water or moisture from the surrounding and gets converted to the expansive gel. The concentration of water also tends to decrease as time progresses, while being absorbed by the hydrophilic ASR gel. This phenomenon has been analyzed and visualized in the author's previous work [58]. However, an interesting thing happens for the seasonal variation in this analysis. There are sudden changes in the concentration of ASR gel and water due to the extreme weather events.



**Figure 11.** Effects of extreme weather on 10-year ASR evolution in concrete: (**a**) concentration of chemical species for seasonal variation, (**b**) ASR expansion.

Case 9, seasonal variation and case 10, stochastic weather, both show sharp changes in the expansion due to the assumed piecewise function of the seasonal weather change. Figure 11b shows that the expansion takes a while to show up initially due to the latency period required for the ASR gel to absorb available moisture from the surroundings. The low temperatures during winter stabilizes ASR gel production to some extent, whereas expansion is increased again by the available moisture from high humidity. Expansion spikes at the beginning of spring, which further spikes during the summer due to high temperature, and then increases significantly later in the winter due to high humidity. On the other hand, stochastic weather shows more expansion (0.26 mole/m<sup>3</sup>) than seasonal variation (0.19 mole/m<sup>3</sup>) after 10 years. Stochasticity shows a major difference in influencing ASR gel production due to extreme weather events. Thus, weather parameters, and their extremes from climate change, trigger the highly non-linear ASR expansion in this case. These findings align with previous studies demonstrating the effects of climate change on the chemo-physical behavior of concrete infrastructures [25–28].

Case 10, stochastic weather conditions, is analyzed further to visualize how ASR expansion evolves at different locations on the concrete prism. In Figure 12a, the color scale represents the intensity of ASR expansion, where the red color identifies the region with maximum expansion. The three red points indicate three regions in the concrete domain. The coordinates as well as the expansions generated at those points are shown in Figure 12b. Expansion is maximum at a point located on the outer surface in the mortar domain (0.35%). Expansions in the middle portion are almost similar to that of the outer face (0.33%). This identifies the uniform ASR expansion over the concrete domain. However, a point located on top of the aggregate on the outer face shows no significant expansion. There is no expansion of the aggregate domain because of its hard, rocky skeleton.



Figure 12. ASR expansion under stochastic weather: (a) two-dimensional plot, (b) point plot.

Moreover, it can be identified from the two-dimensional plot that ASR expansion reaches its maximum around smaller aggregates than the larger one. Smaller aggregates provide more surface area, which interacts with the alkalis available in the surrounding media. Thus, smaller aggregates are more favorable for ASR gel production and expansion. The proximity to reactive aggregate is more likely to show more ASR expansion and damage.

Figure 13 shows that the highly non-linear ASR expansion triggered by extreme weather events can initiate severe damage to the concrete. There is no damage if expansion is within the threshold value (0.1%). However, it eventually surpasses that threshold as time progresses and damage becomes visible. A value of 1 identifies the maximum damage in concrete, i.e., 100%. Thus, ASR damage from case 9, seasonal variations, is zero until three-and-a-half years and ends up with a value of 0.18 after 10 years. On the other hand, in case 10, stochastic weather, initiates ASR damage only after one-and-a-half years. It shows an ASR damage of 0.33 after 10 years, which is more severe than that of seasonal variation. The frequent transition from expansion to the shrinkage stage, and vice versa, keeps worsening the ASR situation rapidly as time progresses.



Figure 13. Impact on the concrete due to ASR expansion: (a) ASR damage, (b) lifetime reduction.

ASR damage can be expressed in percentage to indicate the reduction in the service life of the ASR-damaged concrete. From Figure 13b, it is obvious that after 10 years the reduction in service life is less (18%) for seasonal variation but is very high for stochastic weather conditions (33%).

Thus, it is evident that surrounding weather conditions, especially temperature and humidity, greatly influence ASR expansion. Weather extremes of temperature and humidity worsen the ASR situation and make concrete more prone to damage. The developed model of this work can potentially capture these extreme weather events and predict the ASR damage and service life of concrete in a variably saturated porous media. This development represents a potential improvement over the existing studies on alkali–silica reactions under varying environmental conditions [33–35].

## 4. Conclusions

The alkali–silica reaction is a common concrete problem that can evolve under climate change impacts. It is very difficult to comprehend the effects of weather extremes and global warming from existing experimental or modeling platforms. This work addresses this lack of understanding by regarding ASR expansion under climate change by developing a two-dimensional perspective of concrete at the mesoscale. The novel stochastic approach utilizes Karhunen-Loève expansion to represent weather extremes, allowing for a more realistic representation of real-world scenarios. For the first time in concrete mesoscale, this approach links extreme weather impacts to the alkali–silica reaction. Seasonal variations and stochastic analyses are incorporated to capture the random nature of weather parameters. This study includes well-selected case studies with different temperature and relative humidity conditions in porous concrete media, simulated using Richards' Equation with a retention model for variably saturated porous media in the concrete domain.

The simulation results from the different weather parameters offer new insights into concrete service life assessment under ASR expansion. Concrete exposed to high temperatures and maximum saturation (case 4: temperature 60 °C, humidity 100%) experiences maximum damage, with a 0.32% expansion after 1 year. However, the expansion reduces significantly to 0.03% after 1 year under lower temperatures and high humidity (case 5: temperature 20 °C, humidity 100%). Additionally, a 22 °C temperature increase can double ASR expansion in a favorable environment. Saturated concrete (100% relative humidity) causes 50% more ASR expansion than unsaturated concrete (30% relative humidity) in an ASR-favorable environment (38 °C temperature). Notably, subjecting ASR-damaged structures to late drying or moisture can significantly impact the expansion behavior, leading to potential internal cracking due to cumulative stress. The accurate quantification of ASR damage over time is crucial for further understanding.

Seasonal change and stochastic weather conditions cause non-linear ASR expansion and damage in concrete structures. Seasonal variation results in an 18% service life reduction, while stochastic distribution leads to a 33% reduction after 10 years of ASR expansion. The developed ASR model reveals an 83.33% increase in damage for the stochastic weather case compared to seasonal variation. This work highlights the significant influence of extreme weather events on the service-life reduction in ASR-damaged concrete, with the potential impacts of climate change causing consecutive expansion and shrinkage in the cement–mortar matrix.

The location and service conditions of existing infrastructures play a crucial role in defining their ASR damage, underscoring the need to anticipate climate change's adverse effects on ASR-prone structures. This work incorporates extreme weather cases in the ASR prediction model, which can be adapted to make predictions for any specific location or condition by providing relevant weather data, such as mean temperature, mean relative humidity, temperature increase from global warming, etc., as inputs in the model. The novelty of this work lies in combining multiple steps within the ASR modeling framework, including ASR chemophysics, thermal equation development to address seasonal and global warming effects, stochastic weather parameter analysis, and the numerical assessment of variably saturated porous media in concrete. Thus, it helps to address significant research gaps in current ASR modeling frameworks by integrating physics-informed domain modeling and stochastic analysis. It has practical implications in assessing the long-term durability of concrete structures under the influence of ASR expansion and extreme weather events. We expect this work will potentially advance the practices of resilience and sustainable infrastructure development by supporting on-time prediction and adaptive management to account for the weather extremes in ASR-damaged concrete. The developed ASR model will provide a suitable alternative to the conventional lab testing methods to monitor the performance of existing concrete infrastructures.

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